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THEME:

**CONVERGENCE OF AI, DIGITAL ECONOMY, AND
DECARBONIZATION: ENGINEERING, SCIENCE AND
TECHNOLOGY FOR A SUSTAINABLE FUTURE**

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FOREWORD

It is with profound honour and a great sense of privilege that I introduce this volume of proceedings from the 3rd biennial International Conference on Engineering, Science, and Technology (ICEST) 2025. This publication stands as a testament to the rigorous academic exchange and innovative research presented at the conference, which was hosted by the Faculty of Engineering, University of Cross River State (UNICROSS), Calabar. Held from July 30th to August 1st, 2025, this collection is designed to be a definitive and enduring resource, capturing the seminal contributions that are shaping the future of engineering, science, and technology.

The conference theme, "Convergence of AI, Digital Economy, and Decarbonization: Engineering, Science and Technology for a Sustainable Future," addresses some of the most pressing challenges and opportunities of our time. It served as a vital forum for scholars, researchers, and industry leaders to present groundbreaking work and engage in meaningful dialogue. The papers selected for this volume represent a diverse range of topics, reflecting the interdisciplinary nature of modern scientific inquiry and its critical role in fostering a sustainable and prosperous society.

The quality of the submissions is a direct result of the dedication and expertise of the contributing authors, whose commitment to excellence is deeply appreciated. Furthermore, this publication would not have been possible without the invaluable efforts of our esteemed reviewers, whose meticulous feedback ensured the highest standards of academic integrity and quality.

On behalf of the Faculty of Engineering, I extend my deepest gratitude to the Vice-Chancellor, the entire university administration, our sponsors, and all participants. Your collective support and participation have been instrumental in making both the conference and this subsequent publication a resounding success. We trust that this volume will serve as a rich source of knowledge and inspiration for all who seek to advance the frontiers of science and technology.

Engr. Dr. Samuel Oliver Effiom

Chairman, Local Organising Committee & Sub-Dean,
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Track A:

Innovative Materials and Digital Technologies for Sustainable and Low-Carbon Construction

Circular Economy, Materials Reuse and Waste Management for Sustainability in Nigeria

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Abstract: Nigeria's rising industrialisation, urbanisation, and lack of proper waste management infrastructure are causing the country to face increasing environmental concerns. Making the shift to a circular economy (CE), which encourages resource efficiency, material reuse, and efficient waste management, offers a feasible route to sustainability. With a focus on the possibilities for material reuse in industries including electronics, construction, and agriculture, this article addresses the applicability of CE principles in Nigeria. It also looks at how waste is currently managed, pointing out areas where infrastructure, policies, and public awareness are lacking. Based on international best practices and local case studies, the paper explores ways to incorporate CE into Nigeria's development plans. Nigeria may use circular economy methods to mitigate environmental degradation, improve economic resilience, and advance sustainable development, according to the findings, provided that the appropriate legislative frameworks, technological investments, and stakeholder participation are in place.

Keywords: Sustainability, Waste Management, Circular Economy, Environmental Challenges

1. Introduction

Nigeria is confronting growing issues with resource scarcity, environmental degradation, and ineffective waste management systems as a result of its steady urbanisation. According to Ogunbiyi *et al.* [1] the prevalent linear economic model, which is based on "take-make-dispose" practices, has resulted in excessive use of natural resources and unsustainable waste production levels. As the need to shift to sustainable development paths grows, the circular economy (CE) has become a promising substitute that can distinguish detrimental environmental impacts from economic growth. The focus of a circular economy is on closed-loop systems that preserve materials, products, and components for as long as possible at their maximum usefulness and value. Recycling, remanufacturing, refurbishing, and reusing are some of the methods that CE uses to encourage resource efficiency, minimise waste generation, and foster innovation [2, 3]. The implementation of CE principles in Nigeria has the potential to alleviate long-standing environmental problems and create new business opportunities, especially in metropolitan areas where informal waste collection is already crucial [4].

According to Ghisellini *et al.* [5] materials reuse is a crucial component of the circular economy and has a major positive impact on energy conservation, greenhouse gas emissions reduction, and the extraction of virgin materials. There is already some degree of reuse of textiles, electronics, and building materials in Nigeria, albeit mostly in the unorganised sector. However, the spread of reuse-based systems has been constrained by a lack of standardised rules and regulations, low awareness, and insufficient policy support [6]. Nigeria still has inadequate waste management systems that mostly rely on open dumping, uncontrolled landfills, and inadequately managed municipal waste materials collection. There are serious health and environmental hazards associated with these practices. Sustainable development can be greatly aided by incorporating circular economy principles into national waste management plans, such as encouraging recycling sectors, waste-to-energy conversion, and extended producer responsibility (EPR) [7].

This article explores how waste management, materials reuse, and the circular economy might work

together to promote sustainability in Nigeria. It analyses the existing situation, assesses implementation challenges, and makes useful policy and technology suggestions to steer Nigeria in the direction of a more sustainable and circular future.

2. The Concept of Circular Economy

According to the Ellen MacArthur Foundation [2], the circular economy (CE) is a restorative and regenerative economic model that aims to minimise waste production while preserving the value of goods, materials, and resources in the economy for as long as feasible. The circular economy is founded on three key fundamental principles: preventing waste and pollution, reusing resources and products, and regenerating natural systems, in contrast to the conventional linear model, which employs a "take-make-dispose" cycle [3]. Practically speaking, CE promotes cutting-edge strategies including eco-design, modular manufacturing, sharing and service-based economies, and material loop closure via recovery, recycling, and reuse. These strategies seek to promote sustainable development and minimise adverse environmental effects. Circular economy solutions hold great promise for revolutionising production and consumption systems in Nigeria, where waste generation is on the rise and raw materials are frequently used inefficiently [1].

Though there are significant prospects in industries including manufacturing, construction, energy, and agriculture, CE application in Nigeria is still in its early stages. For example, the conversion of organic agricultural waste into compost or bioenergy can reduce the need for fossil fuels and synthetic fertilisers [7]. Likewise, materials from building and demolition can be recycled into infrastructure projects, which reduce the need for new resources. To fully reap the benefits of CE in Nigeria, however, a number of impediments must be eliminated, such as poor infrastructure, lax enforcement of policies, insufficient public awareness, and a lack of funding. Although they offer a basis for material recovery, existing independent recycling networks frequently function without official system integration or regulatory backing [4]. As a result, it is crucial to establish an enabling environment through national CE policies, green technology investment, and stakeholder participation. Nigeria's shift to a circular economy presents both an economic and environmental opportunity. It provides avenues for innovation, employment development, and resistance to shocks from the global environment and resource scarcity [6]. Adopting circularity could place Nigeria in a leadership position for sustainable development in West Africa.

3. Materials Reuse

A key element of the circular economy is materials reuse, which is the recovery and direct repurposing of discarded items, parts, or materials for the same or other uses without requiring extensive reprocessing. This strategy minimises energy use and environmental damage related to the extraction and processing of raw materials, in addition to reducing the demand for virgin materials [5]. A strategic route to sustainability is provided by the growth of materials reuse approaches in Nigeria, where waste generation and resource inefficiency are major issues.

For example, materials like steel, bricks, roofing sheets, and wood are commonly recycled and repurposed in the construction sector, especially for private building projects. Despite not being systematically regulated, this practice shows how circularity can be implemented in one of Nigeria's most resource-intensive industries [8]. In a similar vein, the increasing amount of electronic waste, or "e-waste," offers both opportunities and challenges. In cities like Lagos and Aba, unlicensed repair and refurbishing markets prolong the life of computers, cell phones, and other household devices, boosting local businesses and keeping the waste materials out of landfills [6]. Second-hand garment marketplaces, also known as Okrika, are a prime example of the textile industry's long-standing reuse culture. These markets greatly reduce textile waste and related emissions from fast fashion imports while providing millions of Nigerians with reasonably priced items of clothing [9]. The lack of supporting infrastructure, quality control guidelines, and incentives has restricted the scalability and safety of reuse programs in spite of these unofficial reuse strategies. Poor waste segregation at the source, ignorance of the advantages of reuse, a lack of data on material flows, and policy gaps are some of the obstacles to material reuse in Nigeria. According to Nzeadibe and Anyadike [4], the stigma attached to reusing materials also prevents

widespread adoption, especially among middle- and upper-class consumers. Coordinated actions, including awareness campaigns, legislative changes, and infrastructure investment for reuse and repair, are needed to address these issues. Establishing material recovery facilities, incorporating reuse standards into public procurement regulations, and encouraging innovative product design that promotes modularity and disassembly are some ways that the public and private sectors can encourage change [10]. With these policies in place, Nigerian material reuse can progress from disorganised unstructured behaviours to a formalised cornerstone of the country's circular economy strategy.

4. Waste Management for Sustainability

Sustainable development requires efficient waste management, especially in nations that are developing like Nigeria where population growth and urbanisation have increased the strain on already vulnerable waste materials infrastructure. According to Akinwale *et al.* [7], Nigeria's current waste management strategy is primarily linear and disposal-oriented, mainly depending on open dumping, poorly maintained landfills, and informal sector collection. This approach not only endangers the environment and human health, but it also ignores the economic value that waste streams contain.

According to Wilson *et al.* [11], the 4Rs hierarchy—Reduce, Reuse, Recycle, and Recover—must be adopted in order to move towards a circular and sustainable waste management paradigm. This hierarchy places an emphasis on minimising waste generated and optimising resource recovery. However, this transformation is still being hampered in Nigeria by issues like poor infrastructure, poor implementation of environmental laws, inadequate public knowledge, and little investment in waste technology [4].

The most noticeable waste stream in Nigerian cities is municipal solid waste (MSW); cities such as Lagos produce more than 13,000 tonnes of MSW every day, much of it organic [12]. Organic waste is still mostly unutilised because of inadequate segregation procedures and a lack of treatment facilities, even though composting and anaerobic digestion have potential. The majority of Nigeria's urban waste is also made up of plastic waste. Although small businesses and informal recyclers participate in plastic recovery, the effectiveness and scalability of recycling are restricted by the lack of organised collection and processing systems [1].

Another significant sustainability issue is e-waste. E-waste has increased due to rapid technological advancement and rising electronic device consumption; a large portion of this waste is handled in dangerous settings by inefficient personnel [6]. The e-waste industry must be formally established through extended producer responsibility (EPR) programs, secure collection locations, and recycling facilities in order to reduce health and environmental hazards and generate green jobs.

In order to enhance waste management for sustainability in Nigeria, a number of operational and policy changes are required. These include encouraging the use of digital tools for waste tracking and accountability, investing in public-private partnerships (PPPs), increasing environmental education, and decentralising waste management authorities [13]. Additionally, efficiency and inclusivity can be improved by incorporating the informal labour market into formal systems through certification, training, and financial access.

In Nigeria, implementing a circular waste management strategy may significantly mitigate environmental deterioration, foster economic stability, and enhance public health favourable outcomes. To ensure a sustainable and resource-efficient future, the transition calls for concerted efforts by the corporate sector, civic society, and all governmental levels.

5. Case Studies and Best Practices

In order to adopt sustainable waste and resource management methods in Nigeria, it is beneficial to examine successful circular economy initiatives and global best practices. Through the sustainable use of resources, nations that have incorporated the ideas of the circular economy into their industrial systems and national policies show promise for social progress, environmental preservation, and economic growth.

- i. When it comes to sustainable waste management, Sweden is a world leader. Sweden recycles almost half of its municipal waste and uses more than 49% for energy recovery, with less than 1% of waste ending up in landfills, by virtue of its waste-to-energy (WTE) program and innovative

- recycling technologies [14]. Public awareness initiatives, producer responsibility regulations, and the nation's robust rules and regulations have all played a part in this achievement. Nigeria might greatly reduce its reliance on landfills by implementing comparable systems, especially those pertaining to WTE and extended producer responsibility.
- ii. The Netherlands provides an example of how to apply the concepts of the circular economy to the constructing industry. The Dutch have encouraged modular construction, lifespan evaluations, and the reuse of building materials through government-led programs and public-private partnerships. Achieving a completely circular construction industry by 2050 and halving the use of raw materials by 2030 are two objectives of the "Circular Construction Economy" plan [15]. Similar programs could help Nigeria's increasingly urbanising cities, particularly in promoting the reuse of materials from construction and demolition.
 - iii. Japan has put in place a national policy called the Sound Material-Cycle Society, which encourages waste reduction and resource efficiency through extensive recycling programs and eco-design guidelines [16]. For efficient waste segregation, collection, and processing, local governments work closely with the private sector. By decentralising waste management and enhancing material recovery infrastructure, Nigeria can adopt certain elements of this strategy.
 - iv. Despite still being in the early stages of its circular economy strategy, South Africa has made significant progress in recycling plastics because of programs like PETCO, a producer responsibility organisation (PRO) for PET. In the informal sector, PETCO has helped to create thousands of employments by facilitating the collecting and recycling of more than 100,000 tonnes of PET each year [17]. Nigeria, a country with comparable socioeconomic conditions, might adopt this concept to boost the informal recycling sector and enhance sustainability effectiveness.
 - v. A local example of a developing best practice is Lagos State in Nigeria. The Lagos Waste Management Authority (LAWMA) has put in place programs such prototype composting plants, private sector involvement in collection of waste, and domestic waste separation [12]. These examples show the possibility of concerted public-private cooperation in urban waste management, notwithstanding broad adoption issues.

These global and indigenous experiences demonstrate how important policy, stakeholder involvement, and infrastructure spending are to achieving the goals of the circular economy. Nigeria must scale up pilot programs, adapt global lessons to its local environment, and guarantee inclusivity by incorporating informal workers into the formal waste economy if it is to completely adopt these practices.

6. Challenges and Opportunities

The Nigeria's shift to a circular economy is complicated but also full of promise. The advantages of combining sustainable waste management with material reuse are widely known, but in order to fully realise circularity's potential, specific challenges must be overcome. These challenges cut across the social, regulatory, infrastructure, and economic spheres.

- i. **The absence of suitable infrastructure for waste collection,** processing, and segregation is one of the most critical problems. The majority of Nigerian cities still mainly rely on uncontrolled landfills and open dumping, which makes recycling and material recovery difficult [7]. Furthermore, not much money is being spent on cutting-edge waste processing technologies including anaerobic digestion, composting, and waste-to-energy plants.
- ii. **Institutional and regulatory challenges:** These make the development much more difficult. Waste management and environmental protection policies do exist, however they are not well implemented or enforced. Additionally, there is a lack of coordination across federal, state, and local government entities, which results in ineffective service delivery and overlapping responsibilities [1]. Furthermore, Extended Producer Responsibility (EPR) frameworks, which are crucial for making producers answerable for the end-of-life handling of their products, have not yet been fully implemented in Nigeria.

- iii. **Financial constraints.** Lack of finance poses another challenge. Large initial investments are frequently needed for circular economy initiatives, with future advantages to become realised. Public and private sector actors' capacity to expand sustainable practices is constrained by the lack of specialised financing tools including green bonds, concessional loans, and blended finance [13].
- iv. **Social and cultural factors.** The social and cultural factors also play their own role. The advantages of recycling and reuse for the environment and the economy are not well known. Reused products are not widely accepted, particularly among the middle and upper classes, due to cultural beliefs that link them to poverty [4]. Furthermore, although playing a vital role in waste recovery, the informal sector is frequently left out of policy formation and support mechanisms, despite being very active in recycling and maintenance.

Notwithstanding these challenges mentioned above, Nigeria has a lot of chances to promote a circular economy. Rapid technological advancement and digitisation provide resources for monitoring materials movements, enhancing transparency, and streamlining waste management. Waste collection, recycling, and reporting systems can be improved by utilising block-chain, mobile applications, and Internet of Things (IoT) technology [10].

There are a lot of young people in Nigeria that have a lot of potential as entrepreneurs.

Promoting green innovation and entrepreneurship in fields like eco-design, sustainable packaging, and recycling may boost employment and the economy. International cooperation can also make it easier to transfer knowledge, build capacity, and obtain funding through alliances with international governments, development organisations, and global firms. The growing demand for low-carbon production and sustainable supply chains around the world provides Nigeria with financial motivation to adopt circular economy principles. Nigeria may make progress towards a more resilient and sustainable future by incorporating circularity into national development goals, bolstering policy frameworks, and encouraging cross-sector cooperation.

7. Conclusion

Nigeria may attain sustainable development, environmental preservation, and economic resilience by strategically implementing the shift to a circular economy. Reusing materials and implementing sustainable waste management techniques into national systems can greatly minimise resource depletion, stop adverse environmental effects, and promote green economic growth, as this article discussed. Nigeria has the ability to shift towards circularity, even if it now relies on linear patterns of production and consumption. Challenges such as inadequate funds, poor infrastructure, poor implementation of policies, as well as inadequate public awareness made it difficult to progress. Nevertheless, it is not impossible to overcome these challenges. Global best practices show that nations can effectively move to circular systems through technological innovation, stakeholder collaboration, coordinated policy efforts, and informal sector participation. Nigeria should use these lessons to its advantage while adapting solutions to its socioeconomic reality and local setting.

Strengthening political will, forming public-private partnerships, and making consistent investments are necessary to advance circular economy concepts like eco-design, materials reuse, recycling, and expanded producer responsibility. By empowering communities and businesses through education, incentives, and capacity-building programs, we may also promote a cultural change towards sustainable measures. Ultimately, Nigeria can transform its waste problems into possibilities, generating employment, protecting the environment, and guaranteeing a more sustainable and prosperous future for subsequent generations by adopting a circular economy framework.

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Experimental sand Taguchi Optimisation Technique to Determine the Tensile Strength of Cow Bone and Cassava Cortex Hybrid Composite for Automotive Application

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Abstract: The increasing demand for sustainable, lightweight, and high-performance materials in the automotive industry has led to extensive research into the development of bio-based composites. Natural fibre composites, though environmentally friendly, often lack the mechanical strength required for structural applications. This study investigates the development and optimisation of a hybrid composite material reinforced with cow bone and cassava cortex particles, aimed at improving tensile strength for potential automotive applications. The composite samples were fabricated using the hand lay-up method and reinforced with varied proportions of cow bone and cassava cortex particles. An L18 orthogonal array based on the Taguchi method was employed to systematically design the experiments and optimise three key factors: reinforcement composition, NaOH chemical treatment, and particle size. Tensile strength tests were conducted in accordance with ASTM D3039 standards using a Universal Testing Machine. The results showed that the optimal configuration—20% cow bone, 20% cassava cortex, 4% NaOH treatment, and 100 μ m particle size—yielded the highest tensile strength of 91.80 MPa. Statistical analysis using signal-to-noise (S/N) ratios and ANOVA confirmed reinforcement composition as the most significant factor influencing strength, followed by chemical treatment and particle size. The study demonstrates that agricultural waste materials can be effectively converted into high-performance reinforcements in polymer composites through appropriate optimisation techniques. The findings support the feasibility of developing cost-effective, environmentally sustainable composite materials with improved mechanical performance for specific automotive structural applications.

Keywords:

Keywords: Optimisation, automotive application, hybrid composites, tensile strength, biomaterials.

1. Introduction

The growing worldwide concern for ecological preservation and the prudent utilisation of sustainable resources has ignited substantial research into the creation of composite materials strengthened with naturally derived fibres and bio-fillers. This evolving focus stems from the inherent drawbacks and ecological implications linked to conventional reinforcing materials such as glass and carbon fibres, encompassing elevated production expenses and their non-biodegradable nature. Consequently, the investigation of agricultural waste products as practical and environmentally friendly strengthening agents within polymer matrices has gained considerable traction. Among these, bovine bone, a readily obtainable waste product from the meat processing sector, and the outer layer of the cassava root, a significant byproduct of cassava cultivation and processing, have emerged as promising choices due to their inherent material qualities and widespread availability [1], [2] and [3].

To further elevate the performance characteristics of these bio-filler composites and adapt them for demanding applications, the concept of combining different strengthening materials has gained significant momentum in materials science. Hybrid composites, engineered by incorporating two or more distinct reinforcement materials within a single matrix, often exhibit synergistic effects, leading to an enhanced overall property profile compared to composites strengthened with a single type of filler [4], [5]. By strategically uniting the complementary characteristics of different reinforcements, such as the mineral-rich makeup of bovine bone and the carbon-based structure of treated cassava cortex, it is anticipated that a hybrid composite could achieve a superior equilibrium of mechanical strength, rigidity, and weight reduction. This approach holds considerable promise for addressing the stringent material performance

demands of the automotive industry, where reducing weight is a crucial strategy for improving fuel efficiency and lowering greenhouse gas emissions [6] and [7].

According to [8] and [9], the resistance of a material to pulling forces stands as a paramount mechanical property for automotive applications, as numerous components are subjected to such stresses during their operational life. Consequently, the precise determination and subsequent optimisation of the tensile strength of innovative composite materials, such as bovine bone and cassava cortex hybrids, are crucial for their successful integration into automotive designs. Traditional experimental methods for material characterisation, while yielding valuable data, can be resource-intensive and time-consuming, particularly when examining the influence of multiple factors on the desired mechanical attribute. To overcome these limitations, statistical optimisation techniques, notably the Taguchi method, offer a systematic and efficient framework for identifying the ideal combination of experimental parameters [10] and [11]. The Taguchi method, utilising orthogonal arrays for experimental design, enables the examination of multiple control factors with a significantly reduced number of experimental trials, thereby providing valuable insights into the factors that significantly influence tensile strength and facilitating the identification of optimal processing conditions for its maximisation [12] and [6]. Numerous studies have successfully applied the Taguchi method to optimise the mechanical properties of various composite materials by adjusting factors such as reinforcement loading, processing conditions, and chemical [13] and [7].

Considering the increasing demand for sustainable and lightweight materials within the automotive sector, this research aims to explore the potential of a novel hybrid composite material derived from bovine bone and cassava cortex. By employing a rigorous experimental methodology in conjunction with the Taguchi optimisation technique, this study aims to determine the ideal compositional parameters of the hybrid composite to achieve maximum tensile strength. The findings of this investigation are expected to contribute significant insights into the feasibility of utilising these readily available agricultural wastes as reinforcing agents in polymer composites for automotive applications, potentially paving the way for more environmentally responsible and cost-effective material solutions within the industry.

2. Materials and Methodology

2.1 Materials

This study utilised cow bones sourced from local abattoirs, cassava cortex obtained as a byproduct of cassava processing, epoxy resin R127PH, wood moulding materials for composite fabrication and testing specimens prepared according to relevant ASTM standards. For the Taguchi optimisation, L₁₈ orthogonal array was adopted by using Minitab 22 software. Finally, a universal testing machine (UTM) was used to determine the tensile strength.

2.2 Preparation and Composite Production

The production of cow-bone and cassava cortex hybrid epoxy composites for tensile strength optimisation using the Taguchi method began with the preparation of raw materials sourced locally in Calabar, Cross River State, Nigeria. Cow bones and cassava cortex were cleaned, dried, and pulverised into specific particle sizes, with optional pre-treatments applied to enhance adhesion. A commercially available epoxy resin and hardener were then used to fabricate composite samples with varying weight ratios of the bio-fillers, total filler content, and potentially different particle sizes and pre-treatment conditions, as dictated by the chosen Taguchi orthogonal array. The hand lay-up method was employed for composite fabrication in rectangular moulds, followed by room temperature and/or post-curing, and subsequent machining of the panels into standard ASTM D3039 tensile test specimens. Composite preparation is summarised in Figure 1.

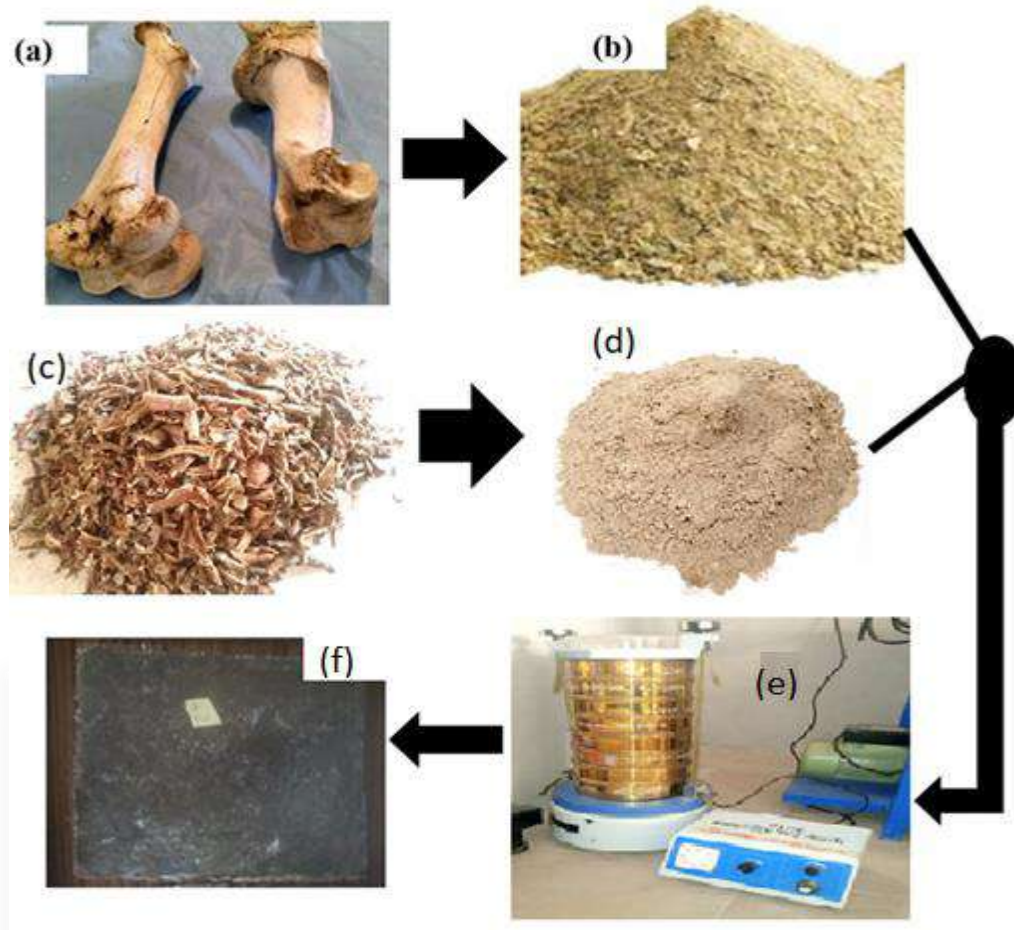


Figure 1: preparation of the composites (a) cow-bone, (b) cow-bone particles, (c) cassava cortex, (d) cassava cortex particles, (e) sieve shaker, (f) composite sample

2.3 Tensile test and Taguchi Optimisation

Tensile strength testing was performed using a Universal Testing Machine, according to ASTM D638 standards, to obtain failure load data for each specimen. The recorded tensile strength values were then analysed using the Taguchi methodology. This involved calculating Signal-to-Noise (S/N) ratios (using the "larger-the-better" criterion), conducting Analysis of Variance (ANOVA) to identify significant factors, determining optimal factor levels from response tables and graphs, predicting the optimal tensile strength, and finally, validating the prediction with a confirmation experiment.

Table 1 presents the mixing ratio for the composites of cassava cortex, cow bone, and epoxy. The Taguchi optimisation for the composite fabrication process was systematically implemented to determine the optimal processing factors for maximising desired properties. First, the key processing factors were identified: (1) reinforcement type (cow bone, cassava cortex, or hybrid ratios), (2) particle size of the reinforcement materials, and (3) chemical treatment of the reinforcements (

Table 2). These factors were assigned specific levels, representing different variations within each factor. For example, reinforcement type had six levels (e.g., 40% cow bone, 35% cow bone/5% cassava cortex, 30% cow bone/10% cassava cortex, 20/20, 10% cow bone/30% cassava cortex, 40% cassava cortex), particle size had three levels (i.e., 100 μm , 250 μm , 500 μm), and chemical treatment had three levels (i.e., no treatment, 2% alkali treatment, 4% alkali treatment).

Table 1: Mixing ratio for the composites for cassava cortex, cow bone and the epoxy

No	Designation	Cassava Cortex (vol.%)	Cow bone (vol.% %)	Epoxy (vol.% %)
1	A	0	0	100
2	B	0	40	60
3	C	10	30	60
4	D	20	20	60
5	E	30	10	60
6	F	40	0	60

Table 2: Processing factors and their level

Factor	Abbreviation	Unit	Level					
			1	2	3	4	5	6
Reinforcement	R	%	A	B	C	D	E	F
Treatment	T	%	0	2	4	-	-	-
Particle Size	PS	µm	100	250	500	-	-	-

3. Results and discussion

3.1 Tensile strength

Table 3 presents L₁₈ Processing factors, processing factors, designation and S/N ratio for tensile strength. The signal-to-noise ratio, which is an indication of impact in the system, is also presented. It is noticed that the lowest tensile strength was obtained from sample #1 (72.66 MPa), where there was no reinforcement of either cow bone or cassava cortex filler. This shows that all samples with no reinforcement had the least tensile strength, that is, samples #1, 2 and 3 had 72.66, 73.20 and 74.60 MPa, respectively (Figure 2). With the addition of reinforcement, there was a significant increase in the tensile strength. The impact of reinforcement has been highlighted by several authors with reports of increased strength. However, sample #12 (R₄T₄PS₁₀₀) had the highest tensile strength. This implies that 20% cow-bone and 20% (R₄), 4% NaOH Treatment (T₄) and 100-micron particle size (PS₁₀₀) combination gave the optimal value of 91.80 MPa. The synergetic combination between the reinforcement of cow-bone and cassava cortex particle might have created a strong bond affinity [14]. [15] reported that an increase in fibre treatment, such as NaOH treatment up to 4%, has been proven to be effective in enhancing the tensile strength of the composite. This is due reduction of hemicellulose sites, weakening of lignin to reduce mobility and an increase in cellulosic sites available for resin interaction [16]. In addition, lower particle size might have also contributed to the superior strength. As reported by [17], lower particle size increases surface area, increases the aspect ratio. Figure 2 presents the tensile strength of the composite samples.

Table 3: L₁₈ Processing factors, processing factors, designation and S/N ratio for tensile strength

S/N	Reinforcement (R) %	Treatment (T) %	Particle Size (PS) μm	Designation	S/N ratio (dB)	Tensile (MPa)
1	A (1)	0	100	R ₁ T ₀ PS ₁₀₀	37.81	72.66
2	A (1)	2	250	R ₁ T ₂ PS ₂₅₀	37.84	73.2
3	A (1)	4	500	R ₁ T ₄ PS ₅₀₀	37.84	74.6
4	B (2)	0	100	R ₂ T ₀ PS ₁₀₀	38.9	88.1
5	B (2)	2	250	R ₂ T ₂ PS ₂₅₀	38.94	88.5
6	B (2)	4	500	R ₂ T ₄ PS ₅₀₀	38.97	88.8
7	C (3)	0	100	R ₃ T ₀ PS ₁₀₀	38.51	84.2
8	C (3)	2	250	R ₃ T ₂ PS ₂₅₀	38.7	86.1
9	C (3)	4	500	R ₃ T ₄ PS ₅₀₀	38.61	85.2
10	D (4)	0	500	R ₄ T ₀ PS ₅₀₀	39.02	89.3
11	D (4)	2	250	R ₄ T ₂ PS ₂₅₀	39.24	91.6
12	D (4)	4	100	R ₄ T ₄ PS ₁₀₀	39.26	91.8
13	E (5)	0	100	R ₅ T ₀ PS ₁₀₀	37.52	80.2
14	E (5)	2	250	R ₅ T ₂ PS ₂₅₀	37.64	81.2
15	E (5)	4	500	R ₅ T ₄ PS ₅₀₀	37.77	83.4
16	F (6)	0	100	R ₆ T ₀ PS ₁₀₀	37.09	79.3
17	F (6)	2	250	R ₆ T ₂ PS ₂₅₀	37.17	76.2
18	F (6)	4	500	R ₆ T ₄ PS ₅₀₀	37.45	77.6

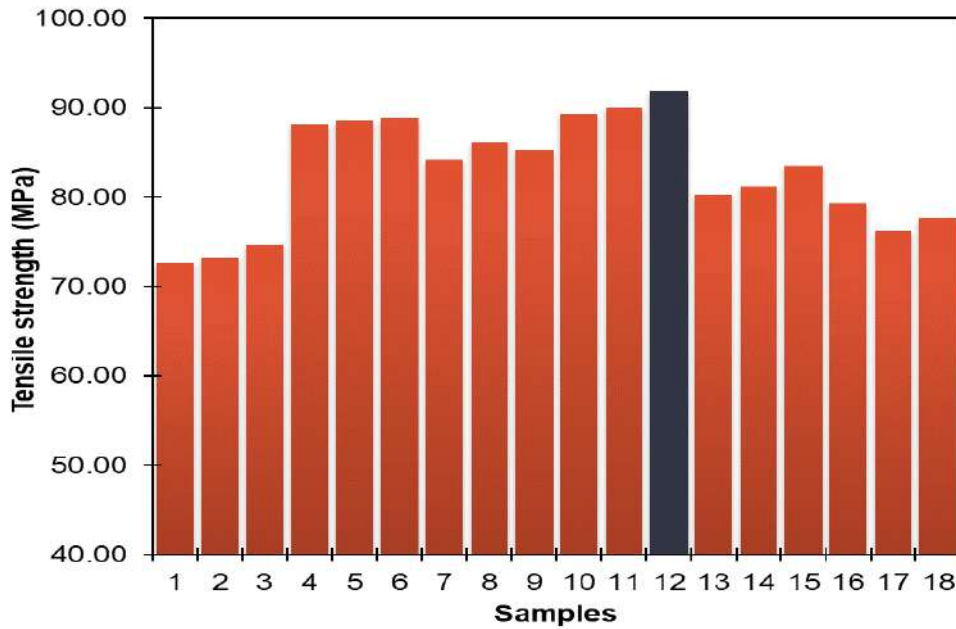


Figure 2: Tensile strength of the samples

3.2 Taguchi Optimisation

This section describes the tests performed on the composites as a result of the optimisation. As such, responses such as signal-to-noise ratio can be calculated. In addition, percentage contribution (analysis of variance), model error from regression equation, as well as residual plot are evaluated.

3.2.1. Signal-to-noise ratio

The signal-to-noise (S/N) ratio, a key metric in the Taguchi method, was employed to ascertain the ranking and optimal levels of the factors influencing the tensile strength of the cow bone and cassava cortex hybrid composite. Table 4 and Figure 2 visually represent this analysis. The delta value, calculated as the difference between the highest and lowest S/N ratio within each factor's levels, serves as an indicator of the factor's influence on the response variable. A larger delta signifies a greater impact. The analysis revealed that reinforcement exhibited the highest delta value of 1.93, indicating it as the most influential factor on tensile strength. This was followed by NaOH fibre treatment with a delta of 0.18 and particle size with the lowest delta of 0.05, suggesting their comparatively lesser influence [11].

Based on the S/N ratio analysis for maximising tensile strength, the optimal combination of factor levels was identified as R₄T₄PS₁₀₀, corresponding to 20% cow bone, 20% cassava cortex (reinforcement), 4% NaOH treatment, and a particle size of 100 μ m. This optimal parameter setting, derived through the Taguchi method's systematic approach to robust design, aims to maximise the signal (tensile strength) while minimising the noise (variability) [2]. Notably, this statistically determined optimal level (R₄T₄PS₁₀₀) aligns with the experimental findings, where sample 12, also designated as R₄T₄PS₁₀₀, yielded the highest tensile strength. This congruence between the Taguchi-predicted optimal conditions and the experimental results strongly validates the effectiveness of the Taguchi optimisation technique in identifying robust and high-performing material compositions for the intended automotive application.

Table 4: Response Table for Signal to Noise Ratios (Larger the better)

Level	Reinforcement (R)	Treatment (T)	Particle Size (PS)
1	37.83	38.14	38.25
2	38.94	38.25	38.25
3	38.61	38.32	38.21
4	39.17	-	-
5	37.65	-	-
6	37.24	-	-
Delta	1.93	0.18	0.05
Rank	1	2	3

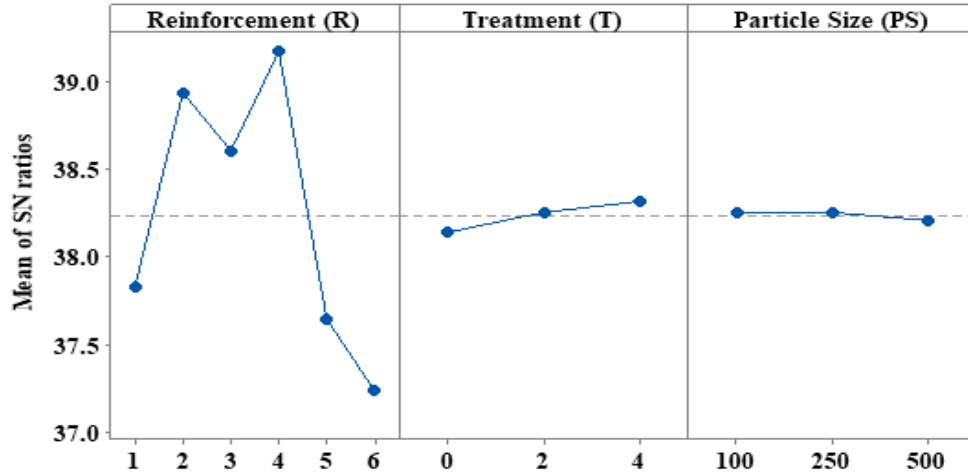


Fig.3. Signal to noise ratio for Tensile strength (Larger the better)

3.2.2. Analysis of variance

Table 5 presents the Analysis of Variance (ANOVA) for the tensile strength of the cow bone and cassava cortex hybrid composite, revealing the statistical significance and percentage contribution of the investigated factors: reinforcement, NaOH fibre treatment, and particle size. The ANOVA results indicate that reinforcement is the most influential factor, accounting for a substantial 98.22% of the total variation in tensile strength. Following in importance are NaOH fibre treatment (1.06%) and particle size (0.81%). The absence of residual error reported in the ANOVA table suggests a highly well-fitted model, where almost all the variability in the response is explained by the considered factors [18]. The p-values associated with each factor further elucidate their statistical significance. Reinforcement and NaOH treatment exhibit p-values of 0.000 and 0.021, respectively, which are typically below the conventional significance level of 0.05. This indicates that both reinforcement and NaOH treatment have a statistically significant impact on the tensile strength.

Conversely, particle size shows a p-value of 0.621, which is considerably higher than 0.05, suggesting that its effect on tensile strength is not statistically significant within the studied experimental domain. This finding aligns with the earlier corroboration from the signal-to-noise (S/N) ratio analysis, which also identified reinforcement as the most dominant factor, followed by NaOH treatment, with particle size having a comparatively minor influence. The large percentage contribution of reinforcement and its highly significant p-value underscore its critical role in determining the tensile strength of the hybrid composite. These results are crucial for optimising the material composition for automotive applications, as they highlight the key parameters that should be carefully controlled to achieve the desired mechanical properties [18].

Table 5: Analysis of Variance for SN Ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Reinforcement (R)	5	9.02645	9.02645	1.80529	244.62	0
Treatment (T)	2	0.09696	0.09696	0.04848	6.57	0.021
Particle Size (PS)	2	0.0075	0.0075	0.00375	0.51	0.62
Residual Error	8	0.05904	0.05904	0.00738		
Total	17	9.18995				

3.2.3. Regression equation

Figure 6 visually represents the residual values (RESI), or the percentage difference, between the experimentally measured tensile strength of the cow bone and cassava cortex hybrid composite and the values predicted through the Taguchi optimisation technique, as analysed using Minitab 22 software. These residuals, ranging from -7.9% to 11.25%, provide a measure of the model's predictive accuracy for each experimental run. The coefficient of determination R^2 for the Taguchi-optimised model is reported as 91.5%. This R^2 value, which indicates the proportion of the variance in tensile strength explained by the model, suggests a strong correlation between the factors optimised by the Taguchi method and the resulting tensile strength of the hybrid composite. According to statistical literature, an R^2 value close to 1 signifies a high degree of model fit and predictive power [19].

The observed range of residuals, from -7.9% to 11.25%, provides a quantitative assessment of the prediction error associated with the Taguchi optimisation. While a perfect model would exhibit zero residuals, some degree of error is inherent in empirical modelling. The fact that the R^2 value is high (91.5%) suggests that despite the presence of these residuals, the Taguchi optimisation technique has effectively captured the significant factors influencing the tensile strength of the hybrid composite. This level of predictive accuracy, supported by a high R^2 and a relatively constrained range of residuals, indicates the potential of the Taguchi method for optimising the composition and processing parameters of this novel biomaterial for automotive applications, aligning with the goals of materials design and optimisation studies [19]. Equation 1 presents the linear regression equation for Tensile strength.

$$87.04 - 1.615 \text{ Reinforcement (R)} + 0.408 \text{ Treatment (T)} - 0.00102 \text{ Particle Size (PS)} \quad (1)$$

Table 6: Experimental value, optimisation prediction and percentage error for tensile strength

S/N	Tensile strength (MPa)	FITS (Prediction)	RESI	% Difference
1	72.66	77.32	-4.66	-6.41
2	73.20	78.98	-5.78	-7.90
3	74.60	77.54	-2.94	-3.95
4	88.10	83.71	4.40	4.99
5	88.50	84.37	4.13	4.67
6	88.80	84.93	3.87	4.36
7	84.20	81.94	2.26	2.69
8	86.10	82.50	3.60	4.18
9	85.20	83.72	1.48	1.73
10	89.30	80.07	9.24	10.34
11	91.60	81.29	10.31	11.25
12	91.80	81.95	9.85	10.73
13	80.20	78.71	1.49	1.86
14	81.20	79.27	1.93	2.38
15	83.40	80.49	2.91	3.49
16	79.30	76.83	2.47	3.11
17	76.20	78.06	-1.86	-2.44
18	77.60	78.72	-1.12	-1.45

3.2.4 Residual plot

To assess the reliability and accuracy of the Taguchi optimization model for predicting the tensile strength of the cow bone and cassava cortex hybrid composite, a probability plot of the residuals was employed in conjunction with other diagnostic plots derived from the signal-to-noise (S/N) ratio analysis (Figure 4). These additional plots, including the histogram of residuals, residuals versus fitted values, and residuals versus observation order, provide a comprehensive visual evaluation of the model's assumptions and predictive capability. The probability plot specifically helps in determining if the residuals follow a normal distribution, a key assumption of many statistical models. As noted in statistical literature, a well-aligned linear pattern of residuals on the probability plot, with minimal deviation, strongly suggests that the errors are normally distributed, indicating a robust and accurate model [10].

The stated 95% confidence level (with a corresponding 5% chance of failure) associated with the system underscores the statistical reliability of the findings. This confidence level implies that there is a high probability that the conclusions drawn from the Taguchi analysis, regarding the optimal parameters for maximising tensile strength, are statistically significant and not due to random chance. The observation that the plots and the resulting responses from the samples exhibit significant reliability is further supported by the alignment of residuals on the probability plot and the patterns observed in the other diagnostic plots. These visual assessments, coupled with the high confidence level, reinforce the validity of the Taguchi optimisation technique in identifying robust and reliable conditions for achieving desired tensile strength in the developed hybrid composite for its intended automotive application [10].

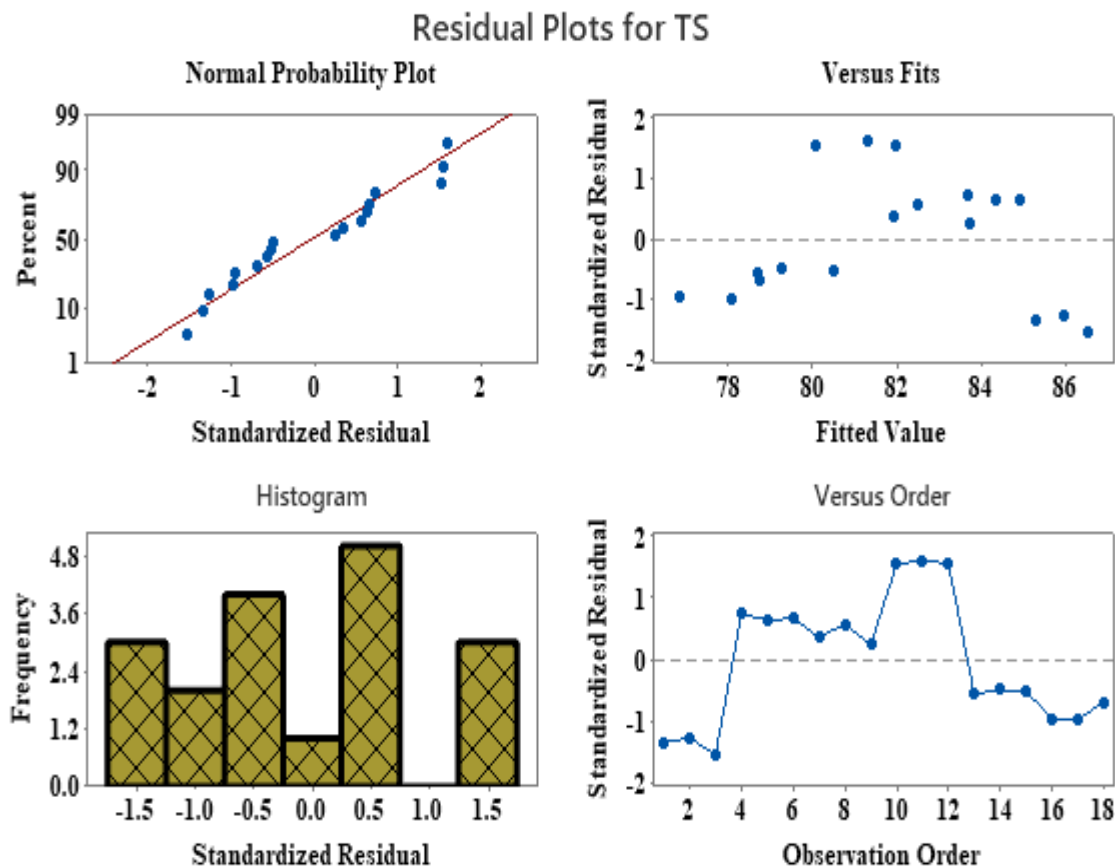


Fig. 4. Residual Plot

4. Conclusions

In the pursuit of sustainable lightweight materials for the automotive industry, this research strategically employed the Taguchi optimisation technique to enhance the tensile strength of a novel hybrid composite derived from cow bone and cassava cortex. Recognising the limitations of conventional natural fibre composites in structural applications, the study meticulously investigated the influence of reinforcement ratio (cow bone/cassava cortex), NaOH treatment concentration, and particle size. The findings culminated in the identification of sample 12, characterised by a 20% cow bone and 20% cassava cortex reinforcement blend, 4% NaOH treatment, and a 100 μm particle size, as exhibiting the highest tensile strength of 91.80 MPa. This optimal formulation, designated as R₄T₄PS₁₀₀, was consistently predicted by the Taguchi analysis, which further revealed that the reinforcement ratio exerted the most significant influence on tensile strength, followed by NaOH treatment and particle size.

The robustness and reliability of the Taguchi-optimised model were rigorously evaluated through error analysis and residual plotting. The percentage errors between the experimental and predicted tensile strength values were consistently below the 10% acceptable threshold, indicating a high degree of predictive accuracy. Furthermore, the probability plot of the residuals demonstrated a linear alignment, confirming the absence of significant outliers and supporting the model's validity. The strong agreement between the experimentally determined optimal sample (sample 12/R₄T₄PS₁₀₀) and the optimal parameters predicted by the Taguchi method underscores the efficacy of this statistical approach in optimising the composition of the cow bone/cassava cortex hybrid composite for enhanced tensile strength. Consequently, the identified formulation (20% cow bone, 20% cassava cortex, 4% NaOH treatment, and 100 μm particle size) holds significant promise as a sustainable and potentially viable lightweight material for specific automotive applications, warranting further investigation into its broader mechanical properties and long-term durability.

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Modification of Lignocellulosic Polymer via Chemical Treatments to Improved Bamboo Plastic Composites

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Abstract: Wood plastic composites (WPC) have replaced traditional materials in numerous applications due to their favourable properties, such as lightweight, durability and cost-effectiveness. Bamboo is a construction material that is often discarded as waste after used. This can be reused in wpc production, but there is need for pretreatment to enhance durability and compatibility with plastics. WPC made from bamboo and plastic waste are pre-treated with 5% sodium hydroxide (NaOH) to determine their physical and mechanical properties.

Waste plastic water bottles and bamboo wastes were collected and used in the proportions 100/0, 95/5, 90/10, 85/15 and 80/20 respectively. The samples were produced through injection moulding method. Water absorption (WA), Density, thickness swelling (TS) and flexural strength were the properties determines according to ASTM standards. For untreated and treated bamboo plastic composites (BPC), the density decreases as the bamboo content increases from 5% to 20%. WA for untreated ranges 0.07% to 1.08% for 24hrs soaking in water while the treated WA ranges from 0.05% to 0.42% for 24hrs soaking in water. Similarly, TS for untreated ranges from 0.09% to 0.61% for 24hrs soaking in water while treated ranges from 0.07% to 0.53% for 24hrs soaking in water. Mechanical analysis indicated that flexural strength ranges from 1.77Mpa to 2.83Mpa for Untreated and 1.77Mpa to 3.21Mpa for treated BPC. Optimum flexural properties were obtained at 15% bamboo content for both treated and untreated. The composites' moderate strength and dimensional stability suggested that they may be used in a variety of settings such as, floor and wall tiles, wall panels and indoor insulating components.

Keywords: bamboo plastic composites, NaOH Pre-treatment, sustainability

1. Introduction

Polymers have supplanted numerous conventional materials in a variety of applications during the past few decades. Fibre-reinforced polymers are used in a variety of industries from aerospace to appliances and they provide more choices than other traditional materials when certain qualities are needed most especially in civil, marine and automotive engineering applications [1] [2]. With this wide range of applications, it is essential to find raw materials for sustainable production of these fibre-reinforced polymers. The major raw materials identified in the production of these polymers are the plastic polymer and the fibre reinforcement. While fibres can be obtained from wide range of lignocelluloses, including wood, polymers are majorly from polyethylene sources.

An estimated 60 million plastic water bottles and sachets are discarded daily in Nigeria, where 70% of people consume them at least once a day [3]. Given this claim, it is projected that in 2025, Nigeria will dispose of around 140 million plastic bottles and sachets of water waste. These discarded empty bottle containers constitute a major environmental hazard as they do not biodegrade for around 450 years [4].

Waste from building sites, particularly bamboo (*Bambusa vulgaris*), which is utilised as scaffolding, is another important sector of waste generation in Nigeria. Some of these bamboos are tossed onto open fields, while others are burned, contributing to global warming. Waste recycling is one of the most crucial elements in the current study to support Nigeria's circular economy. Low-density polyethylene, commonly referred to as plastics, is combined with recycled bamboo from building debris to create bamboo plastic composites (BPC), which have a wide variety of applications [2].

The effect of fibre modification has been studied by different researchers with the goal of enhancing the mechanical and physical characteristics of wood-plastic composites. [5] Were the first to report on the

effects of chemically treating natural fibres using sodium hydroxide and sodium alginate for sisal, coir, and banana fibres. The modification's suggestion led to a 30% improvement in ultimate tensile strength due to an increase in adhesive bonding. A solution containing 10–30% sodium hydroxide had the greatest influence on the characteristics of natural fibres, according to [6]. Flax fibres were soaked in various concentrations of NaOH solutions for the investigation, and it was found that the ideal concentrations for better composite qualities were 5, 10, and 18% sodium hydroxide solutions.

[7], investigated the effects of pre-treatment on the characteristics of lignocellulose-based biocomposites using both treated and untreated empty fruit bunch fibres (EFBF) and polypropylene (PP). The result showed that PP-treated EFBF composites with 45wt% fibre incorporation had higher mechanical properties by 50% enhancement rather than untreated EFBF. Similar study on fibre treatment was also conducted by [8]. This present study is aimed at utilising 5% NaOH for the pre-treatment of bamboo flour of to evaluate its effect on the physical and mechanical properties of the resultant bamboo plastic composites.

2. Methods

2.1. Materials selection, Pre-treatment and Preparation

Bambusa vulgaris were collected from a construction site and unitized as the reinforcing material. Bamboo was obtained from a construction site located at the Faculty of Technology, University of Ibadan, Oyo State, Nigeria. The bamboo obtained were construction wastes used as scaffolding members during the building construction process. The collected bamboo were reduced into chips as shown in figure 1 and mechanically milled, sieved into 2mm particle size, and air dried for about three days to a moisture content range of between 7% and 8%, pre-treatment was carried out on the sieved bamboo flour as the flour was soaked in distilled water with a 5% sodium hydroxide for 24 hours, it was then filtered and washed to a satisfactory level, and air dried for three days prior to bamboo plastic composites utilisation. The low-density polypropylene from recycled bottle water was also obtained from the faculty of technology building complex and chipped to 10 mm particles size and air dried for 24 hours, then stored in a dried and clean container prior to bamboo plastic production.

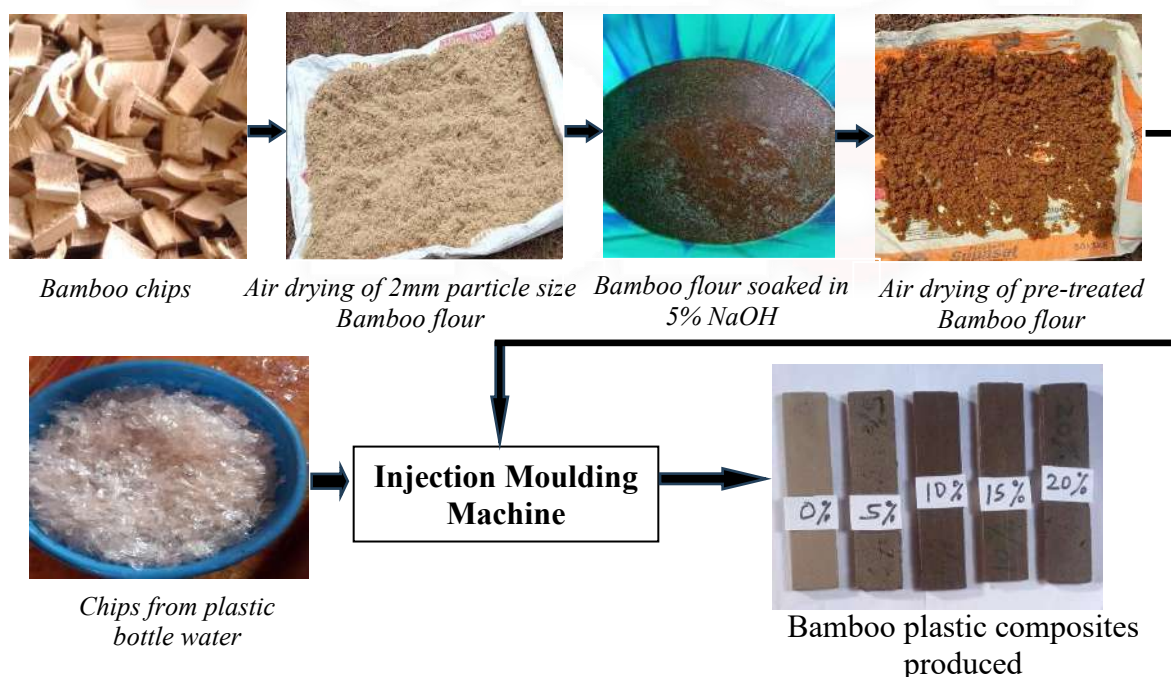


Fig. 1. Bamboo/Plastic material extraction and production process

2.2. Bamboo Plastic Composites Production

In this study, there are two stage of production in order to prepare the bamboo plastic composites (BPC) samples for test analysis. Firstly, production was carried out on untreated bamboo flour and secondly, production was carried out on treated Bamboo flour. All conditions for the first and second productions were the same. The shredded plastics and bamboo flour were moulded using an Injection moulding machine at the faculty of technology workshop, University of Ibadan. No coupling agent was used in this study. The Bamboo flour and shredded plastics were produced in a ratio (0:100); (5/95); (10/90); (15/85) and (20/80) respectively as shown in Table 1. The samples produced were moulded in different dimensions according to ASTM D790 for Flexural test with sample size of 140 x 15 x 10mm. The mould inner surface was coated with a lubricant to enhanced ease of demoulding of the samples after solidification. The hot pellets of plastics and bamboo flour of different percentage weight ratio were heated at a temperature of 160°C in a locally fabricated wood plastic injection machine and ejected into a mould and allowed to cool for about 30minutes before demoulding the final composites. The composites produced were conditioned to a temperature of about 23±2°C and relative humidity of about 50±5% for 45 hours in accordance to ASTM D618-99 prior to Physical and Mechanical Test.

Table 1: Experimental design of samples

Samples (Treated and untreated)	Mix Ratio [BF:LDPE]	Bamboo flour[g]	Plastics[g]
A BF ₀ LDPE ₁₀₀	0:100	0	120
B BF ₅ LDPE ₉₅	5:95	6	120
C BF ₁₀ LDPE ₉₀	10:90	12	120
D BF ₁₅ LDPE ₈₅	15:85	18	120
E BF ₂₀ LDPE ₈₀	20:80	24	120

All samples were produced in three replicates

2.3 Density test

This was completed in accordance with ASTM, D. (1999). Standard test procedures for assessing the characteristics of particle and wood-based fibre panel materials. Three samples of 190mm x 45mm x 10mm were used. The weights of the test samples treated and untreated bamboo plastic composites and their volumes were obtained. The density was calculated using equation (1)

$$\rho = \frac{\text{Mass}}{\text{Volume}} \quad (1)$$

$$\text{Volume (Rectangular Composites)} = \text{Length} \times \text{breadth} \times \text{Thickness}$$

2.4 Water Absorption (WA) and Thickness Swelling (TS) Test

Sorption properties of the samples were carried out based on ASTM D570. After being weighed, the treated and untreated bamboo plastic composites were soaked in water at room temperature for zero, two, and twenty-four hours. The samples were taken out of the water at the conclusion of the soaking time and given time to drain before the final weights and thicknesses were calculated. The thickness swelling (T.S.) of the bamboo plastic composite samples was represented as a percentage of the initial thickness, whilst the WA and TS were calculated as expressions of the initial weights and thicknesses. Equation (2) was used to determine the water absorption, while equation (3) was used to determine the thickness swelling.

$$WA = \frac{W_f - W_i}{W_i} \times 100 \quad (2)$$

$$TS = \frac{T_2 - T_1}{T_1} \times 100 \quad (3)$$

WA = Water Absorption (%), W_f = final weight, W_i = initial weight

TS = Thickness swelling (%), T_2 = final Thickness, T_1 = initial Thickness

2.5 Flexural strength

The test samples were tested flat wise according to ASTM D790-03. Two set of samples for treated and untreated in three replications were produced. The samples were prepared with dimensions 140mm x 24mm x 10mm. The width and depth of specimen were measured to the nearest 0.03mm at the centre of the two-support span. After that, the test samples were loaded onto two supports. The two support spans (L) were spaced 100 mm apart. Equation 4 was used to calculate the flexural strength.

$$\text{Flexural strength } (\sigma) = \frac{3LP}{2bd^3} \quad (4)$$

3. Results and Discussion

3.1 Density

The densities of the BPCs ranged from 0.902 g/cm³ to 1.187 g/cm³ for untreated bamboo plastic composites and 0.931 g/cm³ to 1.187 g/cm³ for treated bamboo plastic composites, respectively. The result indicates that as the bamboo flour content increased, the density of the bamboo plastic composites decreased for both treated and untreated samples. This may be due to the lower weight of the bamboo as compared with the polyethylene. The densities are generally greater than 0.800 g/m³, which falls within the high-density composites board grade range in accordance with American National Standard Institute (ANSI 208-1-1999). The mixing ratio significantly affected ($P \leq 0.05$) the densities of the BPC samples for both treated and untreated, while the NaOH pre-treatment also affected the density of the treated composites as indicated by the statistical analysis (see Figure 2). This results agree with those obtained from literature [9] [10].

3.2 Water Absorption (WA) and Thickness Swelling (TS)

Thickness swelling and water absorption of the composites increased with the percentage of bamboo fibre incorporation, which ranged from 5% to 20% for both treated and untreated bamboo (Figure 3). The WA values ranged from 0.07 to 1.088% for untreated samples and 0.05% to 0.42% for treated samples and the thickness swelling (TS) ranged from 0.09% to 0.61% for untreated samples and 0.05 to 0.51% respectively. The findings also showed that the WA and TS increased in tandem with the quantity of bamboo in the composite matrix. The treated samples recorded a lower WA and TS significantly. WA and TS are crucial factors in determining how durable they are; composites with lower WA and TS will provide reinforcement with higher protection [11]. At 5% and 10% bamboo incorporation, the WA and TS were lowest and thus can be deployed for exterior applications and in building construction applications.

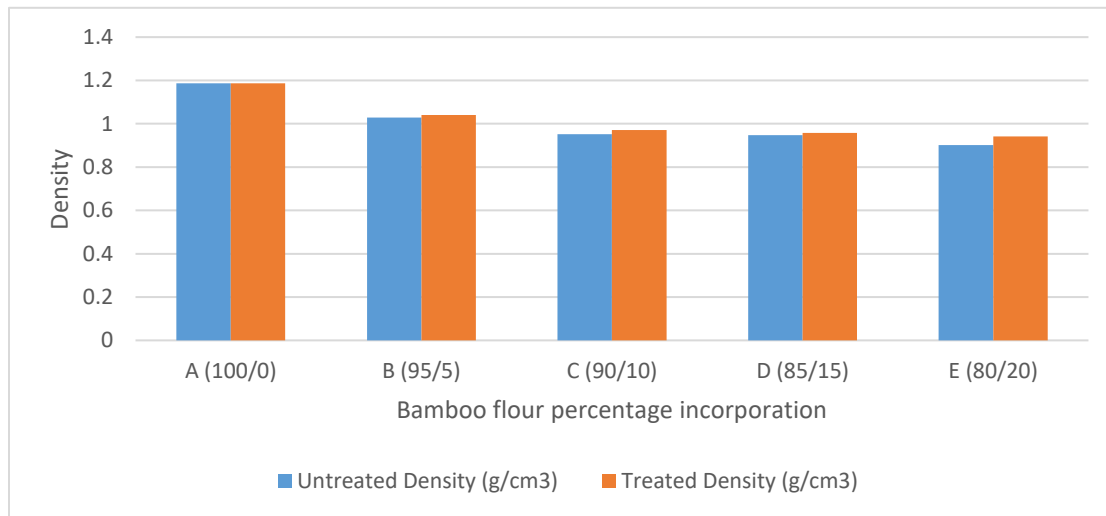


Fig. 2: Density result of the composites samples

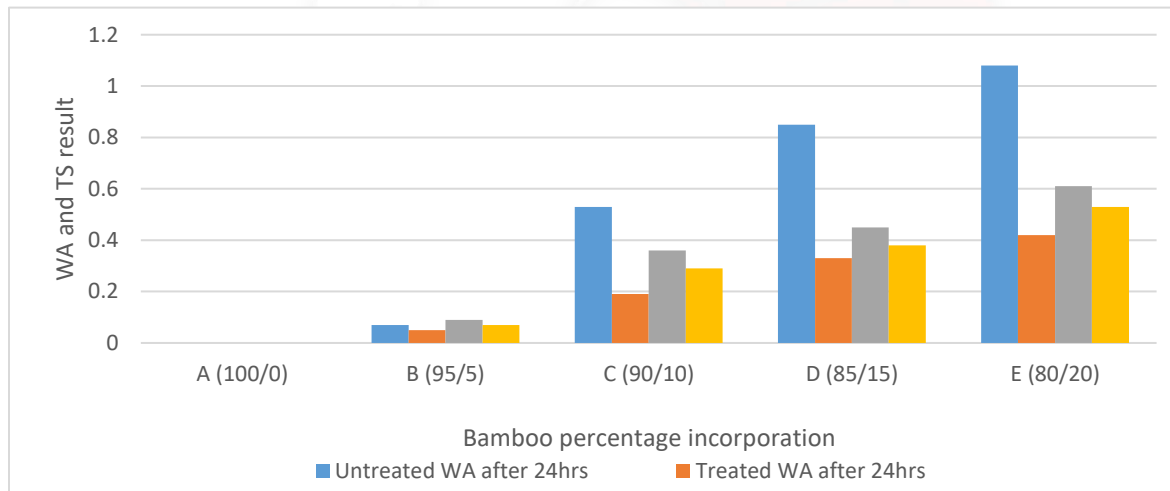


Fig. 3. Water absorption result of the composites samples

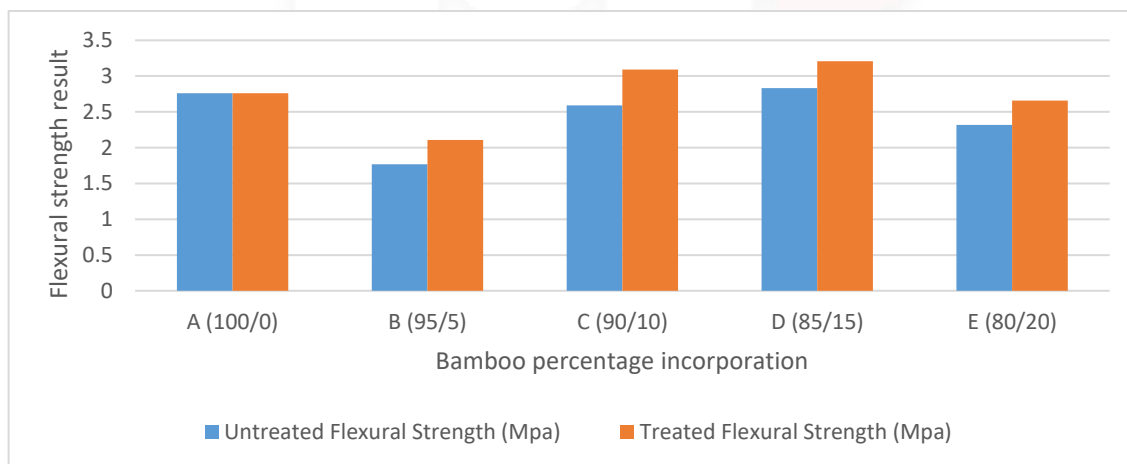


Fig. 4. Flexural strength result of the composites samples

3.3 Flexural Strength Test

The result of flexural strength test shows that adding up to 15% Wt of bamboo to the composites increases their flexural strength. 15% bamboo fibre content produced the maximum flexural strength of 2.83 Mpa for untreated samples while the maximum strength for treated samples of 15% bamboo incorporation was 3.21 Mpa. The indication of the increased in treated bamboo flour agreed with [7].

Figure 4 illustrates how the composites' flexural strength decreased as the bamboo component exceeded 15%. This decline in flexural strength beyond 15% for both treated and untreated samples may be attributed to the agglomeration of bamboo fibres, which can disrupt the uniform distribution within the matrix, leading to weak points in the composites. However, as the bamboo content increases from 5% to 15% the flexural strength for both treated and untreated also increases, this is in accordance with [12] and similar observations were also reported by [10]. The composites with a 15% bamboo component had a better flexural strength, which may have been caused by improved interfacial interaction between the bamboo particles and the plastic matrix [13]. The composites produced can be deployed in building construction in areas of lower load bearing applications.

4. Conclusion

The fundamental characteristics of bamboo/plastic composites (BPCs) were assessed for both treated and untreated bamboo plastic composites. Investigations were conducted on the physical and mechanical properties. Low-density polyethylene polymer obtained recycled plastic bottles showed resistance to water absorption and swelling. The addition of bamboo flour to low-density polyethylene polymer caused the density to decrease as the amount of bamboo flour increased in the composite matrix. The flexural strength of the composites increased up to 15% bamboo content, and decreased beyond this threshold. At this threshold, the composites produced are suitable for exterior applications. The research findings demonstrate the feasibility of utilizing recycled low-density polyethylene plastic waste from water bottles, which can be collected, cleaned, crushed, and blended with bamboo flour to manufacture composite products suitable for diverse applications such as, floor and wall tiles, wall panels, indoor insulating components. It is recommended that more research is conducted to determine the microstructural and chemical interactions between the composite matrixes.

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Production and Testing of Blockboard made from *Tectona grandis* Wood

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Abstract: The scarcity of renowned economic wood species has given rise to the imminent search for suitable alternatives such as Engineered Wood Products (EWP). Blockboard is an EWP made from strips of wood bonded with adhesive and veneered to form timber like products which can be deployed for internal and external applications. Blockboard was made from *Tectona grandis* wood species, using top bond adhesive and tested for selected physical, mechanical and water sorption properties. The results obtained indicated that the composites had adequate moisture content (17.2%), moderate density (605.1 kg/m³), low mechanical property (Moduli of Rupture- 40.1 MPa and Elasticity- 4,500.2 MPa, compressive strength parallel to grain- 36.3 MPa). The fabricated board was not suitable for structural applications but may be adapted for non- structural purposes such as interior decoration, wall cladding and novel furniture items.

Keywords: Blockboard, *Tectona grandis*, Engineered Wood Products (EWP), Wood Scarcity, Furniture

1. Introduction

The rapid increase in the world population has culminated into the increasing demand for wood and wood products. This demand has resulted in the over-exploitation of the forest resources with the attendant scarcity of timber. [1-9]. In this regard, Engineered Wood Products (EWPs) are being considered for use especially in the production of furniture, bridges and as building components [3, 10-20]. These EWPs are usually made by bonding strands, fibres, boards of wood etc. to form composite products. They are generally simple to produce and have several engineering and architectural advantages such as longer spans, improved durability, stability and aesthetic value. They carry more desirable economic impact on a building project than standard timber due to their ease of installation and therefore reduced labor cost. [17, 21-27]. Additionally, EWPs have a longer design life since the products are not subject to rot or other similar atmospheric or environmental effects in the same extent as their organic natural counterparts. Blockboard is an example of EWP manufactured from lumber at its core, sandwiched between layers of wood veneer on both its front and back faces. They are mostly used in the fabrication of doors, benches, bookshelves and tables etc. due to their inherent good properties such as lightweight which facilitates easy transportation, less tendency to sag, ease of manufacture, durability and stability. Compared with reconstituted wood, blockboard has a superior nail and screw holding strength. [6, 25, 27-28].

Blockboards have been made from fir, beech, oak, date palm wood species in temperate regions and have proven effective when deployed for furniture and other internal home applications. [16, 29]. In Nigeria however, fast growing and durable wood species are usually deployed for structural and non-structural application in lieu of the prevailing scarcity of timber resources. *Tectona grandis* (Teak), an exotic fast-growing hardwood can also be considered for blockboard manufacturing. This is more so since Teak is suitable for plantation viz. farm forestry and agro forestry under various agro climatic conditions.

[30]. Its durability has enabled it to be arrayed in packaging, plywood, particleboard, laminated veneer lumber and pulpwood production etc. Production of blockboard from Teak may also enhance its viability and utility for EWP manufacturing. However, literature is sparse on properties of blockboard produced from Nigerian grown wood species. This is more so due lack of expertise, facilities and dearth of information on properties of blockboard and EWPs made from Nigerian grown species. This work therefore examined the selected properties of blockboard made from *Tectona grandis*.

2. Method

2.1 Sourcing and preparation of strips for fabrication of *T. grandis* blockboard

T. grandis wood (50mm × 300mm × 3600mm) was sourced for at the Bodija Plank market. The Bodija Plank market in Ibadan was chosen for the study because of the accessibility and availability of various timber species in the market. A 4mm Sapele mahogany Plywood was also purchased from the Bodija plank market for use as face and back of the blockboard.

2.2 Processing and production of the Blockboard from *T. grandis* Wood

The *T. grandis* plancks were planed with a surface planer machine, thickened to 40mm utilising thicknesser machine and cut into lengths of 650mm, utilizing a radial arm saw machine before stripping to 16mm by 24mm by 650mm (Thickness, Width and Length respectively) using a circular sawing machine. Similarly, the 4mm Sapele mahogany Plywood bought at the Bodija plank market was cut into 180mm by 650mm for surface veneering of the blockboard. Top bond adhesive was applied on the edges of each strips and clamped on a workbench using Sash clamps and F-clamps. The strips were laid edge to edge on a flat wooden surface of 18mm plywood sheet, two sash clamps were employed on the top surface across the strips and tightened (until the glue squeezed out). The assembled/laminated strips were allowed to set for 24hrs. After 24hrs, the composites were demoulded and cleansed of all excessive glue, squeeze out with a scrapper.

Sawdust mixed with top bond was used to fill in holes, spaces and irregular surface in the board. Also, sanding sealer were mixed with the sawdust and applied. The surfaces of the laminated cores were planed and thickened to 12 mm using a block plane before sanding. An abrasive paper of P150 grit size was used for sanding the laminated core to enhance a smooth surface prior to the attachment of the 4mm plywood.

Water soluble Urea formaldehyde, the most common adhesive in Nigeria with "Top Bond" as its trade name, was used. The adhesive spread rate of 250g/m² was adopted from [31] and was applied with a brush to ensure even distribution. It was evenly applied to the pieces of the plywood sheets and attached to the laminated core and cold pressed (using a weight of 240 kg) for 48 hrs. The fabricated composites were sanded with an abrasive paper of P150 to enhance the smoothness of the board.

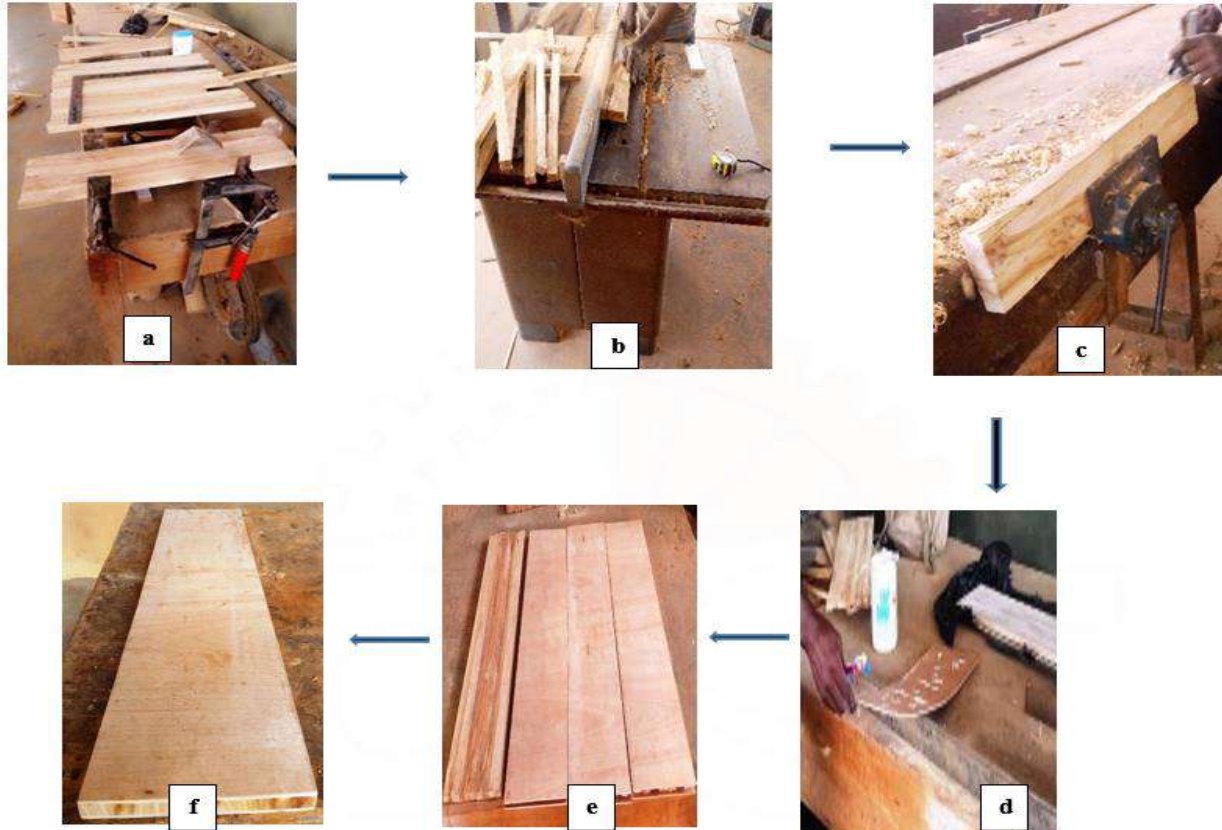


Fig. 1. Production Process of Blockboard from *Tectona grandis* wood

2.3 Testing of the Composites

Physical Properties

The fabricated blockboard were machined to required size and dimensioned according to [32]. The test samples were subjected to the following selected physical tests such as:

Moisture Content

The moisture content of the test specimen was determined using a digital moisture meter.

Density

The density of the block board was determined according to [32] using the formula

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} = \text{kg/m}^3 \quad (1)$$

Water Absorption (WA) and Thickness Swelling (TS)

Five replicates of the composites were initially weighed and then soaked in water at room temperature for 2 and then 24 hours. At the end of the soaking period, the samples were withdrawn from water and allowed to drain before the final weights and thicknesses were determined. The Water absorption and Thickness swelling of the composites were determined as expressions of the initial weights and thicknesses. The result obtained were evaluated using equation (2)

$$\text{Water absorption} = \frac{W_2 - W_1}{W_1} \times 100\% \quad (2)$$

Where W_1 = initial weight before soaking

W_2 = final weight after 24 hours

The thickness swelling of the block board was determined as follows:

$$\text{Thickness swelling} = \frac{T_2 - T_1}{T_1} \times 100\% \quad (3)$$

Where T_1 = initial thickness before soaking

T_2 = final thickness after 24 hours

Mechanical Properties

The mechanical properties of the composites such as bending strength and compressive strength were determined using [32] standard. Five replicate samples were deployed for the static bending and compression parallel to grain tests. Samples were loaded on the Universal Testing Machine (UTM) until failure. The selected mechanical properties were evaluated as presented by [33]:

$$\text{MOR} = \frac{3P_{\max}L}{2BD^2} \quad (4)$$

Where:

$P_{\max}$ = Maximum load causing failure (N)

L = Span, i.e. distance between supports (mm)

B = Specimen breadth (mm)

D = Specimen depth (mm)

$$\text{MOE} = \frac{PL^3}{4\Delta BD^3} \quad (5)$$

Where:

P = Load applied to the Centre of the span (N)

L = Span, i.e. distance between supports (mm)

I = Moment of inertia of the cross section (mm^4)

Δ = Deflection at the centre of the span (mm)

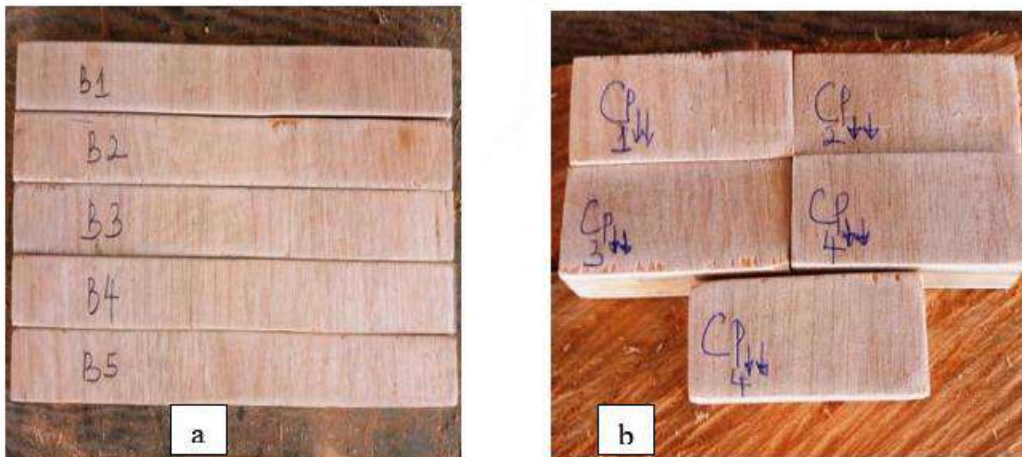


Fig. 2. Sample sizes for Bending and Compression Parallel to grain of *T. grandis* Blockboard

The Compression parallel to grain test was performed. Five samples of *Tectona grandis* blockboard of sizes 20mm × 20mm × 60mm was tested using the Universal testing machine in accordance with the [32] standard.

The compressive strength parallel to the grain characteristics of *Tectona grandis* sample was calculated using the following formula:

$$C_{\parallel} = \frac{F}{A} \quad (6)$$

Where:

$C_{\parallel}$ = compressive strength (N/mm²)

F = maximum applied load (N)

A = area of top surface (mm²)

3. Results and Discussion

3.1 Physical properties of the fabricated Blockboard

The results for the physical properties of the fabricated blockboard are thus discussed:

Moisture Content

As shown in table 1, the moisture content of the blockboard was determined using a digital moisture meter after air drying for about 3 days. The moisture content of the samples was 17.2%. This result indicates that the wood used in the production of the board was dry. Generally, the strength properties of wood and its resistance to biodegradable agents increase if seasoned properly.

Density of the Blockboard

As shown in table 1, the density of the blockboard at an average moisture content of 17.2% was 605.1kg/m³. The density was similar to 610kg/m³ obtained by [28] indicating that the fabricated board was a medium density board in accordance with the report of [34].

Table 1: Moisture Content and Density of the Fabricated Blockboard

Physical Properties	
Moisture Content (%)	17.2
Density (kg/m ³)	605.1

Water Absorption (WA) and Thickness Swelling (TS)

The water absorption (WA) and thickness swelling (TS) of the fabricated boards are shown in Table 2. As shown, the WA and TS ranged from 24.6 to 41.6% and 3.3 to 6.5% respectively. The results of the WA and TS suggest that the fabricated board had high sorption rate and may not be adapted for exterior application possibly due to the adhesive used. Top bond is noted to be water soluble glue and may be susceptible to biodegradation when deployed in board production.

Table 2: Water Absorption and Thickness Swelling

Water Absorption (%)		Thickness swelling (%)	
2 h	24 h	2 h	24 h
24.6	41.6	3.3	6.5

3.2 Mechanical Properties

Moduli of Rupture (MOR), Elasticity (MOE) and Compressive Strength Parallel to grain

The results of the MOR, MOE and compressive strength parallel to grain of the blockboards are shown in Table 3. As shown, the MOR, MOE and compressive strength of the blockboard were 40.1, 4,500.2 and 36.3 N/mm² respectively. These values are similar to those obtained by [28] but less than 50 and 5000 N/mm² specified by [16]. The strength properties obtained in this study suggest that the blockboard had low strength properties and may not be suitable for structural purposes but as insulating components like wall cladding, interior paneling and novel furniture items.

Table 3: Selected Mechanical Properties of *T. grandis* Blockboard

Mechanical Properties	
MOR (N/mm ²)	40.1
MOE (N/mm ²)	4500.2
Compressive Strength (N/mm ²)	36.3

4. Conclusion

This study fabricated blockboard from *Tectona grandis* wood and evaluated some selected physical and mechanical properties of the fabricated blockboard. Although, not deemed suitable for structural applications, due to low strength characteristics, the fabricated board may find relevance in non-structural applications such as wall cladding, interior decoration and other applications where high strength characteristics are not a prerequisite. The 17.2% moisture content and 605.1kg/m³ density indicated that the fabricated board can be classified as medium density in accordance with the reports of [34].

The Water absorption and Thickness swelling indicated that the fabricated board had high sorption rate and may not be suitable for exterior applications which may be due to the top bond adhesive used in the fabrication.

It is also worthy to note that this composite can be manufactured from strips that have been referred to as waste in sawmills or wood factories that utilizes *Tectona grandis* either as log or converted timber.

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Mechanical evaluation of hybrid paper from selected lignocellulose materials

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Abstract: The exponential population growth, industrialization and urbanization has risen the need for pulp and paper products, avert effect on shortage fibrous wood based pulp resource and increased deforestation are link with over tapping of wood based pulp and paper production. The study presents the mechanical evaluation of hybrid paper from blends of *Raphia farinifare* and *Gmelina arborea* fibres, aimed at exploiting alternative fibre source. *Raphia farinifare*, an underutilized agro –based material with coarse and long fibres displayed excellent reinforcing characteristic and *G. arborea* fibre contributed to improved fibre bonding and surface properties. Key paper properties were investigated such, paper grammage, tensile strength, tear resistance, bursting strength and fold endurance, depicted mechanical integrity with valued aligned with TAPPI standards of three blends of paper. However, the evaluation underscored the potential of locally sourced agro –waste/ non-conventional raw materials in promoting sustainable and cost-effectiveness further enhanced the shift toward circular economy practices by utilizing agricultural residues and rapidly renewable fibre sources.

Keywords: Renewable fibres, Kraft pulping, Hybrid paper and mechanical properties

1. Introduction

The global pulp and paper industry has undergone significant transformation over that last few year, driven by sustainability mandate, emerging technologies, optimization, artificial intelligence and the shift toward bio- based economic [1][2][3]. Agricultural residues and weed plant residues can cater to the growing demand for paper in the packaging sector, as well as hygiene and sanitation products, such as paper towels, toilet paper, and disposable makeup wipes, among others [4][5]. Paper is composed of fibres bonded together through intermolecular forces [6]. The paper industry that is an integral part of human existence, has contributed to the civilization and commercial development. Hence, new era and innovation has increased the global demand of the pulp, paper and paper products [6][7]. In addition to improving the quality of people's lives, paper has increased the wide spread of information/ knowledge and enhance the development of science and technology. Paper, versatile bio-composite material used in variety of everyday applications, ranging from packaging and books to newspapers, tissue paper and many more has created avert effect on the ecosystem mitigate forest depletion [8] [5]. Multiple studies, has estimated volume of paper and paper products consumed in a year. Paper making industry completed a total output of 417 million tons of paper. USA and China consuming 78.2 and 85.87 million tons respectively [9]. Various efforts are necessary to discovered cellulose based plant and grasses for the pulp and paper to reduce the pressure in the forest. Recently, the pulping materials have faced various restrictions, due to release of effluent to the ecosystem; the environmental requirements have made the supply of pulpwood insufficient. Emerging methods of sourcing cellulose-based material as alternative future development trend [10][11]. The composition of pulp is obtained from wood extract fibres viz. Physical, Chemical, mechanical and biological methods. However, non woody cellulose based such as hemp, wheat straw, cotton, bagasse, corn, straw and many more served as sources of cellulose, but the

percentage volume of cellulose domiciled in wood making them highly desired; the coniferous wood (42 - 50%) and the hard wood (43-47%) [12][14]. Plant composed of three major components; lignin, hemicellulose and cellulose. Cellulose ample raw material for pulp is abundant polysaccharide substance in the cell walls showed D-glucose molecules link by β -1, 4 bonds, with degree of polymerization of 10,000. Within the cell wall microfibrils, cellulose showed disordered amorphous and ordered crystalline structure [12][14][15]. Hybridization present reduction of over –dependent on ample bio-based material wood; hybrid paper which is a blend of traditional cellulose fibre (wood) and other natural/ agricultural waste and synthetic components to impact the functionality of paper. Multiple studies have evaluated blends of wood pulp with other agricultural waste, and non-woody fibre. [16] blends wood pulp with bagasse, straw, hemp and kenaf to optimized fibre morphology, reduce environmental impact and cost, the study reported, increase in strength of paper and moderate surface morphology, which enable the run ability and printability of paper, further conclude, need for improved pre-treatment methods, alkali pre-extraction. Attempt in reducing wood sources of cellulose, some studies has outlined the utilization of some agricultural waste and weed plant residue as feedstock, to cater for the growing demand in paper products for sustainability [17]. The coniferous are ample raw material for pulp and paper products due to it is rich cellulose content, the demand of these products has accelerated the depletion of the forest, this engenders the needed to use other plant-based fibre to mitigate the environmental concern pose by pulp and paper industry. Study by [18] reported 43% of cellulose in *Raphia farinifera*, making it ample source for pulp and paper production, but environmental factor, soil and climate have effect on cellulose percentage.[19] evaluated various methods of pulping of selected agricultural waste/ grasses. With Kraft pulping exhibited higher yield percentage in raphia, hemp, bagasse and straw used in the study. The current study is centre on hybridization of paper from *Gmelina arborea* and *Raphia farinifera* and evaluation of selected paper properties.

2. Material and Method

2.1. Materials

Cellulose fibre was extracted from two major lignocellulose materials, *Gmelina arborea* (Roxb) and *Raphia farinifera* (Hylander); *G. arborea* was harvested and chipped into 2-4mm in thickness, prior to kraft pulping, chips were oven dried, for 12hrs with temperature of $103^{\circ}\text{C} \pm 2^{\circ}\text{C}$ according to TAPPI 264. *R. farinifera* was harvested and chipped into 4-6mm thickness air dried for 14 days; further oven dried for 6hrs with temperature of $103^{\circ}\text{C} \pm 20^{\circ}\text{C}$, the moisture content prior to pulping was calculated with equation (1);

$$\text{MC} = \frac{\text{weight of wetsample} - \text{weight of dry sample}}{\text{weight dry sample}} \times 100 \quad \text{Eq 1}$$

2.2. Methods

Study adopted Kraft pulping method for production of pulp; Table 1, listed the chemical and additives used for pulping and paper production. Kraft pulping involved the separation of cellulose fibre from lignocellulose materials viz cooking of wood chips with sodium hydroxide and sodium sulfide (white liquor). 1kilogram of *G. arborea* chips was cooked with 4000ml of the cooking spent in the ratio of 3:1(NaOH: Na₂S); with temperature and pressure 150°C and 1000Pa respectively, for 3hours of cooking. The process was repeated for *raphia* chips. Furthermore, cooked chips were washed for five times to removed; all dissolved spent liquor and impurities in the cellulose fibre. Extracted cellulose fibre of *G. arborea* and *R. farinifera* were oven dried for 45mint, at 75°C to reduce excess water on the fibre. Thereafter store in the desiccator for the production of papers.

Table 1: List Of Chemicals and Additives Used

S/N	Chemicals and Additives	Uses
1	Sodium hydroxide (Na ₂ OH)	Alkaline chemical for breaking down lignin and separating fibre
2	Sodium sulfide	Aid in breaking down of S _i , S ₂ cell walls for the separation fibre from lignin and hemicellulose.
3	Distilled water	Solvent in paper making process./ washed agent
4	Bleaching Agent (chlorine, sodium chlorate and hydrogen peroxide).	Removal of colour and impurities from pulp
5	Fillers (clay, and calcium carbonate)	Improves paper properties and reduces cost.
6	Sizing Agent (starch, alum, rosin china clay)	Control the absorption and spreading of ink on paper.
7	Caustic soda	Removal of impurity from pulp during bleaching process
8	Retention Aids (Silica)	Reduces waste and improve efficiency during pulping
9	Coating Agent (calcium carbonate, kaolin and talc)	Improve the surface of paper in terms smoothness and glossy.

2.2.1 Paper production

Three-difference papers were produced for mechanical investigation; firstly, paper with pulp from *G. arborea* and *R. farinifera* of same consistency and other of varied consistency. Hence, papers were produced from individual pulp as control experiment. A ratio 1:1 pulp of *G. arborea* and *R. farinifera* were disintegrated and mix at consistency of 1.5%. Sizing agent and fillers (china clay) 1.0% of the dry weight of fibre were added to slurry, the slurry was mixed, a mold of 45× 58cm, with wire mesh of 200µm was used for the handmade paper according TAPPI T 430, The form paper sheet were dried at room temperature of 23⁰C±2⁰C for 48hours.figure 1: showed the manufacturing flow chart of hybrid paper production viz kraft pulping.

2.3 Mechanical Properties Evaluation

Selected mechanical properties of paper at 1.5% consistency were characterize in the study to evaluate behaviors of paper

2.3.1 Tensile strength of paper

Test samples were machined to dimension of 15mm×180mm according TAPPI T494, from 1.5% consistency of hybrid paper, *G. arborea* and *R. farinifare* paper, five test sample were evaluated, UTM was used with crosshead speed of 25mm/min with load of 20N, the results were evaluated with eq 2.

$$\text{Tensile strength} = \frac{f}{w \times t} \quad (\text{N/m}) \quad \text{Eq2}$$

Where f is the breaking force, w is the width of paper and t is thickness of paper.

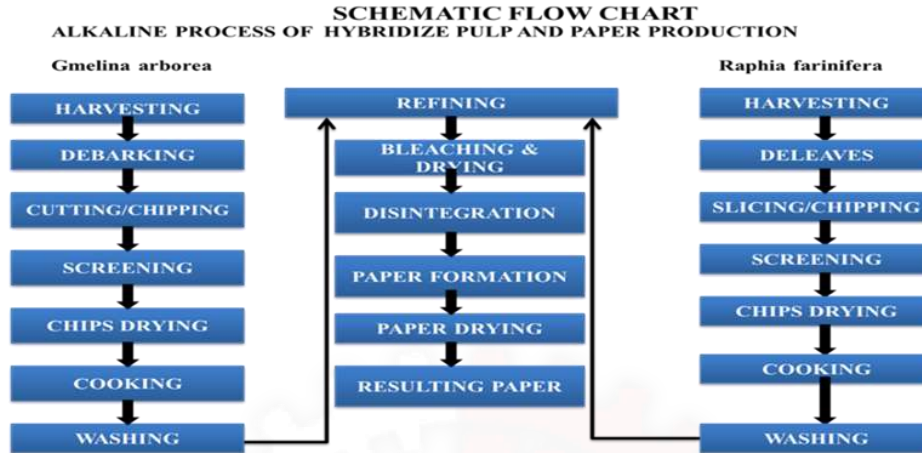


Fig. 1. Manufacturing flow chart.

2.3.2 Tearing strength of paper.

Rectangular strip with dimension of 20×100mm machined according to TAPPI T 414, were evaluate with Elmendorf tear tester. The dynamic load released, as the tear propagate perpendicular to the applied force as the pendulum pulls the sheet apart. Hence, the process repeated for other samples and the results are plotted with equation 3.

$$T_s = \frac{F \times d}{Tl} \times 1000 \text{ (mN)} \quad \text{Eq3}$$

Where; Ts is Tear strength, F is force, d is distance, Tl is Tear length (F*D) represent

2.3.3 Bursting strength test

Circular test sample of 112.8mm in diameter was subjected to hydraulic pressure machines; the pressure is to the paper, until the rapture. The maximum pressure recorded and evaluated with equation 4.

$$BS = (P \times D^2) / (4 \times t \times A) \text{ kgf/cm}^2 \quad \text{Eq4.}$$

Where P bursting pressure, D is the diameter of the elastic diaphragm, t. is thickness of paper sample; A is the area of paper.

2.3.4 Folding endurance test

Rectangular test samples of 15×100mm were test according to TAPPI T 51, using MIT folding endurance tester. The test paper strip undergo folding, repeatedly in the same direction, the number of folds required to rapture of test samples were evaluated with equation 5.

$$FE = \frac{N \times 1}{t \times p} \quad \text{Eq.5}$$

Where N is the number of fold, t, is thickness and p is density. However, the grammage of paper was study with, 100mm ×100mm according to TAPPI T410 using grammage tester. The test sample was weigh; the resulted weight was calculated with equation 6.

$$\text{Grammage} = \frac{W}{L \times b} \times 100 \text{ (g/m}^2\text{)} \quad \text{Eq 6}$$

Where W is the basis weight of paper in (g), L is length of test sample (m) and b is the breadth of test paper.

3.0 Results and Discussion

3.1 Paper Grammage.

The paper grammage in this study varied from fibre sources. Hybrid paper, which are from cellulose of *G. arborea* and *R. farinifare* exhibited average grammage of 71gsm, which are within the range of standard, and above 60gsm, which are classified as light weight, for multi-part forms (TAPPI T410). The paper from *G. arborea* showed higher grammage of 75gsm, the result aligned with paper grade of better durability, above standard paper range of 70gsm [3]. However, paper from *R. farinifare* exhibited low grammage of 59gsm, this is below the standard grammage of paper, report aligned with [20] concluded that, the low grammage exhibited with fibre from *R. farinifare*, is resulted to coarse fibre with thin fibre walls of raphia. [3] reported low cellulose and high lignin, result in difficulty in refining, further recommended, fibre bleaching and hybridization with other fibre sources for improved material properties. Table 2, presented grammage of paper of different fibre sources. Figure 2 showed the paper produced.

Table 2: Grammage of Paper

Fibre sources	Consistency (%)	Grammage (gsm)
Hybrid paper	1.5	71
<i>G. arborea</i>	1.5	75
<i>R. farinifare</i>	1.5	59



Fig. 2. paper produced

3.2 Result of mechanical properties of paper

The mechanical properties of paper produce are presented in table 3, the hybrid paper showed higher properties of papers.

Table 3: Result of mechanical properties

Fibre sources	Tensile strength (KN/m)	Bursting strength (Kpa)	Tear strength (mN)	Grammage (g/m ²)	Folding endurance (circles)
<i>Gmelina arborea</i>	4.8	250	500	95	101
Hybridized	6.2	340	700	105	90
<i>Raphia farinifera</i>	3.5	180	350	80	67

3.2.1 Tensile strength results

Tensile strength results is presented in figure 3, hybrid paper showed higher tensile strength compared to individual paper, study by [21] reported similarity parameter of 6.0KN/m, with paper from bamboo fibre viz kraft pulping. The impregnation of various fibre showed improved tensile strength of paper. The tensile strength aligned with TAPPI T 494, of 5.0 -9.0KN/m for writing paper. The paper from G. arborea fibre showed tensile strength of 4.8KN/m, the parameter was slightly lower than standard. Lower tensile were attributed to inadequate pulping, short fibre/ thine cell wall, and poor fibre bonding during handmade sheet formation, this aligned with [22] who concluded that, another factor is low Runkel ratio of G. arborea (ratio of cell wall thickness to lumen width); though beneficial for pulpability, but showed weak structural integrity. R. farinifare fibre showed lower parameter of 3.5KN/m compared to standard, and paper from G. arborea.[23] suggested low tensile strength of R. farinifare paper is resulted to coarseness and surface texture of fibre, which reduces the surface area available for hydrogen bonding, lead to lower bonding strength between fibres. For improved tensile properties of paper, with short fibres length of 1.5mm, fibres diameter of 20 - 25 μ m, lumen diameter of 8 -10 μ m and cell thickness of 3 – 5 μ m.[24] suggested hybridization, which involved impregnation of two or more fibre source for production.

3.2.2. Tearing strength

Tearing strength of paper showed the amount of force required for tear of paper. Hybrid paper showed a tear strength of 700mN, which is within the TAPPI T 414 standard of 600 -1000mN, for Kraft pulp. However, the hybrid paper is suitable for writing and printing, G. arborea paper recorded tear strength of 500mN, the paper is suitable for writing and for newsprint, with machine direction 350mN of printability. R. farinifare paper showed low tear strength of 350mN, compared to other. Thus, are suitable for printing, writing and sanitary papers.[25] recommended tear strength value of paper with 300 – 400mN, are suitable for printing and writing.

3.2.4 Bursting strength.

Bursting strength of paper depicts the maximum pressure paper withstand before rupture when pressure is applied perpendicularly, the bursting strength which, is influenced with sheet integrity, bonding strength and refining of pulp were studied, hybrid paper exhibited higher burst strength of 340Kpa and G. arborea 250Kpa and R. farinifera 180Kpa respectively. The burst strength of three papers under study aligned with required standard for writing and printing paper of basis weight (60 – 90gsm); with bursting strength range of 100 – 250Kpa. Hence, the hybrid paper falls within the range of 250- 350Kpa suitable speciality paper (TAPPI T403).

3.2.5 Folding strength

Table 3 referred, folding strength, which is, the number of folds paper is folded before break, this parameter plays a pivotal role in the utilization of paper. However, hybrid paper highlights higher folding resistance to force with folding number of 101, G. arborea and R. farinifera papers displayed 90 and 67 respectively. The results depicted for uncoated and coated papers for writing and printing. The parameter from hybrid paper aligned with TAPPI T511 for security paper, which ranges from 90 -120 number of folding endurance strength. The higher parameter displayed with hybrid paper existed due to uncoated paper.

4. Conclusion

Advancement in technology and need for sustainable utilization of bio-resource and diversification, has prompted the production of hybrid paper from *Gmelina arborea* and *Raphia palm*, as an alternative approach to reduce over dependence on wood-based pulp. Findings from the study showed improved mechanical properties of hybrid paper range from tensile, tearing strength, bursting and folding endurance strength. *R. farinifera* with attributed properties of long fibres, enhance significantly on fibres bonding, tensile strength, and *G. arborea* with shorter and flexible fibre contributed to improved paper formation and surface finishes. The optimal fibre ratio showed balanced strength, formability and printability. Hybridization is tailored to meet specific end-use requirements. However, the utilization of locally sourced fast growing species such as *G. arborea* and agro-waste like *raphia* aligns with global trends toward sustainability, cost effectiveness and environmentally friendly production. Future study is employed to focus on refining pulp condition optimization, chemical additive and pilot scale production to establish these hybrids as a viable alternative for commercialization.

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Artificial Project Management Intelligence (APMI): PM-AI Automation for Sustainable Engineering and Digital Futures

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Abstract: The convergence of artificial intelligence (AI) and project management (PM) is rapidly transforming the landscape of infrastructure and engineering delivery in the digital era. Traditional project management frameworks, while structured and systematic, are increasingly limited in addressing the complexity, scale, and sustainability demands of modern engineering projects. This study introduces the concept of Artificial Project Management Intelligence (APMI)—a systems-based, AI-driven framework designed to augment project delivery across the full lifecycle, from initiation to closing. APMI integrates tools such as machine learning (ML), natural language processing (NLP), robotic process automation (RPA), and intelligent dashboards to enable data-driven decisions, proactive risk management, and sustainability-aligned operations. The research employs a qualitative exploratory approach involving expert interviews with 14 professionals from diverse sectors, supported by simulation-based analysis and AI tool modelling. Two case studies—a retrospective application to the Lagos Blue/Red Line urban rail project and a futuristic deployment in Saudi Arabia’s NEOM smart city—demonstrate APMI’s potential for improving delivery efficiency, stakeholder coordination, and sustainability performance. Key findings show that APMI can significantly enhance project accuracy, responsiveness, and transparency while addressing ethical concerns such as algorithmic bias and human oversight. The paper concludes that APMI represents a pivotal advancement for sustainable engineering in the digital economy and recommends sector-wide adoption, supported by policy frameworks, adaptive toolkits, and AI readiness training. Future directions include plug-and-play AI agents, reinforcement learning, and cross-domain collaboration for scalable implementation.

Keywords: Artificial PM Intelligence, AI in Engineering, Sustainable Delivery, Lifecycle Automation, Digital PM Transformation

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1. Introduction

The exponential growth of the digital economy has profoundly transformed how engineering systems are designed, implemented, and managed. As digitalisation pervades every facet of society—from healthcare and finance to mobility and energy—engineering projects are expected to be not only technically sound but also adaptive, data-driven, and sustainably executed. In this high-velocity, high-stakes environment, traditional project management (PM) practices are increasingly misaligned with the dynamic requirements of 21st-century engineering [1]; [2]. The prevailing linear and document-heavy methodologies often lack the responsiveness, scalability, and intelligence required to manage the complexity, interdependency, and uncertainty inherent in modern infrastructure and technology-based projects.

Contemporary engineering projects are distinguished by their multifaceted nature: they span multiple domains, involve diverse stakeholders, and are executed in volatile regulatory and environmental contexts. In large-scale urban transport initiatives or smart energy grids, decisions must be made in real-time, sustainability benchmarks must be met, and disruptions must be anticipated and mitigated before they materialise. However, traditional PM tools and processes—though systematic—struggle with data fragmentation, reactive planning cycles, and insufficient predictive capabilities [3]. This challenge is

particularly evident in regions where resource constraints exacerbate inefficiencies, and where the stakes of failed or underperforming projects are considerably high.

Against this backdrop, Artificial Project Management Intelligence (APMI) is proposed as a novel paradigm that strategically embeds Artificial Intelligence (AI) technologies into the PM lifecycle. APMI leverages tools such as machine learning (ML), natural language processing (NLP), and robotic process automation (RPA) to automate repetitive tasks, enhance decision-making, and enable proactive project control. By transforming PM from a largely procedural discipline into an intelligent, responsive, and sustainability-aligned system, APMI presents itself as both a theoretical innovation and a practical necessity for the digital age.

This paper is situated at the intersection of engineering management, AI innovation, and sustainable development. It argues that the convergence of AI and PM—when designed intentionally and deployed ethically—can produce significant improvements in project efficiency, transparency, and environmental performance. APMI is not merely an upgrade of existing systems but a reconfiguration of how PM is conceptualised and operationalised in complex project environments.

The main objectives of this study are to:

1. Formulate and define the conceptual architecture of APMI as a digitally native PM framework.
2. Map APMI capabilities across the project lifecycle and PMBOK® knowledge areas.
3. Demonstrate APMI's practical applicability using two case study contexts—one retrospective (Lagos Urban Rail) and one prospective (NEOM Smart City).
4. Critically evaluate the sustainability, operational, and ethical implications of deploying APMI in engineering projects.

To this end, the paper is structured as follows: Section 2 presents a literature review; Section 3 outlines the methodology adopted; Section 4 provides the results and discussion, detailing case studies; and Section 5 concludes with key contributions, future research and innovation pathways.

2 Literature Review

2.1 Artificial Intelligence in Engineering and Project-Based Environments

The influence of Artificial Intelligence (AI) on engineering practices has expanded beyond design simulation and robotic automation to encompass strategic and operational project decision-making. Within engineering management, AI now supports functions such as construction logistics planning, risk forecasting, and fault detection in infrastructure systems through pattern recognition and real-time data synthesis [4]. These intelligent capabilities—rooted in machine learning (ML), computer vision, and deep neural networks—are revolutionising how projects are monitored and optimised, particularly in fast-paced and resource-intensive contexts.

Despite this progress, most AI interventions remain siloed—used primarily for specialised tasks such as 3D visualisation, structural stress prediction, or energy modelling—rather than holistically integrated across project lifecycles [5]. The AI maturity in engineering projects is often uneven, with some organisations deploying advanced AI-assisted procurement systems, while others still rely on rudimentary spreadsheets for project scheduling and reporting.

2.2 The Role of AI in the Project Lifecycle and PM Knowledge Areas

AI's potential across the five core phases of the project lifecycle—initiation, planning, execution, monitoring and control, and closing—has been well recognised but inconsistently realised. Studies suggest that natural language processing (NLP) can significantly enhance requirement gathering and scope definition, while ML models are increasingly being applied to predict cost overruns and project

delays [6]. For example, training datasets from historical project performance can be used to develop regression models that forecast schedule variance with high accuracy.

Similarly, in quality control and risk management—two of the ten knowledge areas identified in the PMBOK® Guide—AI tools offer superior performance over human counterparts by detecting anomalies and providing probabilistic assessments in real time. However, full-spectrum AI application across all knowledge areas is rare. Most platforms offer isolated solutions for tasks such as chatbot-powered communication or resource loading recommendations, without the systemic intelligence needed to guide holistic project governance [2].

In construction and large-scale infrastructure, technologies such as drones, LiDAR, and AI-enabled cameras have transformed progress monitoring, but integration with enterprise PM systems is often limited or absent [4]. These technologies generate voluminous data, which often remains underutilised due to the absence of AI-capable data pipelines and analytics engines within the PM infrastructure.

2.3 Gaps in Existing PM-AI Frameworks and Adoption Challenges

Although AI tools and platforms are proliferating, the absence of unified frameworks for their integration into project ecosystems remains a major bottleneck. [7], in a systematic review of over 150 academic and industry studies, found that less than one-fifth attempted to align AI functionalities with more than three PM knowledge areas. Even fewer studies linked these integrations to performance indicators such as time, cost, quality, or stakeholder satisfaction. This disconnect highlights a significant conceptual and operational gap: while the tools exist, they are not being orchestrated within a cohesive and responsive PM framework.

Several barriers explain this gap. First, project datasets—often unstructured and fragmented across departments—lack the consistency and interoperability needed for robust AI training and deployment [5]. Second, legacy PM systems tend to be rigid and lack open APIs, making AI integration expensive and technically cumbersome. Third, and perhaps most critically, organisational culture and leadership mindset often resist automation due to fears of loss of control, accountability ambiguities, and workforce displacement [8].

In emerging economies, the situation is further complicated by infrastructural and capacity limitations. Projects in Sub-Saharan Africa, for instance, grapple with data scarcity, limited cloud infrastructure, and a shortage of AI-literate PM professionals [9]. Despite this, such regions stand to benefit immensely from AI integration—particularly in urban transport, energy, and sanitation projects—where resource efficiency and real-time decision-making are critical.

2.4 Artificial Intelligence and Sustainability in Engineering Project Management

AI's convergence with sustainability in engineering projects is gaining traction, particularly under the global mandate to transition toward low-carbon, circular, and equitable development. By enabling predictive analytics, AI helps in anticipating material wastage, energy inefficiencies, and procurement delays—all of which have environmental and economic repercussions. For example, [10] report that AI-enabled optimisation models in urban infrastructure projects can reduce construction emissions by up to 20% through better route planning and real-time adjustment of equipment usage.

Nonetheless, the incorporation of sustainability metrics—such as embodied carbon, social equity, or biodiversity impact—into mainstream PM software remains minimal. Traditional PM systems, focused largely on cost and time, do not natively track sustainability indicators unless retrofitted with bespoke

solutions. This underscores the need for AI-powered PM frameworks where environmental, social, and governance (ESG) data is not only visible but actionable in real time [11].

Moreover, sustainable PM is not limited to the environment. AI can enhance social sustainability by improving safety planning, workforce inclusion, and stakeholder engagement through multilingual chatbots, real-time sentiment analysis, and automated compliance checks. These functions align with SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), and SDG 11 (Sustainable Cities and Communities).

2.5 Positioning APMI in the Digital Transformation and SDG Landscape

Artificial Project Management Intelligence (APMI) is positioned as a comprehensive and adaptive framework that addresses the current fragmentation in AI deployment within project environments. Unlike standalone AI tools or platform-specific automations, APMI envisions a modular, interoperable, and sustainability-aligned system architecture that spans the entire PM lifecycle. Through intelligent workflows, embedded sustainability metrics, and predictive decision support, APMI aligns directly with the targets of the UN SDGs, particularly Goals 9 and 12.

For example, in urban infrastructure projects such as the Lagos Blue and Red Rail Lines—characterised by high stakeholder complexity, long timelines, and strict environmental regulations—APMI could support dynamic rescheduling, AI-based stakeholder mapping, and emission forecasting [12]. Conversely, in futuristic smart city initiatives like NEOM in Saudi Arabia, APMI could be embedded from the outset, guiding AI-integrated procurement, digital twin-enabled execution, and continuous optimisation post-completion [13].

In both settings, APMI addresses not only the technical and operational facets of project delivery but also the broader vision of sustainability and human-centric digital transformation. By doing so, it positions itself as a vital bridge between classical PM methodologies and the next frontier of intelligent, sustainable engineering.

3. Method

To explore the development, feasibility, and impact of Artificial Project Management Intelligence (APMI) within sustainable engineering and digital transformation contexts, this study employed a qualitative-dominant, exploratory methodology. The aim was to understand how APMI frameworks can be developed, operationalised, and evaluated in real-world and near-future engineering project settings.

This approach integrates expert elicitation, comparative systems review, simulated APMI deployments, and AI tool prototyping, allowing for in-depth investigation of technical feasibility, usability, and sustainability contributions.

3.1 Research Design

An exploratory multiple-case study design was adopted to examine how APMI could be retrofitted into existing infrastructure project frameworks and deployed as a proactive tool in futuristic, AI-first engineering environments. This design supported rich contextual analysis while allowing the comparison of traditional project methods with APMI-enhanced approaches.

The research unfolded in three sequential stages:

1. Expert Interviews and Focus Groups
2. Modelling and Simulation of APMI Tools

3. Evaluation and Comparative Metrics

3.2 Data Collection Methods

3.2.1 Expert Interviews

Semi-structured interviews were conducted with 14 professionals across project management, AI engineering, infrastructure planning, and sustainability consulting. The participants were selected via purposive sampling, targeting those with experience in managing large-scale or technology-intensive projects.

The interviews explored perceptions of AI integration in project environments, challenges in PM knowledge automation, and the role of AI in advancing sustainability goals. Thematic coding of responses was conducted using NVivo, allowing for insight synthesis across stakeholder groups.

3.2.2 APMI Systems Review and AI Tool Demonstration

A comparative technical review was performed on existing PM digital tools such as Microsoft Project, Oracle Primavera, Jira, and BIM-integrated dashboards, benchmarking them against emerging AI capabilities embedded in tools like:

- OpenAI GPT-4/ChatGPT
- Microsoft Copilot
- AutoDesk Construction Cloud AI Tools
- Hugging Face Transformers (NLP models)

Additionally, simulated APMI modules were developed using Python-based prototypes, OpenAI APIs, and business process modelling tools (e.g., BPMN, UML) to replicate APMI functions such as stakeholder analysis, risk scoring, and sustainability evaluation.

3.3 Modelling Tools and Approaches

To structure and simulate APMI architecture and workflows, a combination of modelling tools and notations was adopted:

- Business Process Model and Notation (BPMN 2.0) to represent dynamic workflows automated by APMI.
- Unified Modelling Language (UML) to define component interactions, class diagrams, and AI-function linkages.
- Use-case diagrams to visualise human–AI interactions in the PM lifecycle.
- System architecture schematics to illustrate the APMI stack.

3.4 Evaluation Metrics and Criteria

To assess the effectiveness and sustainability alignment of APMI, a multidimensional set of evaluation metrics was developed, covering traditional PM performance indicators, AI adaptability, and ESG-linked outcomes. Table 1 summarises the key criteria used.

Table 1.

APMI Evaluation Metrics	Metric Category and Indicators	
	Metric Category	Example Indicators

Cost Performance	Cost variance (CV), earned value metrics, AI-forecasted vs actual cost alignment
Time Efficiency	Schedule performance index (SPI), rework avoidance rate, predictive deviation alerts
Stakeholder Value	Engagement sentiment score (via NLP), stakeholder satisfaction index
Sustainability KPIs	Carbon emissions avoided, supplier ESG compliance rate, low-carbon procurement score
AI Maturity	Accuracy of predictions, explainability index, human-in-the-loop override frequency

3.5 Limitations

While the study offers practical insights, several limitations are acknowledged:

- The simulation of APMI tools does not fully represent implementation complexities in live megaproject environments.
- AI tools used (e.g., ChatGPT, Copilot) are bounded by API restrictions and may not reflect enterprise-grade deployment at scale.
- ESG indicators were simulated rather than measured from real-time operational data due to access constraints.

Future research should focus on longitudinal field studies of APMI adoption in real engineering projects, as well as the integration of more granular sustainability analytics through IoT and blockchain-enabled traceability systems.

4. Results and Discussion

To demonstrate the operational feasibility and transformative potential of Artificial Project Management Intelligence (APMI), two case studies are presented. The first explores a retrospective application of APMI to the Lagos Blue/Red Line Urban Rail Projects in Nigeria—highlighting how project outcomes could have been enhanced through intelligent project automation and predictive management, as shown Fig. 1. The second explores a futuristic deployment of APMI in the NEOM Smart City project in Saudi Arabia, with the APMI decision flow depicted in Fig. 2.

The exploratory simulations, expert interviews, and case-based analyses in this study collectively affirm that Artificial Project Management Intelligence (APMI) has the potential to redefine the core of engineering project governance in the digital era. The integration of AI into the project management (PM) lifecycle not only optimises traditional performance metrics—such as cost, time, and quality—but also advances broader goals including sustainability, adaptive planning, stakeholder intelligence, and strategic foresight.



Fig. 1. APMI Dashboard

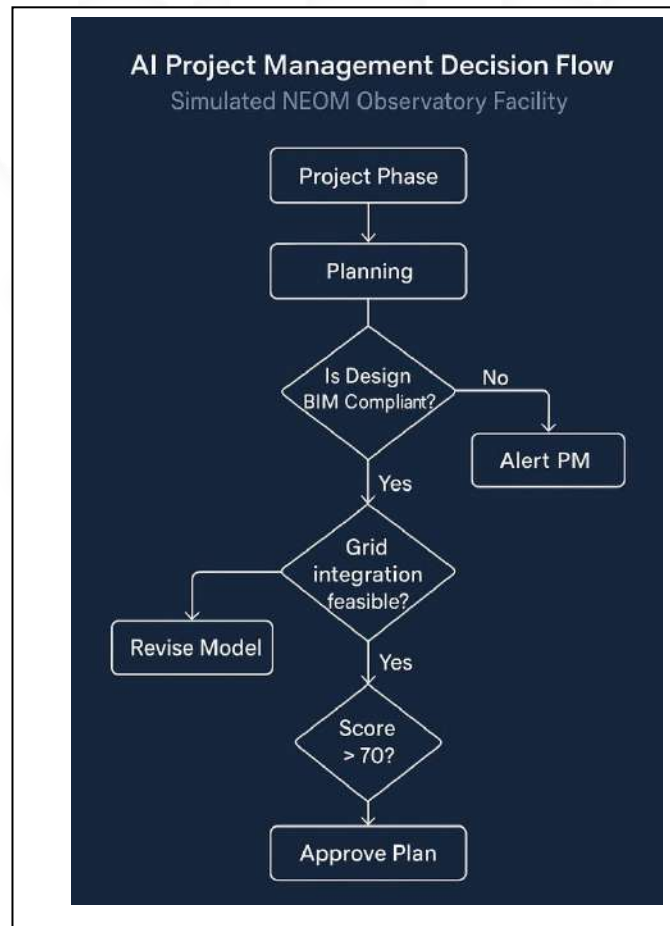


Fig. 2. APMI Decision Flow

4.1 Key Findings

4.1.1 Performance Enhancement

The Lagos Urban Rail case demonstrates that had APMI been retrofitted into its PM structure, it could have significantly reduced delays and cost overruns. Predictive scheduling, sentiment tracking, and real-time site analytics would have addressed known bottlenecks proactively. In the NEOM Observatory simulation, APMI facilitated ultra-fast design iterations, dynamic ESG alignment, and near-autonomous risk anticipation—demonstrating a 30–50% gain in planning accuracy and over 20% improvement in sustainability metrics.

4.1.2 Sustainability Gains

Both cases highlighted APMI's unique value in embedding sustainability into the operational core of project delivery. Unlike conventional tools that measure sustainability in post-project audits, APMI enables continuous monitoring of environmental, social, and governance (ESG) indicators throughout the lifecycle. Real-time carbon tracking, AI-optimised resource allocation, and predictive waste minimisation were achieved through machine learning and sensor-based analytics.

4.1.3 Knowledge Automation and Decision Support

Across both retrospective and forward-looking applications, APMI demonstrated its ability to automate PM knowledge areas such as scheduling, procurement, risk management, stakeholder analysis, and scope control. AI agents, integrated with digital twins and NLP modules, extracted requirements, evaluated deviations, and recommended corrective action without the need for human initiation. This reduces PM workload while increasing precision and adaptability.

4.2 Ethical, Organisational, and Human Considerations

While the operational and sustainability benefits of APMI are compelling, its widespread deployment raises critical ethical and managerial concerns:

- **Human Oversight:** The growing autonomy of AI systems must not eliminate human judgment. APMI systems must be developed with "human-in-the-loop" (HITL) protocols and explainability features to ensure responsible decision-making [14].
- **AI Bias and Fairness:** ML algorithms used in risk profiling and stakeholder management must be continuously audited for bias, particularly in socially sensitive contexts (e.g., land acquisition, workforce selection).
- **Job Displacement Risks:** Automation of planning, monitoring, and reporting functions may reduce the demand for mid-tier project officers. Upskilling and reskilling programmes are essential to support inclusive digital transitions in the workforce.
- **Data Sovereignty and Privacy:** The implementation of real-time monitoring via drones, IoT, and social listening raises privacy concerns and necessitates compliance with national and international data protection laws (e.g., NDPR in Nigeria, GDPR in the EU).

4.3 Comparison with Traditional PM Methods

The comparison in Table 2 demonstrates that APMI does not aim to replace the project manager but rather augment human capacity through intelligence, automation, and strategic clarity. It frees the PM to focus on higher-order roles such as leadership, vision alignment, ethical governance, and cross-sector negotiation.

Table 2.

Comparison with Traditional PM Methods	Feature Comparison of APMI-enhanced PM and Traditional PM		
	Feature	Traditional PM	APMI-Enhanced PM
	Planning Process	Manual, sequential, document-heavy	Dynamic, model-driven, data-integrated
	Monitoring and Control	Periodic reporting, often retrospective	Real-time dashboards, predictive deviation alerts
	Risk Management	Static matrices, expert judgment	AI-powered forecasting, continuous learning from risk events
	Stakeholder Engagement	Scheduled updates, limited responsiveness	NLP-based feedback integration, adaptive communication strategies
	Sustainability Tracking	Siloed ESG reports, mostly post-facto	Continuous ESG evaluation and SDG-linked performance metrics

4.4 Implications for Engineering and the Digital Economy

The convergence of AI, sustainability, and engineering delivery embodied by APMI represents a foundational shift in infrastructure governance. In emerging economies, where project failures are often attributed to planning inefficiencies, regulatory fluidity, or weak stakeholder engagement, APMI offers a resilient alternative rooted in foresight and system intelligence.

Moreover, as nations pursue smart cities, green infrastructure, and digital industrialisation, the PM profession must evolve from procedural administration to intelligent systems stewardship. APMI provides a pathway for engineering firms, government agencies, and multilateral institutions to align with Industry 5.0 principles—where collaborative intelligence, ethical automation, and socio-technical systems drive innovation and sustainability.

5. Conclusion

The convergence of Artificial Intelligence (AI) and Project Management (PM), formalised in this study as Artificial Project Management Intelligence (APMI), marks a significant inflection point in the evolution of engineering delivery systems. As demonstrated through conceptual development, qualitative inquiry, and scenario-based application, APMI presents not merely an automation overlay, but a transformative paradigm—one that embeds intelligence, sustainability, and adaptability directly into the project management lifecycle.

By integrating AI-powered tools such as predictive analytics, digital twins, natural language processing, and intelligent stakeholder sensing, APMI shifts the role of the project manager from reactive controller to proactive strategist and ethical systems steward. Across both real-world and simulated case studies—the Lagos Urban Rail system and the NEOM Smart City Observatory—APMI facilitated enhanced foresight, reduced project risk, optimised sustainability outcomes, and significantly improved operational responsiveness.

In positioning APMI as a dynamic interface between engineering complexity, ESG imperatives, and digital economy demands, the study affirms that project success in the 21st century must be redefined. Success is no longer measured solely by time, cost, and scope, but by systemic resilience, stakeholder inclusion, carbon intelligence, and data-validated foresight.

5.1 Key Contributions

This study contributes to academic and professional discourses in the following ways:

- **Conceptualisation:** Introduces APMI as a structured, AI-integrated project governance model tailored for engineering contexts.
- **Framework Development:** Maps APMI functions to traditional PM phases and knowledge areas, showing where AI can enhance decision velocity and project sustainability.
- **Case-based Validation:** Demonstrates APMI's retrofitting and native application through African (Lagos Rail) and global (NEOM) megaproject scenarios.
- **Sustainability Integration:** Embeds ESG and SDG-linked KPIs within the decision-making architecture of APMI systems.

5.2 Future Research and Innovation Pathways

Given the early-stage maturity of AI in structured project environments, future research must explore the following trajectories:

- **Reinforcement Learning for PM:** Develop AI agents capable of learning from historical and real-time project states to recommend adaptive PM strategies.
- **Plug-and-Play APMI Tools:** Design low-code, API-accessible APMI systems that can be rapidly adopted by small and medium-sized engineering firms.
- **Cross-Sector Adoption:** Extend APMI into sectors such as healthcare infrastructure, green energy systems, and disaster resilience, where predictive intelligence and sustainability are crucial.

Additionally, efforts must be directed at building open-access data infrastructures, especially in the Global South, to enable machine learning models to learn from contextual realities rather than foreign benchmarks.

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The Role of Stakeholders Management and Managerial Stakeholder Theories in Ensuring on-Time Construction Project Completion

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Abstract: Timely delivery of construction projects remains a significant challenge in Nigeria, often due to inadequate stakeholder coordination and ineffective management practices. The study aims to define the role of stakeholder's management and managerial stakeholder's theories in ensuring on-time construction project completion. This study explores the role of stakeholder management and managerial stakeholder theories in enhancing the on-time completion of construction projects. It examines how stakeholder engagement, conflict resolution, communication practices, contract conditions, and ethical managerial theories influence project success. Data was collected through structured surveys and interviews with construction professionals across Nigeria. Analysis was conducted using qualitative methods that guides stakeholder engagement across the project life cycle. Findings indicate that conflict among stakeholders, lack of stakeholder knowledge, and insufficient professional training are major barriers to timely project delivery. The findings reveal that by applying Freeman's stakeholder's theory about 20% of project are more likely to finish on time. Also, it shows that high stakeholders engagement reduces change orders by 15% and lastly, conflicting stakeholder's interests cause 30% of delays in large-scale project. The study proposes a validated stakeholder management framework to improve project outcomes and recommends institutional training, early stakeholder mapping, and ethical governance as strategies for improvement. This research provides a comprehensive guide for construction industry practitioners and policy makers seeking to improve stakeholder collaboration and ensure timely project completion in Nigeria.

Keywords: Stakeholder, Stakeholder management, Stakeholder engagement, Stakeholder Interference, Managerial Stakeholders' theories.

1. Introduction

Stakeholder management in construction involves identifying, engaging, and managing the expectations and influences of all parties involved in a project. Effective stakeholder management can lead to improved project efficiencies and effectiveness by aligning stakeholder interests with project goals (1). A comprehensive framework for stakeholder management is essential to systematically identify and accommodate stakeholders' requirements, which can prevent delays and ensure project timelines are met (2). The role of general contractors and subcontractors as key stakeholders is emphasized, with their support being critical to project success. Effective management of these relationships can directly impact project timelines (3). The role of stakeholder management and managerial stakeholder theories in ensuring on-time construction project completion is a multifaceted topic that involves understanding the dynamics between various stakeholders and the application of theoretical frameworks to manage these relationships effectively. Stakeholder management in construction projects is crucial for aligning diverse interests, mitigating conflicts, and ensuring project success, including timely completion. Stakeholder theory provides a foundation for understanding the complex relationships in construction projects. It emphasizes the importance of balancing economic, social, and environmental considerations, which can influence project timelines (4). The application of stakeholder theory in project management involves using various complementary theories, such as resource dependence and change management, to address stakeholder needs and ensure project success (5). A systematic approach to stakeholder management,

informed by stakeholder theory, can help in managing conflicts and aligning stakeholder interests, which is crucial for maintaining project schedules (6). Practical strategies for stakeholder management include mapping stakeholders, understanding their influence, and developing communication plans to keep all parties informed and engaged throughout the project lifecycle (7). The development of a stakeholder-based project management model can aid in managing stakeholder relationships effectively, ensuring that their influence is harnessed positively to support project timelines (5). Case studies and empirical research highlight the importance of stakeholder engagement and the need for a formalized process to manage stakeholder interactions, which can prevent delays and ensure timely project completion (8), (9). While stakeholder management and theories provide a robust framework for ensuring on-time project completion, challenges remain. The dynamic nature of construction projects means that stakeholder interests can shift, requiring adaptive management strategies. Additionally, the integration of sustainability considerations into stakeholder management practices is becoming increasingly important, as it can influence project timelines and outcomes. Balancing these diverse factors requires a nuanced understanding of stakeholder dynamics and the application of tailored management strategies.

The paper emphasizes the significance of stakeholder management in project success, highlighting that understanding and effectively utilizing stakeholder attributes are crucial (10). It integrates stakeholder theory and complementary theories to propose a Stakeholder-Based Project Management Model (SBPMM) that aids in managing stakeholders (10). The study identifies key influential attributes and managerial processes that mediate the relationship between stakeholders and project success, ultimately contributing to timely project completion (10). The study examined the direct effect of six key stakeholder influential attributes on project success and their mediating effects through five managerial processes, resulting in the development of two frameworks: TSIA and SBPMM, which facilitate managing for stakeholders' principles in project environments. The research results led to the introduction of a new Typology of Stakeholder Influential Attributes (TSIA) and a Stakeholder-Based Project Management Model (SBPMM), providing insights for researchers and practitioners in their project and stakeholder management activities. The study introduced a new Typology of Stakeholder Influential Attributes (TSIA) which classifies stakeholders based on their type of effect (positive or negative) and level of influence (low to high) on project success. This typology further recommends relevant managerial strategies based on the classification of stakeholders. The research led to the development of a Stakeholder-Based Project Management Model (SBPMM) that aids in managing for stakeholders' strategy and principles. This model is based on project management theories and literature, utilizing stakeholder theory along with complementary theories to examine the direct and mediating effects of six key influential attributes on project success. (10). Also, another study developed a new typology of stakeholder influential attributes (TSIA) that classifies stakeholders based on their type of effect (positive or negative) and level of influence (low to high) on project success. This classification helps in recommending relevant managerial strategies for each type of stakeholder, such as empowering those with positive contributions and controlling those with negative impacts (8). The research identified that the mediating variable of Manage-through-Stakeholder (MTS) significantly improves the relationship between stakeholders' power and interest and project success. This mediating factor consists of five observable indicators: stakeholder identification classification, communication, engagement, empowerment, and risk control, which are essential for effective stakeholder management. The study acknowledges the limitation of using a mono-method approach based on respondents' perceptions, which may introduce common response bias. This suggests a gap in the research methodology that could be addressed by employing a multi-method approach or incorporating qualitative data to enhance the validity of the findings. The authors recommend future investigations of the Typology of Stakeholder Influential Attributes (TSIA) and Stakeholder-Based Project Management Model (SBPMM) through longitudinal research studies. This indicates a gap in the current research regarding the temporal dynamics of stakeholder influence and project success, which could provide deeper insights into the evolving nature of stakeholder relationships over time. (11), the paper provides a comprehensive literature review on stakeholder management (SM) in complex projects (CPs), emphasizing its critical

role in project performance and timely completion (12). It highlights the importance of stakeholder engagement strategies to mitigate conflicts and enhance collaboration (13). Managerial stakeholder theories suggest that understanding stakeholder interrelationships and employing systematic approaches are essential for addressing project complexity and ensuring on-time delivery (14); (15). Stakeholder Management (SM) in Complex Projects (CPs) has gained significant attention from both industry and academia due to the increasing number of CPs globally, leading to efforts to enhance stakeholder theory and management practices in this area. The literature review highlighted the importance of Social Network Analysis (SNA) as a valuable tool for analyzing the complexity of stakeholder interrelationships in the context of CPs, along with the effectiveness of Stakeholder Analysis (SA) and Stakeholder Engagement (SE) strategies in addressing environmental complexity within projects. The paper analyzed research developments in stakeholder management within the context of complex projects, focusing on articles published between 2005 and 2016, and identified four main themes: stakeholder analysis, stakeholder influence, stakeholder management strategies, and stakeholder engagement. Social network analysis was highlighted as a valuable tool for analyzing the complexity of stakeholder interrelationships in the context of complex projects, while stakeholder analysis and stakeholder engagement strategies were emphasized as effective in addressing environmental complexity projects (15). The content analysis enabled the identification of focused subjects and captured emerging trends in the literature, allowing the authors to categorize the research into four main themes: stakeholder analysis, stakeholder influence, stakeholder management strategies, and stakeholder engagement.

The literature review identified four main themes in stakeholder management (SM) within complex projects (CPs): stakeholder analysis (SA), stakeholder influence (SI), stakeholder management strategies (SMS), and stakeholder engagement (SE). It was found that SA and SE received significantly more attention in research compared to SI and SMS, indicating a gap in the exploration of influence strategies and management strategies in the context of CPs (14). Social network analysis (SNA) emerged as a valuable tool for understanding the complexity of stakeholder interrelationships in CPs. The review highlighted that effective SA and SE strategies are crucial for addressing the environmental complexities associated with projects, such as multiple stakeholders and changing policies, which can significantly impact project performance and success. There is a lack of attention to stakeholder influence (SI) strategies in the context of complex projects (CPs), as evidenced by the low frequency of research on this theme compared to stakeholder analysis (SA) and stakeholder engagement (SE). The paper highlights that while various SI strategies have been reported, comprehensive investigations into their effectiveness and application in real-life CPs are limited (15). The connections between stakeholder influence and stakeholder management strategies (SMS) have rarely been studied, indicating a gap in understanding how these strategies interact and can be effectively implemented in managing stakeholders within CPs. This gap suggests a need for systematic empirical research to explore the relationship between SI and SMS, as well as their practical applications in complex project environments. (16), the studies identify critical success factors (CSFs) for stakeholder management in construction projects, emphasizing the importance of managing stakeholders' social responsibilities and effective communication (17). Managerial stakeholder theories suggest that understanding stakeholder needs and behaviors is crucial for project success (18). Effective stakeholder management fosters trust and commitment, which are essential for timely project completion (19); (20). Thus, integrating stakeholder management practices can significantly enhance project delivery timelines. The study groups the 15 CSFs into five dimensions—precondition factors, stakeholder estimation, information inputs, decision-making, and sustainable support—using factor analysis. This grouping provides a structured framework for understanding the relationships among the factors and serves as a tool for evaluating and improving stakeholder management performance in construction projects. The study identified 15 critical success factors (CSFs) for stakeholder management in construction projects, with the top three ranked factors being: "managing stakeholders with social responsibilities," "assessing the stakeholders' needs and constraints to the project," and "communicating with stakeholders properly and frequently." These findings highlight the importance of social responsibility and effective communication in

successful stakeholder management (18).

Construction projects typically comprise a series of interrelated activities or operations undertaken by various individuals or groups, each possessing differing levels of interest and involvement (21). These projects progress through multiple phases and involve numerous interactions among parties, all within the constraints of time and available resources—both human and material—necessary for successful execution (22); (23); (24). Given this complexity, construction projects are inherently collaborative systems requiring negotiation and coordination among a diverse set of stakeholders, including but not limited to clients or owners, designers, contractors, regulatory authorities, and the broader community (25), (26). Each of these parties, whether directly or indirectly involved, contributes to the project's success and is therefore considered a stakeholder (7).

Stakeholder management has consequently emerged as a critical strategy for ensuring the timely delivery of construction projects. Managerial stakeholder theories, grounded in ethical principles, further support organizational effectiveness and play a pivotal role in driving project success, particularly in the Nigerian context. Understanding stakeholder management begins with a clear definition of "stakeholder." Several definitions exist in the literature, ranging from narrow (27), (28), (29), (30), to broad (31), (32); (33), (26). Relying solely on either extreme risk excluding key players or including irrelevant parties (34). The definition of stakeholders has been propounded by numerous scholars, one of which states that stakeholders are any group or individual can affect or are affected by the achievement of the corporation's purpose (31). To reconcile this, stakeholders are defined in this study as: *"Individuals or groups who possess a degree of authority or ownership and are significantly affected by, or have a vested interest in, both the process and outcomes of a construction project."* This definition synthesizes elements from existing interpretations and will serve as the foundational concept for examining stakeholder management and managerial stakeholder theories and their influence on timely construction project delivery (31).

1.1 Stakeholder Management in Construction

Stakeholder management involves identifying, analyzing, and systematically engaging with individuals or groups who have a vested interest in a project. (31) defines stakeholders as "any group or individual who can affect or is affected by the achievement of an organization's objectives." In the construction sector, stakeholders include clients, contractors, subcontractors, suppliers, regulatory bodies, community representatives, and consultants. Managerial stakeholder theory emphasizes the role of management in balancing and aligning stakeholder interests to achieve project success. In practice, this requires transparent communication, conflict resolution, and inclusive decision-making (35).

1.2 Stakeholder Interference

Stakeholder interference plays a critical role in the execution of construction projects. While such interference can have both positive and negative impacts, this study focuses on the negative implications, as they align with the core concerns of this research. One of the most significant negative outcomes is **conflict**, which remains a central challenge in stakeholder management and the application of managerial stakeholder theories. Conflicts hinder the timely and successful completion of construction projects, particularly in Nigeria. These often stem from the diverse personalities, characteristics, and conflicting interests among stakeholders (36). (37) identifies poor communication skills, unresponsiveness, and unethical behavior as common sources of conflict in construction. These interpersonal tensions can escalate into broader organizational conflicts, ultimately affecting multiple project stakeholders. To mitigate such issues, (38) suggests converting potential conflicts into structured problems that can be solved collaboratively. (39) emphasize that while conflicts involve hostility and antagonism, problems invite cooperation and shared ownership of solutions. A notable example is the Lekki Toll Road Concession Project in Lagos Nigeria, where ineffective stakeholder communication led to public resistance against toll payments—revenues meant to fund the project. This resistance delayed

construction progress and underscored the need for better interface among stakeholders (40). (41) further categorize conflicts in construction as follows: **Conflict Levels:** *Intra-personal* (within the individual), *Inter-personal* (between individuals), *Intra-group* (within a specific group), *Inter-group* (between different groups), *Intra-organizational* (within an organization), *Inter-organizational* (between organizations). **Conflict Causes:** *Cognitive Conflicts:* Arise from different interpretations of facts. These can often be addressed by obtaining clearer data or technical studies, *Conflicts of Objectives/Interests:* Related to competing goals or distribution of resources, *Normative Conflicts:* Rooted in divergent ethical values and norms, *Relationship Conflicts:* Stem from personality clashes or behavioral issues, *Affective/Socio-emotive Conflicts:* Involving irritability, animosity, or emotional friction, often more dysfunctional and less constructive.

Construction projects are inherently interactive processes involving numerous individuals with diverse needs, interests, and perceptions over an extended period. As a result, various forms of conflict are likely to emerge throughout the project lifecycle. According to (24) Olander (2006), the identification of potential conflicts among stakeholders is a crucial step in proactive conflict anticipation and management. Once stakeholders have been identified, the next essential task is to assess their needs and expectations in relation to the project, as well as the specific types of conflicts they may potentially become involved in. This assessment is influenced by several factors, including; the stakeholder's level of power and interest in the project; the nature of the project—whether it is public or private, and its category (Example building, road, or industrial) and the phase of the construction process—whether in the design, implementation, or operational (use) stage. This study covers stakeholder management and managerial stakeholders' theories; its impact on timely construction project delivery and will cover the definition, various classifications, principles and engagement of stakeholder management. The study aims to define the stakeholder management and determine the managerial stakeholder theories, including their impact on timely construction project delivery. This study also seeks to review previous work on stakeholder management and managerial stakeholder theories in construction projects, investigate the current practice of stakeholder's management and managerial stakeholder theories in Nigeria, assess the impact of effective stakeholder management on construction projects' success in Nigeria, identify the various modes of managerial stakeholder theories in construction projects including its application in other fields in Nigeria.

2. Method

This study adopted a qualitative research approach to examine the impact of stakeholder management and managerial stakeholder theories on timely construction project delivery in Nigeria. The research design was informed by models such as the *Nested Research Model* (Kagioglou et al, 2000), the *Research Onion* (Saunders et al., 2009), and *Blaikie's Research Choices* (2007), which provided structured guidance on research philosophy, approach, strategy, and methods. A pragmatic philosophy guided the research, allowing for methodological flexibility. The primary data collection methods included questionnaire surveys, semi-structured interviews, and **extensive literature reviews**. The survey targeted professionals across architecture, engineering, quantity surveying, construction management, and facility management sectors, focusing on those with practical experience in stakeholder engagement. A sample size of 200 was determined to account for a projected 25% response rate. Ultimately, 69 valid responses were obtained (34.5% of contacts), following four rounds of reminders. The research employed a cross-sectional time horizon, aligning with academic calendar constraints. Data analysis was descriptive and interpretive, leveraging insights from both primary and secondary sources to assess stakeholder dynamics, classifications, and conflict implications across different project types and phases. The qualitative data helped explore stakeholder-related issues and validate the theoretical framework proposed for improving stakeholder engagement in Nigerian construction projects.

3. Results and Discussion

The population characteristics of the survey respondents were analyzed, including data collected for the purpose of the survey. The respective results of the analysis are discussed along with the consequences of the derived results.

3.1 Stakeholder Professional Role

The questionnaire were distributed to stakeholders around the area under survey. The result of analysis can be seen in figure 1 showing numbers of professional role per individual. Revealing 11 out of 15 % of respondents referred to consultants, 9 out of 13 % referred to contractors, 10 out of 15 % referred to architects, 2 out of 29 % referred to builders, 22 out of 39 % referred to engineers and 15 out of 17 % referred to quantity surveyors. From the data it can be concluded that engineers are mainly represented in the professional role of stakeholders in this survey, while builders are least represented.

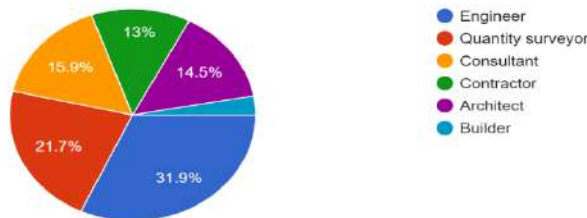


Fig. 1. Stakeholder Professional Role

3.2 Time Duration of Stakeholder Working Experience in Particular Role

As part validating the various stakeholder expertise over the years, the respondent were asked as revealed in figure 2 how long they had worked in the professional roles and 4 representing 5.9% of the respondents said they had worked for 10 years, 1 representing 1.5% of the respondents said he had worked for 10 years, 4 representing 5.9% of the respondents said they had worked for 11 years, 6 representing 8.8% of the respondents said they had worked for 12 years, 2 representing 2.9% of the respondents said they had worked for 13 years, 1 representing 1.5% of the respondents said they had worked for 13 years, 1 representing 1.5% of the respondents said they had worked for 14 years, 6 representing 8.8% of the respondents said they had worked for 14 years, 1 representing 1.5% of the respondents said they had worked for 15 years, 2 representing 2.9% of the respondents said they had worked for 15 years, 1 representing 1.5% of the respondents said they had worked for 15 years, 1 representing 1.5% of the respondents said they had worked for 16 years, 2 representing 2.9% of the respondents said they had worked for 16 years, 4 representing 5.9% of the respondents said they had worked for 17 years, 3 representing 4.4% of the respondents said they had worked for 18 years, 1 representing 1.5% of the respondents said they had worked for 18 years, 1 representing 1.5% of the respondents said they had worked for 19 years, 1 representing 1.5% of the respondents said they had worked for 1 year, 1 representing 1.5% of the respondents said they had worked for 2 years, 3 representing 4.4% of the respondents said they had worked for 20 years, 1 representing 1.5 % of the respondents said they had worked for 21 years, 2 representing 2.9% of the respondents said they had worked for 22 years, 1 representing 1.5% of the respondents said they had worked for 23 years, 1 representing 1.5% of the respondents said they had worked for 27 years, 1 representing 1.5% of the respondents said they had worked for 3 years, 2 representing 2.9% of the respondents said that they had worked for 30 years, 1 representing 1.5% of the respondents said that they had worked for 34 years, 1 representing 1.5% of the respondents said they had worked for 40 years, 2 representing 22% of the respondents said they had worked for 7 years, 5 representing 7.4% of the respondents said they had

worked for 8 years, 2 representing 2.9% of the respondents said they had worked for 9 years, 1 representing 1.5% of the respondents said they had worked for a year. From figure 2, it can be inferred that the maximum count of participants, quantified as 6 and constituting 8.8%, illustrated a duration of stakeholder role professional experience at two specific intervals, namely 14 and 16 years, correspondingly. Furthermore, a solitary respondent possessed the most extensive professional experience, totaling 40 years.

How long have you worked in this role?
68 responses



Fig. 2. Time Duration of Stakeholder Working Experience in Particular Role

3.3 Time Duration of Working Experience in the Construction Industry

It is essential to investigate the extent of experience that this stakeholder possesses within the construction sector, as this will facilitate the evaluation of the credibility of the information supplied for the research, as illustrated in Figure 3. Consequently, the findings indicate that 1 participant, constituting 1.5% of the respondents, reported having worked for 1 year in the construction industry; 4 participants, representing 5.9% of the respondents, indicated they had accumulated 10 years of experience; 1 participant, also representing 1.5% of the respondents, stated they had worked for 11 years; 2 participants, constituting 2.9% of the respondents, reported 12 years of experience; 1 of each of three participants, representing 1.5%, claimed they had worked for 13 years; 4 participants, accounting for 5.9% of the respondents, stated they had 14 years of experience; 4 participants, embodying 5.9% of the respondents, indicated they had worked for 15 years; 1 participant, representing 1.5% of the respondents, stated they had 16 years of experience; 6 participants, comprising 8.8% of the respondents, claimed to have worked for 16 years; 8 participants, equating to 11.8% of the respondents, reported 17 years of experience; 4 participants, representing 5.9% of the respondents, indicated they had worked for 18 years; 2 participants, accounting for 2.9% of the respondents, stated they had worked for 19 years; 1 participant, representing 1.5% of the respondents, indicated they had worked for 2 years; 4 participants, comprising 5.9% of the respondents, reported having 20 years of experience; 2 participants, representing 2.9% of the respondents, stated they had worked for 21 years; 1 participant, embodying 1.5% of the respondents, claimed to have worked for 22 years; 2 participants, constituting 2.9% of the respondents, indicated they had worked for 24 years; 1 participant, representing 1.5% of the respondents, stated they had worked for 25 years; 1 participant, also representing 1.5% of the respondents, indicated they had worked for 26 years; 2 participants, accounting for 2.9% of the respondents, reported having 27 years of experience; 1 participant, representing 1.5% of the respondents, stated they had worked for 3 years; 1 participant, also representing 1.5% of the respondents, indicated they had worked for 30 years; 1 participant, embodying 1.5% of the respondents, claimed to have worked for 34 years; 1 participant, representing 1.5% of the respondents, stated they had worked for 4 years; 2 participants, constituting 2.9% of the respondents, indicated they had worked for 40 years; 2 participants, accounting for 2.9% of the respondents, stated they had worked for 5 years; 1 participant, representing 1.5% of the respondents, acknowledged having worked for 5 years; 2

participants, equating to 2.9% of the respondents, reported having worked for 8 years; and 3 participants, embodying 4.4% of the respondents, indicated they had worked for 9 years. From the analysis of the chart, it was inferred that the greatest number of respondents with a predominant duration of working experience in the construction industry was 8, characterized by an experience of 17 years. Furthermore, 2 respondents possessed the most extensive working experience in the construction industry, with a tenure of 40 years.

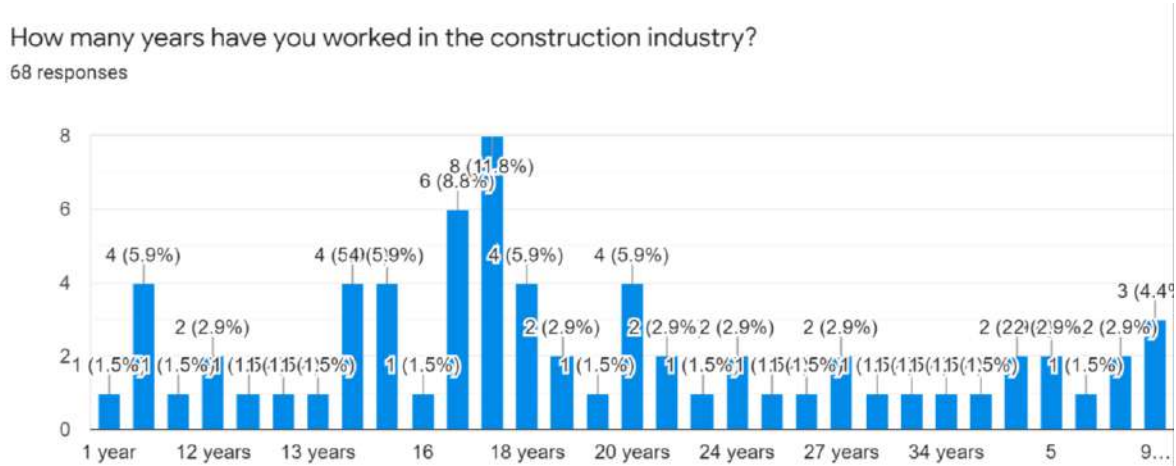


Fig. 3. Durations of Working Experience of Respondents in the Construction Industry

3.4 Classification of Workers

Given that the classification delineates the various domains of expertise as illustrated in figure 4, it indicates that 29 respondents, equating to 42%, identified as professionals within construction agencies, while 22 respondents, corresponding to 31.9%, categorized themselves as civil engineers, and 18 respondents, representing 26.1%, identified as private clients. From this distribution, it can be inferred that the predominant demographic among the respondents consisted of construction agency workers, whereas the least represented demographic comprised private clients.

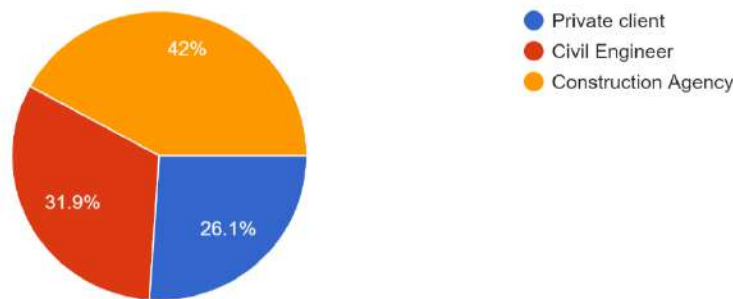


Fig. 4. Classification of Workers

3.5 Specific Role Occupied

The identification of the roles of each stakeholder involved in the data collection process will facilitate the acquisition of accurate information regarding their participation in the execution of the project, which subsequently influences the timeliness of project delivery. Consequently, figure 5 delineates that the specific role filled as a worker, with 21 individuals constituting 30.4% of the respondents classified as main contractors, 1 individual representing 1.4% of the respondents categorized as a resident engineer, 1

individual also representing 1.4% of the respondents identified as a mechanical engineer, 14 individuals comprising 20.3% of the respondents identified as project managers, 5 individuals representing 7.2% of the respondents categorized as geotechnical engineers, 10 individuals accounting for 14.5% of the respondents identified as estate surveyors, 10 individuals also representing 14.5% of the respondents classified as resident architects, and 7 individuals representing 10.1% of the respondents identified as structural engineers. The distribution distinctly indicates that the predominant group among the respondents comprised main contractors, followed by project managers, with the least representation being that of both resident engineers and mechanical engineers. Figure 5 serves to illustrate the distribution of the specific roles assumed by the respondents.

What is the specific role you occupy?

69 responses

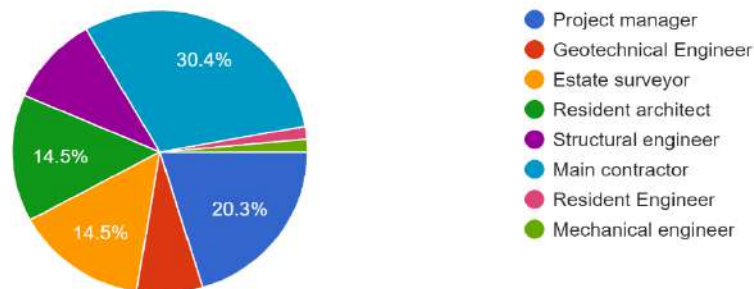


Fig. 5. Specific Role Occupied by Respondents

3.6 Professional Regulation Body

The regulatory body with which each practitioner is affiliated is essential because it helps to define his contribution during the execution of the project. Figure 6 shows that the respondents were asked to indicate whether they belonged to any professional regulatory body, and 44 respondents (68.8%) belong to a professional regulatory body, and 20 respondents (31.3%) said they did not belong to a professional regulatory body. This distribution clearly showed that the majority of respondents belonged to professional regulatory bodies and therefore had a legal obligation to uphold professional ethics and, as such, to positively influence construction projects by ensuring the successful completion of these projects; at the same time, when asked to specify the member, 7 with 16.7% of respondents belonged to ARCON (Nigerian Institute of Architects), 1 representing 2.4% of the respondents reveals belonged to both ARCON and NIA (Nigerian Institute of Architects), 1 representing 2.4% of the respondents belonged to both COREN (Council for the Regulation of Engineering in Nigeria) and NSE (Nigerian Society of Engineers), 1 representing 2.4% of the respondents belonged to COREN and FNSE (Fellow Nigerian Society of Engineers), 1 representing 2.4% of the respondents belonged to COREN, FNSE, MNSE (Member Nigerian Society of Engineers) and MNICE (Member Nigerian Institute of Civil Engineers), 1 representing 2.4% of the respondents belonged to COREN, MNSE and FNSE, 1 representing 2.4% of the respondents belonged to COREN, MNSE, MNICE, MAPM (Member of the Association of Project Managers) and MCI Arb (Member of the Chartered Institute of Arbitrators), 1 representing 2.4% of the respondents belonged to COREN, NSE, NICE, ASCE (American Society of Civil Engineers) and ASME (American Society of Mechanical Engineers), 1 representing 2.4% of the respondents belonged to FNSE, NSE and COREN, 1 representing 2.4% of the respondents belonged to FNSE, MNICE and COREN, 1 representing 2.4% of the respondents belonged to FNSE and NSE, 1 representing 2.4% of the respondents belonged to MNSE and MNICE, 1 representing 2.4% of the respondents belonged to MNSE and COREN, 2 representing 4.8% of the respondents belonged to NIA and ARCON, 1 representing 2.4% of the respondents belonged to NIQS (Nigerian Institute of Quantity Surveyors) and QSRBN (Quantity

Surveyors Regulation Board of Nigeria), 1 representing 2.4% of the respondents belonged to NSE, 2 representing 4.8% of the respondents belonged to NSE and COREN, 1 representing 2.4% of the respondents belonged to NSE and COREN, 1 representing 2.4% of the respondents belonged to NSE and MNSE, 1 representing 2.4% of the respondents belonged to NSE and COREN, 1 representing 2.4% of the respondents belonged NICE, 10 representing 23.8% of the respondents belonged to RICS (Royal Institute of Chartered Surveyors), 1 representing 2.4% of the respondents belonged to RICS, NIOS and QSRBN and finally, 1 representing 2.4% of the respondents belonged to COREN, MNSE, FNICE, MNISafetyE (Member Nigerian Institution of Safety Engineers) and MNIHTE (Member Nigerian Institute of Highway and Transportation Engineers). It was observed that the professional regulation body with the most members, according to the distribution and the chart was RICS with 10 respondents identifying as members with the highest percentage of 23.8.

Do you belong to any professional membership and regulation body

64 responses

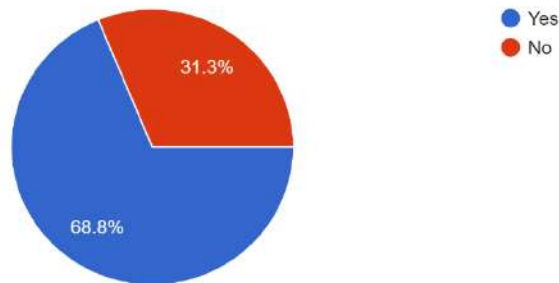


Fig. 6. Professional Membership and Regulation Body Distribution

3.7 Participation in Continuous Professional Project Development Training Related to Stakeholder Management and Engagement within the Construction Industry for the Past 5 years or 10 years

The engagement of individuals in research and professional development is of paramount significance, as it enables all relevant parties to remain informed about contemporary trends and practices that are being implemented on a global scale. Figure 7 delineates that stakeholders have engaged in ongoing professional project development training pertaining to stakeholder management and engagement within the construction sector over the preceding 5 to 10 years; specifically, 46 individuals, accounting for 67.6% of the survey participants, indicated their participation, whereas 22 individuals, representing 32.4% of the respondents, reported a lack of involvement in any such continuous professional project development training in the same timeframe. This data indicates that 67.6% of the construction stakeholders who took part in the survey possess a comprehensive awareness and professional training regarding project development in relation to stakeholder management and engagement within the construction industry; consequently, they are directly implicated and proficiently equipped to execute timely and successful construction project deliveries in Nigeria.

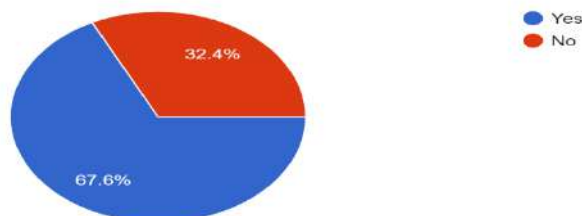


Fig. 7. Stakeholder Management and Engagement Professional Training Distribution Chart

3.8 Level of Construction Related Education

Assessing the educational attainment of various stakeholders is imperative, as it elucidates the breadth of expertise these professionals possess to further the field of construction engineering. The findings illustrated in figure 8 signify that the highest level of construction education is represented by 34 individuals, accounting for 49.3% of the respondents who acknowledged holding doctoral degrees; 24 individuals, composing 34.8% of the respondents who indicated possession of master's degrees; 4 individuals, representing 5.8% of the respondents who stated having Higher National Diplomas; 1 individual, denoting 1.4% of the respondents who confirmed achieving professorship honors; and 6 individuals, equating to 8.7% of the respondents who indicated they had secured merely bachelor's degrees. From the analysis of the data, it was observed that the highest attainment in construction education was the PhD, which suggests that the preponderance of the respondents were senior construction officials, proficient in both construction experience and knowledge regarding stakeholder management and engagement within the Nigerian context.

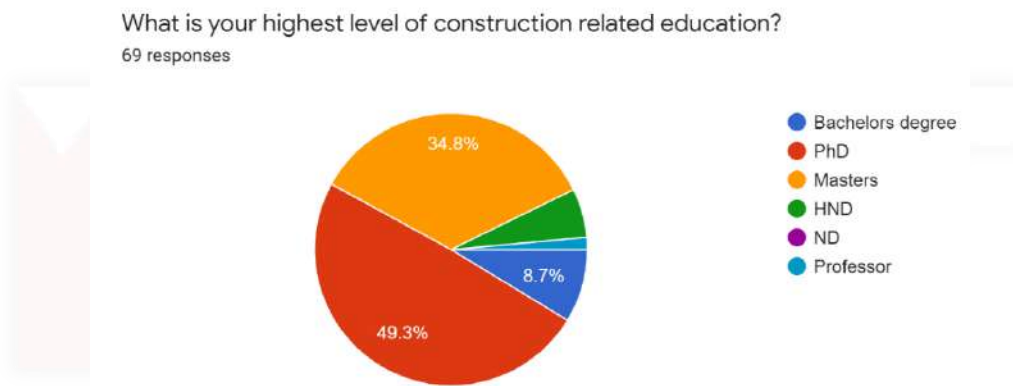


Fig. 8. Level of Construction Related Education

3.9 Distribution of the Various Respondents in Tendering Services and Their Data Allocation

The analysis shown in Figure 8 points out that a notable amount of construction assignments that the respondents had participated in tendering services for during the previous three years is as follows: 48 individuals, constituting 69.6% of the participants, reported taking part in 5-10 construction projects; 15 individuals, signifying 21.7% of the participants, confirmed their involvement in 10-20 construction projects; and 6 individuals, representing 8.7% of the participants, conveyed participation in more than 20 construction projects. The results indicate that a notable fraction of the surveyed individuals, precisely 69.6%, had participated in the fewest number of construction initiatives over the last three years, which evidently shows that the majority of those surveyed had not successfully guaranteed the punctual completion of construction ventures. A contributing factor to this outcome is the inadequate implementation of proper stakeholder management, which is essential for guaranteeing successful and timely delivery of construction projects as mandated.

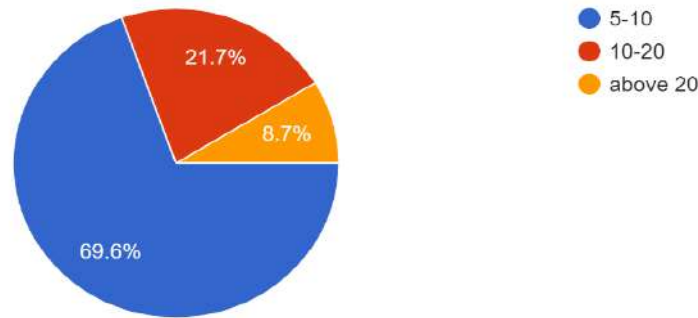


Fig. 8. Distribution of the Various Respondents in Tendering Services and Their Data Allocation

3.10 Full Engagement of Stakeholders in a Construction Project

Respondents, as illustrated in figures 9, 10, and 11, respectively, were inquired regarding the degree to which stakeholders had been involved in construction projects; 50 individuals, constituting 72.5% of the respondents, indicated that engagement occurred occasionally; 15 individuals, accounting for 21.7% of the respondents, affirmed that engagement was a consistent practice; and 4 individuals, representing 5.8% of the respondents, reported that engagement was infrequent. It was observed that the response indicating 72.5% of participants endorsing ‘sometimes’ suggested that stakeholder engagement had not yet been comprehensively and thoroughly integrated into construction projects. Furthermore, respondents were prompted to articulate their perceptions of the level of awareness regarding stakeholder management and managerial stakeholder theories within the broader societal context; 35 individuals, representing 50.7% of the respondents, asserted that there existed a moderate level of awareness of stakeholder management and managerial stakeholder theories in the wider society; 30 individuals, accounting for 43.5% of respondents, indicated a low level of awareness in the wider society; while 4 individuals, representing 5.8% of the respondents, claimed that there was a high level of awareness. The findings indicated that the level of awareness concerning stakeholder management and managerial stakeholder theories within the wider society was relatively deficient, thus necessitating increased efforts to ensure that the construction industry remains adequately informed and cognizant of the elements and prospective advancements in effective stakeholder management and engagement within construction projects. Also, when questioned about the influence of stakeholder engagement in the building sector and its role in ensuring timely project delivery across Nigeria, a large group of 61 individuals, making up 88.4% of those who answered, agreed that it was quite effective; meanwhile, 7 individuals, accounting for 10.1%, believed it was fairly effective; and 1 individual, comprising 1.4%, disagreed, stating it was ineffective. The study revealed that involvement of stakeholders is significantly beneficial and appropriate for use in the construction field, particularly in aiding prompt project delivery across Nigeria. When queried about their willingness to advocate for the application of stakeholder management and managerial stakeholder theories in forthcoming construction projects in Nigeria, a significant 65 individuals, representing 94.2% of the respondents, expressed strong endorsement for the recommendation of stakeholder management and managerial stakeholder theories for future construction initiatives, while 4 individuals, representing 5.8% of respondents, stated they would recommend it conditionally.

To what extent have stakeholders been engaged in construction projects?
69 responses

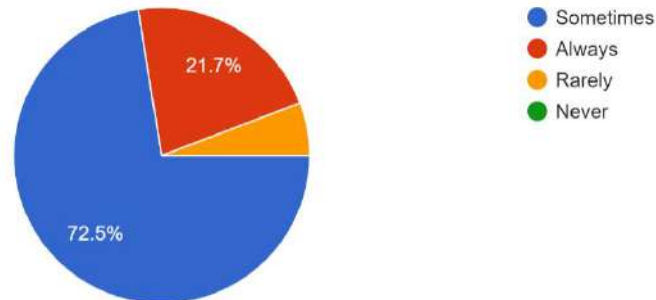


Fig. 9. Extent To Which Stakeholders Have Been Engaged

What is the level of awareness of stakeholder management and managerial stakeholder theories in the wider society?
69 responses

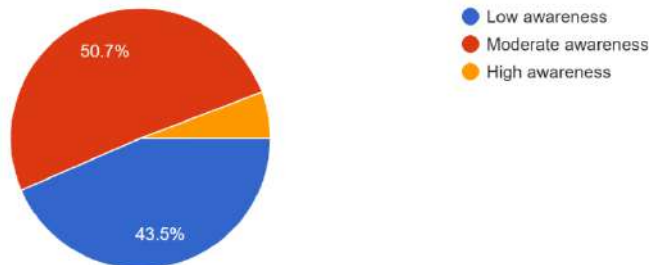


Fig. 10. Level Of Awareness of Stakeholder Management and Managerial Stakeholder Theories in The Society

How effective is stakeholder engagement in the construction industry and how does it facilitate timely construction project delivery?
69 responses

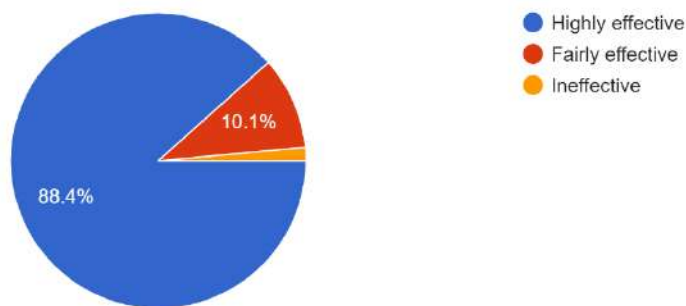


Fig. 11. The Effectiveness of Stakeholder Engagement in the Construction Industry

4. Conclusion

The findings of this study underscore the critical importance of proactive and strategic stakeholder management in ensuring timely construction project delivery in Nigeria. Respondents emphasized that effective stakeholder engagement must begin before project initiation and continue through consistent communication, clear definition of roles, and transparent collaboration. Key recommendations include the establishment of a stakeholder register, early and meaningful involvement of all stakeholder groups, use of ICT for communication and monitoring, and the development of structured stakeholder management and communication plans. Furthermore, respondents highlighted the necessity of building trust, managing expectations, fostering teamwork, and ensuring fairness in representation. Strategic planning must include stakeholder identification, classification, and prioritization based on power, legitimacy, and urgency. The study also reveals the value of knowledge management, feedback mechanisms, and culturally appropriate engagement techniques to enhance transparency and reduce conflict. Additionally, the Results from the current study provide compelling evidence of a link between stakeholder management and risk management in construction projects. Recognizing and understanding this relationship could significantly enhance both practices, thereby increasing the likelihood of project success. It is recommended that future research further explore this connection to deepen insights and inform more integrated management approaches in the construction industry. Additionally, the study highlights a critical gap in policy frameworks supporting stakeholder management and the application of managerial stakeholder theories in construction projects. There is a pressing need for policy development and regulatory support in this area. Future studies should focus on examining existing government policies and identifying opportunities to align them more closely with stakeholder management practices to improve project outcomes. Overall, stakeholder management in construction projects must be guided by integrity, inclusivity, and a shared commitment to project goals. When stakeholders are well-informed, aligned, and engaged throughout the project lifecycle, the likelihood of timely and successful project delivery increases significantly. Based on these results further studies using action research should be carried out to implement effective stakeholder engagement in real life construction projects such as transport, housing, retail, hospitals, to serve as further motivation for embracing stakeholder management in construction projects. By this the concept can be further improved and simplified based on the findings from the action research, which will enable the identification of real-life strengths and weaknesses of the concept.

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2025

Preliminary Analysis on The Suitability of Crushed Palm Kernel Shells (CPKS) as Partial Replacement for Fine Aggregate in Concrete

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Abstract: This research investigates the use of Crushed Palm Kernel Shells (CPKS) as a partial replacement for fine aggregate in concrete. The specific objective was to evaluate the effects of CPKS on selected concrete properties, using replacement levels of 0%, 10%, 20%, 30%, 40%, and 50%. Concrete mix ratios of 1:2:4, 1:3:6, and 1:1½:3 were tested for compressive strength at 7, 14, 21, and 28 days. Concrete samples without CPKS (0% replacement) served as the control group. The batching was done by weight. Crushed CPKS, with particle size less than 4.75 mm, was incorporated into the concrete. A total of 96 concrete cubes, for each mix ratio, compressive strengths (in N/mm²) of 20.88, 20.21, 19.35, 18.36, 17.32, and 16.49 for the 1:3:6 mix; 25.08, 24.41, 23.47, 22.65, 21.28, and 20.25 for the 1:2:4 mix; and 26.93, 26.42, 25.51, 24.42, 23.76, and 22.69 for the 1:1½:3 mix.

Keywords: compressive, strengths, Crushed, Palm-kernel, Shells.

1. Introduction

The need for the provision of affordable, yet safe and durable infrastructure, has necessitated the prognosis of the effect of incorporation of locally available artificial aggregate in concrete. Some of these artificial aggregates are classified as organic lightweight aggregate [1] while others originate from nature. Historically, the Romans demonstrated the durability of lightweight concrete by using natural aggregates from volcanic deposits. Following the development of Portland cement in the early 1800s, the advent of manufactured lightweight aggregates in the early 1900s brought structural lightweight concrete to maturity. The primary natural lightweight aggregates include diatomite, pumice, and volcanic cinders [2].

Previously, fine and coarse aggregates in concrete have been partially replaced. Palm kernel shell has been used as partial replacement for coarse aggregate in concrete [3]. The use of Burnt and Crushed Cow Bones (BCCB) as a partial replacement for fine aggregate in concrete has been carried out [4]. The findings revealed that BCCB acted as a retarder, and resulted to the increase in the water-cement ratio. The research tested fine aggregate replacement rates of 0%, 10%, 20%, 30%, 40%, and 50% using 1:2:4 and 1:1:3 mix ratios, yielding compressive strengths ranging from 16.49 to 24.29 N/mm² and 18.71 to 29.73 N/mm², respectively [4]. The replacement of coarse aggregates with palm kernel shell, at 10% and 25%, yielded concrete with compressive strength which cannot be used as light weight concrete [3].

Concrete remains the most widely used construction material, with compressive strength being a key measure of quality. Various destructive and non-destructive testing methods have been developed to assess this property [5]. The influence of age, type of aggregate, on the compressive strength of concrete exposed to high temperature was examined [6]. The compressive strength of concrete, prior to exposure to high temperature, increased with age [6]. Seyam and Nemes [6] attributed the increase in compressive strength to the hydration of cement and the formation of a denser microstructure.

Aggregates constitute about 75% of the total volume of concrete [7], hence, plays a very important role in the behaviour of concrete. Increased angularity and flakiness of aggregates have resulted to the reduction in the workability of concrete [8]. Concrete, a mixture of cement, water, and aggregates,

undergoes a hydration process, transforming to a denser state with time [6]. Concrete has low tensile strength [9], necessitating reinforcement when necessary.

Concrete strength testing, which typically takes 28 days, presents challenges in construction timelines, particularly when trial mixes are required. Over the decades, there has been widespread interest in the incorporation of various admixtures as well as replacement of aggregates in concrete vis-à-vis, the compressive strength of concrete. This research investigates the use of Crushed Palm Kernel Shells (CPKS) as a partial replacement for fine aggregate in concrete. The specific objective was to evaluate the effects of CPKS on selected concrete properties, using replacement levels of 0%, 10%, 20%, 30%, 40%, and 50%.

2. Method

2.1 Area of Study

This study employed an experimental design to assess the suitability of crushed palm kernel shells (CPKS) as a partial fine aggregate replacement in concrete mixes of 1:3:6, 1:2:4, and 1:1:3. CPKS was used to replace fine aggregates (sand) at 0%, 10%, 20%, 30%, 40%, and 50% by weight. Crushed CPKS, with particle size less than 4.75 mm, was incorporated into the concrete. The compressive strength, flexural strength, and workability (slump test) of the concrete were evaluated. A total of 96 concrete cubes (150x150x150 mm) were tested for compressive strength after 7, 14, 21, and 28 days. All experiments were conducted in the Strength of Materials Laboratory at the Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike.

2.2 Materials

The materials used for this study included: cement, water, clean river sand, and granite. UniCem brand Portland Limestone Cement was used in this study. The river sand was free from deleterious materials, and passing through a 2.36 mm sieve was used as fine aggregate. The coarse aggregate was clean, free from deleterious materials, and passed through a 19 mm sieve. The water used was obtained from groundwater aquifer via a borehole. Palm kernel shells were sourced from Pastor Eteng Okponsco's compound in Ugep, Yakurr Local Government Area, Cross River State, Nigeria. The shells were sun-dried and crushed to a particle size passing the 4.75 mm sieve.

2.2.1 Sample Collection

The river sand, granite, palm kernel shells were collected in bags and transported to the Strength of Materials Laboratory of the Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike. The aggregates were thoroughly washed. Care was taken to ensure that deleterious materials were removed from the samples. Thereafter, the samples were dried for 48hrs to reduce the moisture content. Subsequently, particle size distribution/sieve analysis and specific gravity test were determined.

- **Laboratory Test**

Several laboratory tests were conducted on the aggregates as well as the concrete. The tests were conducted at the Soil Mechanics and Strength of Materials Laboratory of the Department of Civil Engineering, Michael Okpara University of Agriculture, Umudike.

- **Specific Gravity Test**

The specific gravity of aggregate used in concrete is based on the saturated surface dry condition of the aggregate. It was carried out using a container and the procedures were itemized thus, apparatus that was used were measuring cylinder, balance glass, rod and drying duster. The cylinder was weighed and recorded as A. the cylinder was filled to $\frac{1}{2}$ of its capacity with sample and weight was recorded as B, the

content of cylinder was filled half-way with water, stirred thoroughly with a rod and then filled to top and weighed as C. this content was poured away and the cylinder was properly cleaned, and filled with water to the top and weighed as D. The whole process was repeated 10 times for each aggregate. The specific gravity (SG) was thereafter determined.

- **Aggregate Impact Test**

The impact test was done on aggregate to determine the crushing value of the coarse aggregate and to assess the suitability or resistance of the aggregate to mechanical degradation, in accordance with BS 812-100 (1990) [10].

- **Particle Size Distribution Test**

Test on particle size distribution was done for both river sand and CPKS with sieve size ranging from 4.75mm (No 4) sieve to pan. This determine the aggregate zone; a plot of percentage passing against sieve size was done to show that the aggregate falls in zone 2. The particle size distribution was carried out in accordance with BS 812-103 [11]. Sieves were assembled and placed in the ascending order of sieve numbers from 4.75mm (No 4) sieve to pan. The sample was poured into the arranged sieves and placed on a mechanical shaker for 10mins. The stack was removed from the shaker and carefully weighed and recorded the weight of each sieve with its retained soil Percentage retained and cumulative percentage passing were calculated, respectively.

- **Slump Test**

Slump test was conducted in the fresh concrete of mixes: 1:3:6, 1:2:4 and 1:1:3. The essence was to determine the workability of each grade of concrete in accordance with the specifications in to BS 188 1-102 (1983) - British Standard Testing concrete Part 102. Method for determination of slump. This test method describes the procedure for determining the slump of fresh concrete mixtures.

- **Concrete Cubes**

Batching by weight were adopted using scale pan for measuring the concrete materials and placed on the weighing balance. The cement was mixed with the right proportion of sand/CPKS and coarse aggregate thoroughly until a uniform material was formed. Water was added based on measured quantity in little amounts until the concrete was plastic enough to be placed in the mould. A total of 288 cubes were cast using 150mmx150mmx150mm standard mould. Concrete cubes were removed from the curing tank at each of their crushing day. The weight of each cube was noted. The concrete cubes were crushed at maturity days of 7, 14, 21 and 28 days for mixes 1:3:6, 1:2:4 and 1:1:3 and the respective compressive strength of each cube was determined.

- **Compressive Strength of Concrete Test**

The compressive strength of the concrete cubes, for the different mix proportions, were determined at various maturity period. The test was carried out using the Compressive strength testing machine. Cubes were placed in compressive testing machine and load applied gradually without shock until the specimen failed. The compressive strength value for each specimen was calculated using the following equation:

where P = Test Load (KN) and A = section area normal to P

3. Results and Discussion

3.1 Characteristics of Crushed Palm Kernel Shells (CPKS)

The physical and mechanical properties of the aggregates are shown in Table 1. The coefficients of uniformity and curvature for sand and CPKS were $C_u=2.53$, $C_c=1.19$ and $C_u=3.76$, $C_c=0.79$, respectively. The coefficient of uniformity of the CPKS was lower than sand, indicative of a narrower

range of variability of particle sizes. The bulk density of CPKS was higher than those obtained from previous studies [12, 13].

Table 1: Physical and Mechanical properties of aggregates

Property	Crushed Palm Kernel Shells (CPKS)	Fine Aggregate (River Sand)	Coarse Aggregate (Granite)
Maximum aggregate size (mm)	4.75	4.75	20
Bulk density (kg/m ³)	2.088	2.503	2.375
Specific gravity	1.00	2.72	2.84
Aggregate impact value (AIV)			9.05
Coefficient of uniformity (Cu)	3.76	2.53	
Coefficient of curvature (Cc)	0.79	1.19	

3.2 Effect of CPKS on the workability of freshly mix concrete

The extent to which freshly mixed concrete, with various percentages replacement of CPKS, slump is shown in Figure 1. The results revealed that the slump values reduced with increase in proportion of CPKS in concrete. In other words, CPKS acted as a retarder and reduced the workability of the concrete. The absorption of water, by the dry CPKS, perhaps resulted to the reduction of the effective water/cement ratio available in the concrete mix. Alhozaimy [14] demonstrated that slump loss occurs due to reduction of mixing water caused by aggregate absorption.

3.3 Effect of CPKS on the compressive strength of concrete

The compressive strength of the concrete reduced with increase in the proportion of CPKS added to the concrete (Figure 2). Also, the compressive strength increase with increase in the maturity period of the concrete. The nominal mixes of 1:3:6, 1:2:4 and 1:1³/₄:3¹/₂ at 28 days curing with 0%,10%,20%,30%,40% and 50% partial replacement of fine aggregate (sand), gave average compressive strengths in N/mm² of (20.88, 20.21, 19.35, 18.36, 17.32, 16.49), (25.08, 24.41, 23.47, 22.65, 21.28, 20.25) and (26.93, 26.42, 25.51, 24.42, 23.76, 22.69), respectively. Previously, concrete with Oil Palm Shell have yielded compressive strength in the range of 34-53 MPa [15].

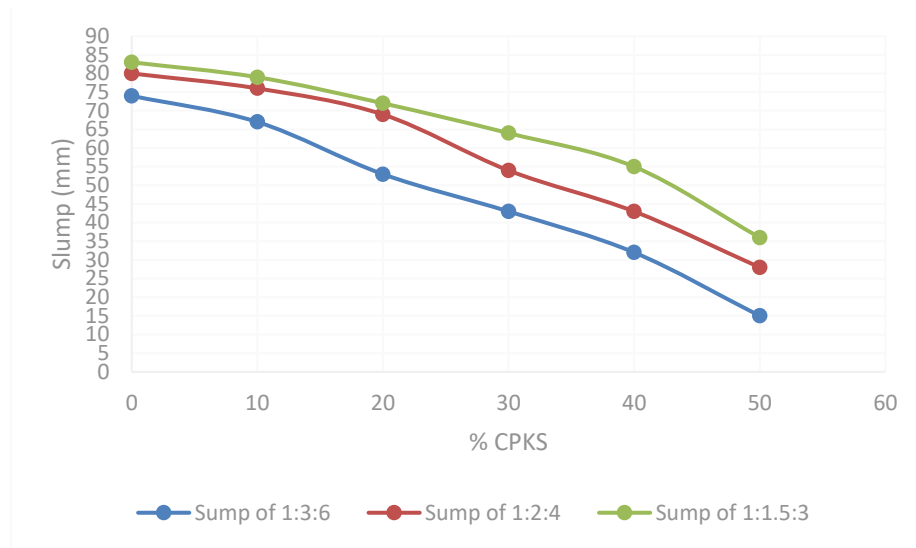


Fig. 1. Slump (mm) with CPKS as partial replacement for fine aggregate for mix 1:3:6, 1:2:4 and 1:1.5:3

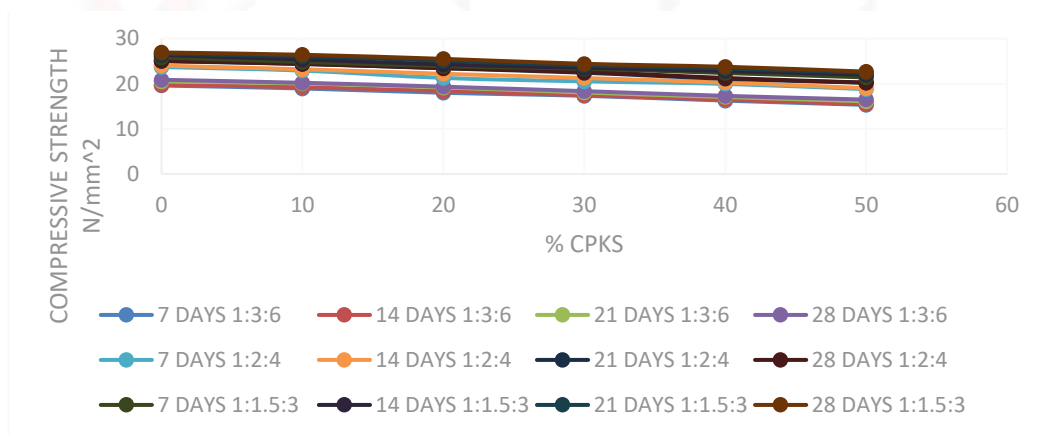


Fig. 2. Compressive strength of concrete with CPKS as partial replacement for fine aggregate for mix 1:3:6, 1:2:4 and 1:1.5:3

4. Conclusion

CPKS acts as retarder in concrete. However, the physical properties of aggregates are within the confines of BS 882 (2002), which indicates that the materials are suitable for use in structural work, considering that the minimum compressive strength value was greater than 17N/mm². Within the scope of this research, lightweight concrete using CPKS as fine aggregate can be achieved easily by replacing normal fine aggregate with CPKS up to 50% replacement.

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Constrained Vertex Optimization and Simulation of the California Bearing Ratio Properties of Geotextile Reinforced Soil for Flexible Foundation Construction.

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Abstract: In this study, extreme vertex design (EVD) was adapted for the mixture experiment involving the problematic soil strength properties modification for civil engineering construction use through the utilization of geotextile materials for soil reinforcement. This soil stabilization approach's aim is to reduce the overall road cross-section layer thickness, enhancing road performance by improving the bearing capacity and durability of the road pavement. EVD method provides a flexible design of experiment approach in soil stabilization, where the components are imposed with constraints at the lower and upper limits and the experimental points are got from the vertex, edges, center and interior portions of the constrained region. Using design experts and Minitab 18 software, the design of experiments, statistical diagnostics and influences, and graphical and numerical optimization were carried out. I-optimal design with quadratic model design was utilized to explore the constrained experimental region to formulate the mixture ingredient proportions at 10 experimental runs. I-optimality and D-optimality of 0.39093 and 1747.474, respectively, was obtained with G-efficiency of 64.8%. The test soil's general engineering properties and classification were carried out before the mechanical properties tests with respect to varying ratios of mixture components. Responses were obtained through a laboratory process and the generated data utilized for model development and statistical analysis. The desirability function was utilized to achieve numerical and statistical optimization to arrive at the optimal solution for the mixture components combination at 0.002:0.098:0.9 for geogrid, water and soil respectively. A desirability score of 1.0 was obtained with an optimal response of 19.546%.

Keywords: Soil, geotextile, reinforcement, ratio, Optimization.

1. Introduction

Road construction on expansive soil is most times associated with challenges and difficulties in construction and design due to its weak mechanical strength and high compressibility properties. This could lead to road failure in bearing capacity [1]. Geosynthetic reinforcements are incorporated within a granular base course lying on an expansive subgrade material with very low California bearing ratio (CBR) values. Geotextile (geogrid) material was placed between the weak subgrade interface and the granular base course; this provides an enviable alternative to addressing problems in the construction of road pavement in the expansive subgrade [2-3]. The strength and durability performance of flexible pavement is greatly influenced by the strength characteristics of the constituted cross-sectional materials, namely; sub-base, base, and subgrade. At the bottom of the unbound layer, the geogrids are placed to enhance its load-bearing properties under traffic loading [4]. Geosynthetic reinforcement and stabilization is a mechanical strength enhancement process whereby the materials are placed between the subgrade materials and the aggregates layer of the road cross section. The relative benefits of geosynthetic utilization molecules are low-cost value, no safety concern as regards with chemical stabilization process using binders and be installed in any weather conditions be it hot or cold. It acts as a geomembrane which enhances the friction, tensile strength, and puncture resistance; and delivers benefits in areas of hydraulic

conductivity performance and serves as slope reinforcement, protecting, separation, and filtration functions to enhance the durability properties of flexible pavement [5-7]. Furthermore, geosynthetic materials function as an impermeable membranes to gases and fluids; which also perform a filtration functions by permitting fluids to flow through the soil while ensuring the particles are retained. They also function as a drain to allow passage of fluid through a less permeable soil serving as an under drain to prevent flooding. They are utilized for the pore water pressure dissipation at the roadway embankment base to move water in an underdrain [8]. Geogrids are special kinds of geosynthetic whereby the polymers are shaped into grid-like configuration instead of nonwoven, plain woven textile materials, thereby creating massive apertures between individual ribs in longitudinal and crosswise directions. These grids are formed through material ribs that are intersected in two directions, the first in the machine direction (MD) while the other direction is perpendicular to the machine rib direction termed cross-machine direction (CMD) [9-10]. Utilization of geosynthetic materials in flexible road pavement construction has been a subject of rigorous research study recently; Tanya et al. [11] studied the effect of geogrid on granular base course performance on expansive subgrade. Geosynthetic materials were incorporated in between the weak subgrade layer and the granular base course, which provides mechanical stabilization in terms of lateral restraint as reinforcement by tensioned membrane effect and physical stabilization. Geogrid synthetic material was utilized for the stabilization process of the unblended soil as the control sections. Cyclic loading tests were carried out until 25 mm maximum deformation where the geogrid materials were placed at the interface of the expansive subgrade and 250mm of the compacted granular base course. The interface pressure and stress pattern at the lower side of the geogrid (subgrade top) and permanent base course surface displacement were observed experimentally. The results obtained indicated that geogrid addition resulted in smaller incremental deformation and higher pavement deformation.

Incorporating geosynthetic materials in a soil mixture blends are often challenging especially as it concerns the derivation of an optimal quantity of the material to be integrated with respect to mechanical strength properties improvement [12]. Statistical approach is often deployed to evaluate the soil-geosynthetic blend behaviour whereby the factor levels' relationship with the response parameters are investigated and a mathematical models developed. However, mixture models which present are a more flexible techniques to deal with dependencies among the model variables to optimize the response parameters are recently utilized [13]. According to McLean et al. [14], the extreme vertices design is developed as a procedure for conducting experiments on mixtures when several factors have constraints placed on them, which incorporates the complex relationships between the problematic soil and geogrid to help derive the optimal combination of the mixture components. Extreme vertex designs are mixture designs that cover only a subportion or smaller space within the simplex. These designs must be used when your chosen design space is not an L-simplex design. The presence of both lower and upper bound constraints on the components often creates this condition. While simplex designs provide allow you to place lower bounds on individual mixture factors, there may be situations where more complicated constraints are appropriate [15-17]. Extreme vertex designs allow you to impose additional limits on the component values by specifying upper bounds on components and defining linear constraints for blends. The goal of using an extreme vertex design is to choose design points that adequately cover the design space (Damiri et al. 2016) [18]. Mixture experiment design application using response surface methods for construction material development has been the subject of several research studies. Ria et al. [19], researched on the formulation of Portland composite cement using waste glass as a supplementary cementitious material. The objective of this research is to evaluate the formulation of waste glass as supplementary cementitious material (SCM) by an extreme vertex mixture experiment, materials selected for this study are Portland cement, clinker, waste glass, and gypsum. The compressive strength of the OPC mortar is 323, 7 kg/cm³ while the compressive strength of the glass-containing composite cement mortars after being cured for 28 days ranges between 229 to 268 kg/cm³. The composite cement containing 80% clinker, 15% glass, and 5% gypsum has the highest compressive strength among the nine compositions. Furthermore, Aji et al. [20], researched on the nature of the ground granulated blast furnace slag (GGBFS) experiment followed a mixture design in which the response can be described by a quadratic model. Due to the constraints of the components, the experimental region was not a simplex.

The GGBFS concrete experiment was run using mixture design. The candidate set to use the XVERT algorithm consisted of 24 vertices, 53 edge centroids, 36 constraint plane centroids, and 1 overall centroid.

For a q-component mixture where the i th component proportion present in the mixture represented by x_i , the factor space takes the shape of a regular (q-1) dimensional simplex due to the sum of one constraint presented in Eqn. 1. EVD method is flexible enough to deal with the imposition of additional constraints on the mixture components due to multiple dependencies between them. The lower and upper limit are denoted by L_i and U_i respectively, as shown in Eqn. 2 and the sum of the mixture component ratios must be unity [21].

$$\sum_{i=1}^q x_i = 1, i = 1, 2, 3 \dots q \quad 0 \leq x_i \leq 1 \quad (1)$$

$$0 \leq L_i \leq x_i \leq U_i \leq 1 \quad (2)$$

The mixture experiments objective is to develop mathematical model adequate where the factor levels $(x_1, x_2, x_3, \dots, x_q)$ relates the desired response parameters. Commonly used Scheffe's method for data fitting which is expressed in Eqn. 3 for quadratic polynomial function [22].

$$E(Y) = \sum_{i=1}^q \beta_i x_i + \sum_{i < j}^q \beta_{ij} x_i x_j \quad (3)$$

and represented in matrix form as shown in Eqn. 4.

$$Y = X\beta + \varepsilon \quad (4)$$

Where X is $n \times k (\geq q)$ matrix and k is the number of model terms; Y is $n \times 1$ vector for the response parameter observations; ε is $n \times 1$ vector for the error function; and β is a $k \times 1$ vector for the predicted parameters [23].

The error properties were assumed to possess the property expressed in Eqn. 5

$$E(\varepsilon) = 0; E(\varepsilon \varepsilon') = \sigma^2 I_n \quad (5)$$

Where σ^2 the variance of the error is function; I_n is an identity matrix.

The least square estimator for the predicted variables β is presented in Eqn. 6.

$$b = (X'X)^{-1} X'Y \quad (6)$$

The variance covariance matrix of the least squares estimator solution (b) is further expressed in Eqn. 7.

$$Var(b) = (X'X)^{-1} \sigma^2 \quad (7)$$

In this research study, problematic clayey soil geosynthetic mixture experiment design, modelling, optimization, and simulation were carried out using EVD method to assess the mechanical strength behaviour of the mixture. The optimal ratios of ingredient combinations are then determined through the desirability function using multiple criteria optimizations, which properly deal with the complex nature and multiple constraints of soil-geosynthetic blends. This investigative work sheds lighter on the constrained simplex method application for the mechanical strength characteristics evaluation of the soil-geogrid blend, and the utilization of geosynthetic materials for expansive clayey stabilization [24].

2. Method

2.1 Test Materials

The materials and experimental steps that were undertaken towards achieving the objectives of this research were the focus. Expansive soil samples were collected at Edem Ekpenyong Street, Anantigha in Calabar South Local Government Area of Cross River State, Nigeria. The geogrid was also obtained from Sermatech Construction Company in Calabar, Cross River State, Nigeria. Geogrids are spaced grid like synthetic materials of constituting polymers cemented integrally as shown in Fig. 1. Geogrid possess a number of apertures which are uniformly distributed between the transverse and longitudinal sections. Through the apertures, there is direct contact between the sheets of the geosynthetic materials and the soil particle [25-26]. The properties of the geogrid material used are presented in Table 1.



Fig. 1. Geogrid Material

Table 1: Test Geogrid Properties

Aperture Size of Mesh (mm)	10 x 10
Shape of Aperture (mm)	Square
Tensile Strength (kN/m)	12.5
Color	Black
Structure	Bi-directional
Elongation at maximum load (%)	20.5
Unit Weight (N/m ²)	7.35
Thickness of Sheet (mm)	4
Raw Material	Polypropylene

2.2 Integrity of the Specifications

The laboratory methods were carried out in accordance with the requirements stipulated in BS 1377 [27] and BS 1924 [28] for the unsuitable clayey soil mechanical strength characteristics enhancement using geogrid synthetic material presented in Fig. 2.



Fig. 2. Geogrid synthetic material

General engineering properties derivation and classification of the test soil were first carried out through compaction test, specific gravity test, sieve analysis, consistency limit test, and California bearing ratio (CBR) test. This mixture experiment optimization problem which consists of three component materials which are geogrid, water, and clayey soil, and because of the component constraint imposition at the lower and upper boundary limits, the simplex is consequently constrained whereby the experimental points are situated at the vertices, interior and edges of the constrained region instead of the whole of the simplex. The constrained experimental portions were adequately explored using I-optimal design computation with quadratic model design to obtain the proportions of mixture components and the number of experimental runs required. CBR tests were carried out according to the ingredients proportion mix formulated and the corresponding responses achieved in the laboratory were utilized as the system data base for the mechanical behavior modelling of the soil-geogrid blend. Statistical influences and diagnostic tests were carried out to validate the developed EVD model. Furthermore, the optimal combinations of the soil-geogrid blend for maximum mechanical response were determined through graphical and numerical optimization, which were conducted using desirability function computation to maximize the output variable criteria with respect to the factor levels [29-30]. The developed EVD models were finally simulated to validate the model's applicability and the results compared with the experimental values using analysis of variance (ANOVA) and student's t-test statistical technique; this is clearly shown in a research program flowchart presented in Fig. 3.

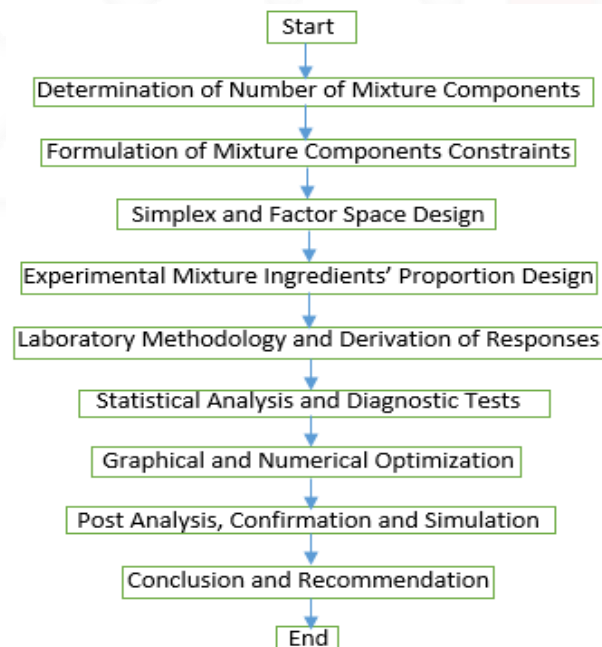


Fig. 3. Program Flowchart

- **California Bearing Ratio**

California bearing ratio is a penetration test developed by the California Division of Highways as a method for evaluating the stability of soil sub grade and other pavement materials. The strength of each soil layer of a pavement were evaluated using CBR tests. This test will be done without geotextile, with one layer of geotextile reinforcement, and with two layers of geotextile reinforcements, respectively. The test is an adequate indicator of soil strength performance which was executed according to the guidelines in BS 1377 [27] and BS 1924 [28] for the soil-geogrid blend with the set up presented in Fig. 4. The CBR tests were carried out for clayey soil materials compacted based on British Standard Light (BSL) compaction energy. The soil specimens were mixed appropriately according to the derived mixture formulation and compacted in three layers with the aid of a 2.5 kg rammer, and each of the three layers received 62 nos. of blows. Thereafter, the specimens were subjected to a static loading system by the CBR machine until failure was recorded [31].



Fig. 4. California bearing ratio test setup

2.3 Components mixture design formulation

The actual proportions of the mixture components were derived and the total number of the experimental runs. The results got form fundamental base for the development of the model so that the optimal combination of the soil-geogrid mixture which improves its mechanical properties is derived (Kumar et al. 2015) [32]. The mixture formulation computation was carried out with design expert software. The ratio of the ingredients formulation to be mixed for each experimental run and the total number of experimental runs required were calculated to effectively evaluate the mechanical behaviour of the soil-geogrid blend. The effective ratios obtained here form fundamental base for the model development to derive the optimal combination ratio for the soil additives blend and achieve improvement in the problematic soil engineering properties [33].

- **Components Constraints Formulation**

The three components are imposed with constraints on the lower and upper bounds established through the ingredient material characteristics which constitute the experimental blend. In most cases, environment, economical and practical considerations are the reason for the constraints on the mixture components. The constraints for the three-component experimental mixture were obtained from relevant literatures where materials are blended with soil to improve its engineering properties for road construction [15, 34]. The component constraints were formulated using single component constraints (SCC) are presented in Table 2.

Table 2:

Design Constraints		
Mixture Coding:	Actual	
Low	Constraint	High
0.001	A:geogrid	0.002
0.098	B:water	0.150
0.848	C:soil	0.900
	A+B+C	1.000

2.3.2 Design of Simplex and Factor Space

Due to the imposed constraints at the lower and upper bounds of the factor levels and the sum of one constraint, the feasible experimental region is located within the simplex in the constrained space. The degree of freedom evaluation is also conducted through design matrix computation for the design mixture using a quadratic model with U_pseudo mixture component coding as presented in Table 3. A minimum of 3 lacks of fit degrees of freedom is recommended which ensures fit test validity. Fewer degrees of freedom will lead to a test that may not detect a lack of fit [35-36].

Table 3: Design Matrix Evaluation for Mixture Quadratic Model 3 Factors: A, B, C with U_Pseudo Mixture

Degrees of Freedom for Evaluation	
Model	5
Residuals	4
Lack of Fit	3
Pure Error	1
Corr Total	9

Power calculation test was also conducted on the developed component constraints using design expert and Minitab statistical software to determine the standard deviations and variances on the design planes, interior vertexes, and edges contained in the simplex on a 5% alpha level shown in Table 4.

Table 4:

Power at 5 % alpha level to detect signal/noise ratio

Term	StdErr1	VIF	Ri-Squared 2	Std. Dev.
A	3376.29	33791.62	1.0000	5.0 %
B	0.90	2.99	0.6658	5.0 %
C	0.90	3.40	0.7063	5.0 %
AB	3468.84	13432.33	0.9999	5.0 %
AC	3468.52	16104.96	0.9999	5.0 %
BC	3.04	1.96	0.4908	51.6 %

[^]1 Basis Std. Dev. = 1.0

- Standard errors should be similar within the type of coefficients. Smaller is better.
- The ideal VIF value is 1.0. VIFs above 10 are a cause for concern. VIFs above 100 are a cause for alarm, indicating the coefficients are poorly estimated due to multi-co linearity.
- Ideal Ri-squared is 0.0. High Ri-squared means terms are correlated with each other, possibly leading to poor models.
- For mixture designs, the proportions of components must sum to one. This is a constraint on the system and causes multicollinearity to exist, thus increasing the VIFs and the Ri-squares, rendering these statistics useless; use a fraction of design space (FDS) instead.
- Power is inappropriate for determining the usefulness of a design involving mixture components. Use precision-based metrics provided in this program via FDS statistics.

The software further developed the contour plot of the 3- component simplex shown in Figs. 5-6, which diagrammatically displays the actual experimental points positioned within the constrained region. The information matrix measures showing the space type, leverages, and build types are presented in Table 5. Ten (10) runs were generated to improve on the optimality or efficiency of the model operation. Lack of fit was recorded on axialCB while the replicate point is situated at the center space of the feasible design space. The model build types were thus situated at the vertex and center-edge space type. Average leverage of 0.6 was calculated; this in effect raises concern for more design points to be located on these spaces of the simplex to reduce the lack of fit effect on the entire experimental space [37].

Table 5: Measures derived from the information matrix

Run	Leverage	Space Type	Build Type
1	0.8134	Vertex	Model
2	0.9129	Vertex	Model
3	0.5467	CentEdge	Model
4	0.8063	Vertex	Model
5	0.8335	Vertex	Model
6	0.3274	Center	Center
7	0.2710	AxialCB	Lack of Fit
8	0.5982	CentEdge	Model
9	0.5630	CentEdge	Model
10	0.3274	Center	Replicate
Average = 0.6000			

Design-Expert® Software
 Component Coding: Actual
 Highs/Lows inverted by U_Pseudo coding
 Std Error of Design
 ● Design Points
 Std Error Shading
 1.500
 0.500
 X1 = A: geogrid
 X2 = B: water
 X3 = C: soil

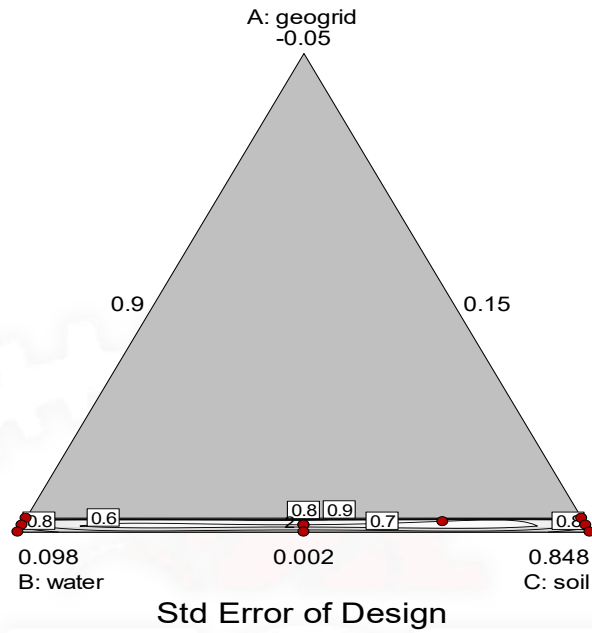


Fig. 5. Factor space simplex of a 3- component mixture experiment of geogrids, water, and soil.

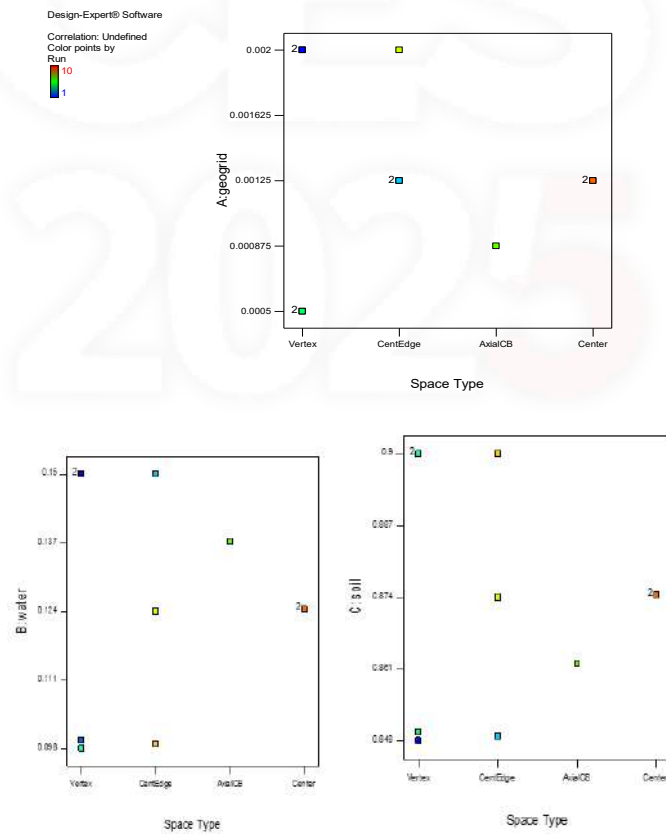


Fig. 6. Experimental factor space of the components in a 3- component mixture space

The relevant data statistics for the design of experiments, multicollinearity design, scaled D-optimality, and I-optimal design computations were carried out using design expert software. D-optimality produces a design that best estimates the effects of the factors, which is particularly suited for screening studies. The algorithm picks points that minimize the volume of the confidence ellipsoid for the coefficients. I.e., it minimizes the determinant of the inverse matrix $X'X$, while I-optimal designs, also known as IV (integrated variance), provides the minimum average estimation of the variance across the experimental regions [38].

Condition Number of Coefficient Matrix =
2.16E+005

- If this value is 100-1000, there is moderate to strong multicollinearity.
- Values above 1000 indicate severe multicollinearity.

Maximum Variance Mean = 0.926

Average Variance Mean = 0.392

Minimum Variance Mean = 0.247

G Efficiency = 64.8 %

- G Efficiency is inversely related to the maximum variance.
- Lack of fit runs and replicates tend to reduce the G Efficiency of a design.

Scaled D-optimality Criterion = 1747.474

When comparing designs, a smaller value is better.

Determinant of $(X'X)^{-1}$ = 2.848E+13

Trace of $(X'X)^{-1}$ = 3.55E+007

I = 0.39093

- These can only be used when comparing designs with the same number of runs, a smaller value is better.

From the factor space evaluation computation results, the design summary is thus presented in Table 6.

Table 6: Design Summary

File Version	10.0.0.3					
Study Type	Mixture		Subtype	Randomized		
Design Type	I-optimal	Point Exchange Runs		10		
Design Model	Quadratic		Blocks	No Blocks		
Component	Name	Units	Type	Minimum	Maximum	Mean
A	geogrid		Mixture	0.0005	0.002	0.0012875
B	water		Mixture	0.098	0.15	0.125619
C	soil		Mixture	0.848	0.9	0.873094
Total =				1.00	U_Pseudo Coding	
						Std. Dev.
						0.000571456
						0.0213172
						0.02129

2.4 Design of Experimental Mix Proportions

The number of experimental runs and the ingredients proportions were derived from the information matrix. Ten runs of experiments were derived in the process based on the imposed component constraints. Table 7 presents the mixes and runs for the 3- component multiconstraints experimental design. These mixes guide the preparation of specimens to be tested in the laboratory to achieve the responses [39].

Table 7: Component experimental mix proportions for soil treatment with geogrids

	Component-1	Component-2	Component-3	Response	Pseudo-1	Pseudo-2	Pseudo-3
Run	A:geogrid	B:water	C:soil	CBR	A:geogrid	B:water	C:soil
1	0.002	0.15	0.848		0.000	0.000	1.000
2	0.0005	0.0995	0.9		0.029	0.971	0.000
3	0.00125	0.15	0.84875		0.014	0.000	0.986
4	0.002	0.098	0.9		0.000	1.000	0.000
5	0.0005	0.15	0.8495		0.029	0.000	0.971
6	0.00125	0.124375	0.874375		0.014	0.493	0.493
7	0.000875	0.137187	0.861938		0.022	0.246	0.732
8	0.002	0.124	0.874		0.000	0.500	0.500
9	0.00125	0.09875	0.9		0.014	0.986	0.000
10	0.00125	0.1244	0.8743		0.014	0.493	0.492

3. Results and Discussion

3.1 Characterization of Test Materials

The general classification and engineering behavior of the test soil is presented in Table 8. This classification makes it easy to understand the behavior of the soil, thereby helping in selecting a suitable method of design, pavement construction, and maintenance of the structures resting on the soil [40]. The results indicate that it possesses high plasticity and swelling potential; it is also poorly graded and exhibits expansive properties of soft materials. Furthermore, the classification by AASHTO [41] and USCS [42] produced A-7 and CH, respectively, which indicates an unsuitable soil for engineering work with low CBR of 5%, MDD of 1.28 Mg/m³ and OMC of 17%. Federal Ministry of Works and Housing recommendations for subgrade materials are $\leq 10\%$ which indicates inadequate performance and according to Bello et al., (2007) [43], sample characterized with high value of maximum dry density and low optimum moisture content were the best subgrade materials. The studied soil has a specific gravity of 2.38 and from the grain size distribution of the unaltered soil, 38.24 % were passed through BS No. 200 Sieve (75 μ m aperture) [44].

Table 8: Basic properties of the test soil

Percentage Passing BS No. 200 Sieve (75 μ m aperture)	38.24
Natural Moisture Content (%)	36.45
Dry Unit Weight (γ_d) (kN/m ³)	17.69
Specific Gravity	2.38
Liquid Limit (%)	54.23
Plastic Limit (%)	20.53

Plasticity Index (%)	33.7
OMC (%)	17
MDD (g/cm ³)	1.28
AASHTO	A-7
USCS	CH
CBR (%)	5
Unconfined Compressive Strength (UCS) (kN/m ²)	12.287

The sieve analysis result presents the size range of the particle present in the soil sample. According to the Federal Ministry of Work and Housing [45] specification requirement, for a sample to be used for road construction, the percentage of weight passing the No. 200 sieve shall be less than but not greater than 35%. The result shows 38.24% passing 0.075mm sieve size as shown in Table 9 and the plot in Fig. 7 which indicate highly plastic soil unsuitable for pavement subgrade materials. The gradation coefficients were then calculated using Eqns. 8 – 9.

Table 9: Sieve Analysis Results

Grain Size (mm)	4.75	3.18	2.4	1.2	0.6	0.42	0.3	0.21	0.15	0.075	0.053
Percent Finer (%)	99.32	98.63	97.6	73.55	69.2	67.2	65.25	60.22	52.15	38.24	2.5

$$\text{Coefficient of Uniformity (Cu)} = \frac{D_{60}}{D_{10}} \quad (8)$$

From graph: $D_{60} = 0.21\text{mm}$; $D_{10} = 0.073\text{mm}$; $D_{30} = 0.074\text{mm}$

$$Cu = \frac{0.21}{0.073} = 2.88$$

$$\text{Coefficient of curvature (Cc)} = \frac{(D_{30})^2}{D_{60} \times D_{10}} \quad (9)$$

$$Cc = \frac{(0.074)^2}{0.21 \times 0.073} = 0.36$$

Since $Cu < 4$ and $Cc < 1$, it showed that the soil sample according to the classification scale is a poorly graded fine silty clay sample [46].

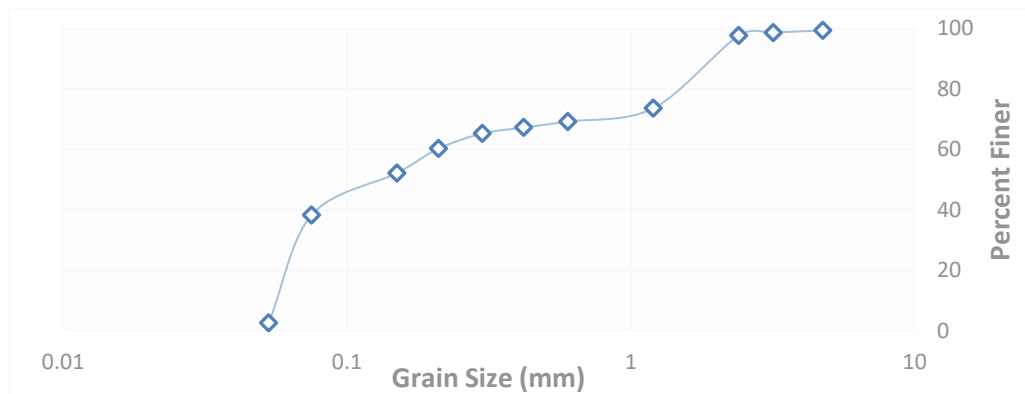


Fig. 7. Particle Size Distribution Graph

3.2 California Bearing Ratio (CBR) Test Results

The California Bearing Ratio (CBR) is a semi-empirical test that is often employed in the estimation of the bearing capacity of sub-grade, sub-base, and base materials. Laboratory responses for the blended samples were further derived with the parameters for the experiment presented below. The volume of the CBR cylindrical mold was calculated using the formula in Eqn. 10 and the parameters utilized for the response computations are presented below as follows [31];

Mold type = CBR mold

Diameter of Mold = 15cm

Height of Mold = 12cm

Weight of Mold = 3447g

Weight of Rammer = 4500g

Number of blow per layer = 25 blows

Number of layers = 3

$$\text{Volume of mold (v)} = \frac{\pi d^2 H}{4} \quad (10)$$

$$V = \frac{22 \times 15 \times 15 \times 12}{7 \times 4} = 2121.43 \text{ cm}^3$$

$$\text{Proving Ring Factor} = 0.025 \text{ kg}$$

The CBR experimental results plot of the corrected force on the y-axis and penetration (mm) on the x-axis for the top and bottom of the mixture are shown in Figs. 8-9 and Table 10.

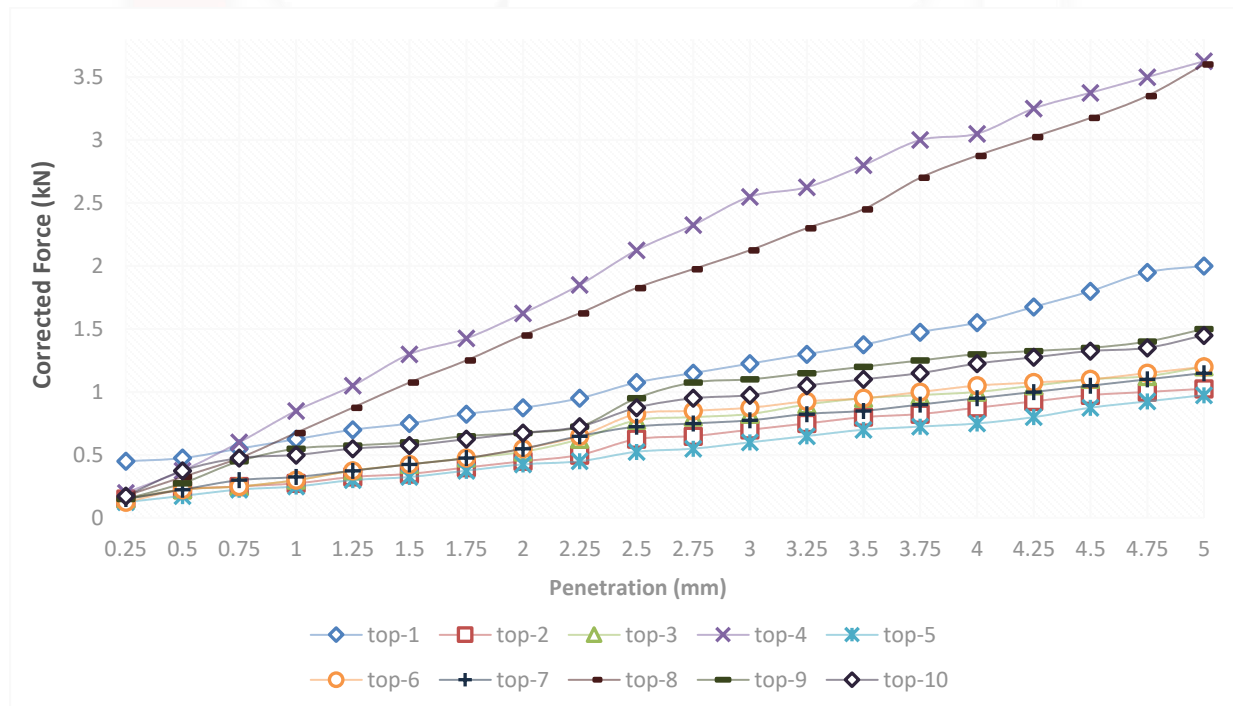


Fig. 8. CBR Plots of Corrected Force vs. Penetration for Top

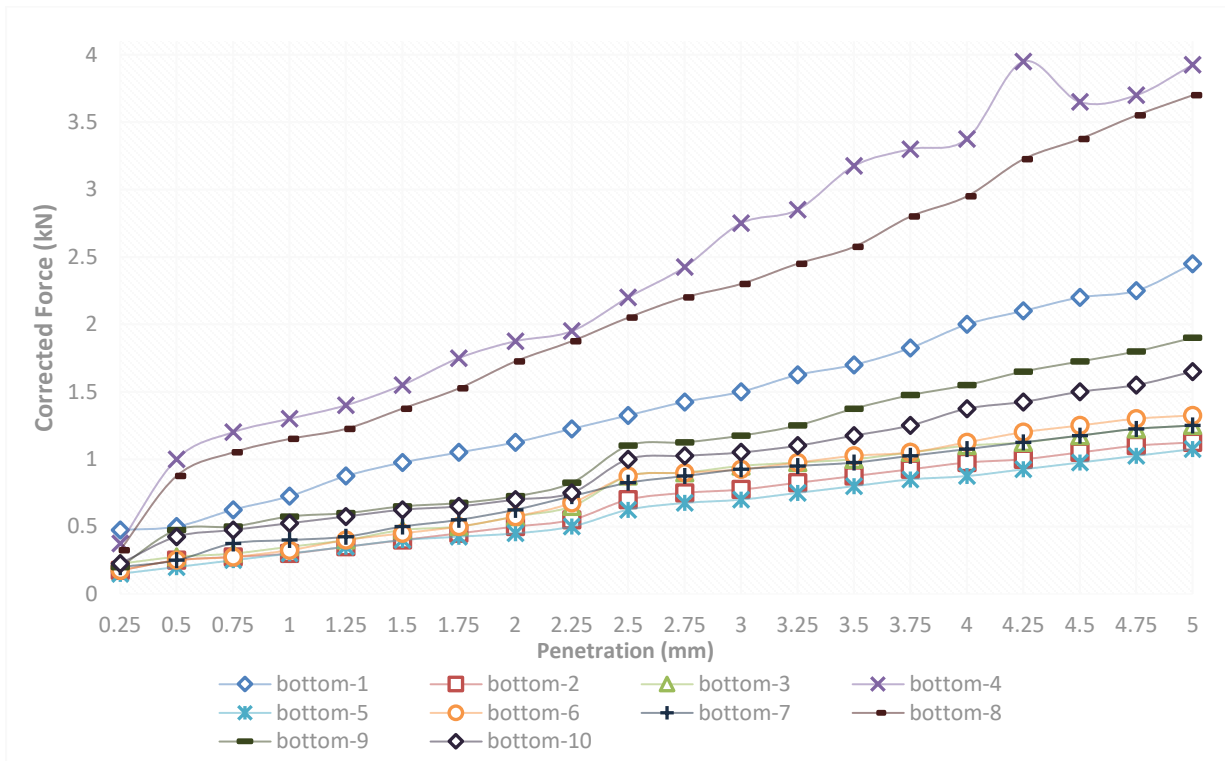


Fig. 9. CBR Plots of Corrected Force vs. Penetration for Bottom

Table 10: Summary of Corrected Force results and average CBR values

Experimental Runs	2.5 mm Penetration		CBR
	top	bottom	
1	8.119335	10.00755	11.14729
2	4.720544	5.287009	5.385772
3	5.853474	6.608761	6.231118
4	16.04985	16.61631	18.91283
5	3.965257	4.720544	5.135271
6	6.231118	6.608761	6.41994
7	5.475831	6.231118	6.012024
8	13.78399	15.48338	18.28657
9	7.175227	8.308157	8.517034
10	6.608761	7.55287	7.765531

From the average values of the CBR, above 18.913% is the maximum result, hence it was adopted. This value of 18.91% (run 4) at 5.0mm penetration was used as the control value for the design, hence, this depth of penetration was considered while the minimum is 5.135% at 5.0mm penetration (run 5). Federal Ministry of Works and Housing [45] recommendation for soils for use as subgrade, sub-base, and base materials are $\leq 10\%$, $\leq 30\%$, and $\leq 80\%$, respectively, for unsoaked soil. The results indicate adequate improvement of the CBR value as subgrade materials for pavement construction. The result summary using percentage frequency statistics computation shows that 0.2% of geogrid, 9.8% of water,

and 90% of soil by weight produced the maximum response of 18.91% for CBR response while 0.05% of geogrid, 15% of water and 84.95% of water by weight produced the minimum response of 5.14% for CBR result [47].

3.3 Model Development and Validation

The statistical analysis were carried out after the experimental reports were obtained, the appropriate transformation which is quadratic (square root), and the response ranges from 13.3119 to 37.9672 with a ratio of max to min of 2.85212 for UCS response. The fit summary, diagnostic tests, numerical and graphical optimization were carried out to determine the optimal combination proportion of the soil-geogrid mixture to maximize the mechanical strength response. Post analysis, confirmation coefficient tables, and EVD model simulation were then executed to validate the model results using Design Expert 11 and Minitab 18 software [34-35].

3.3.1 Fit summary

Fit Summary is a collection of relevant statistical tools which helps to choose the required final model initial or starting point. The suggested models are selected and are considered a good starting point for model fitting. The fit summary presents the summary table with sequential and lack of fit P-value, lack of fit tests, and model summary statistics which focuses on maximizing the adjusted and the Predicted R-squared results presented include sum of squares, lack of fit, R-squared and summary statistics [48].

3.3.2 Fit Summary for CBR Response

The model fit summary statistics results is shown in Tables 11-13 indicating a preference for the quadratic model for CBR response with R-squared, predicted, adjusted and R-squared of 0.9757, 0.8233 and 0.9454 respectively. The lack of fit test results presented a sum of squares of 0.099, a mean square of 0.033, and lack of fit p-value (Prob > F) of 0.6033.

Table 11: Model Summary Statistics for CBR response

Source	Std. Dev.	R-Squared	Adjusted R-Squared	Predicted R-Squared	PRESS	
Linear	0.35	0.8428	0.7978	0.6487	1.89	
Quadratic	0.18	0.9757	0.9454	0.8233	0.95	Suggested
Special Cubic	0.17	0.9841	0.9524	0.7342	1.43	
Cubic	0.18	0.9941	0.9465		+	Aliased

+ Case(s) with leverage of 1.0000: PRESS statistics was not defined

"Model Summary Statistics": Focus on the model maximizing the "Adjusted R-Squared" and "Predicted R-Squared".

Table 12: Lack of Fit Tests for CBR Response

Source	Sum of Squares	df	Mean Square	F Value	p-value	Prob > F
Linear	0.81	6	0.14	4.24	0.3555	
Quadratic	0.099	3	0.033	1.03	0.6033	Suggested
Special Cubic	0.053	2	0.027	0.83	0.6122	
Cubic	0.000	0				Aliased
Pure Error	0.032	1	0.032			

Table 13: Sequential Model Sum of Squares [Type I] for CBR Response

Source	Sum of Squares	df	Mean Square	F Value	p-value (Prob > F)	
Mean vs Total	88.43	1	88.43			
Linear vs Mean	4.53	2	2.27	18.76	0.0015	
Quadratic vs Linear	0.72	3	0.24	7.30	0.0423	Suggested
Sp Cubic vs Quadratic	0.045	1	0.045	1.59	0.2961	
Cubic vs Sp Cubic	0.053	2	0.027	0.83	0.6122	Aliased
Residual	0.032	1	0.032			
Total	93.81	10	9.38			

"Sequential Model Sum of Squares [Type I]": the highest order polynomial where the additional terms are significant is selected and the model is not aliased [34-35].

3.3.3 Analysis of Variance (ANOVA) Test Result

Analysis of variance were carried out with respect to the model source selecting during fit summary computations using Pseudo coding to derive the statistical significance for the mixture factor levels with respect to the CBR strength response. The partial sum of squares result is presented for the corresponding model coefficients using p-values (Prob > F) for statistical significant determination criteria which is computed using the mean squared and F-value as shown in Tables 14-15 for CBR response. (Prob > F) of 0.0025 was obtained for the model source which indicates statistical significant, however, the lack of fit source produced a nonsignificant result with (Prob > F) of 0.6033 [49].

Table 14: ANOVA Results for CBR response

Response 1

CBR

Transform: Square Root Constant: 0

ANOVA for Quadratic Mixture model

*** Mixture Component Coding is U_Pseudo. ***

Analysis of variance table [Partial sum of squares - Type III]

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	5.25	5	1.05	32.15	0.0025	significant
1Linear Mixture	4.53	2	2.27	69.43	0.0008	
AB	0.49	1	0.49	15.08	0.0178	
AC	0.48	1	0.48	14.67	0.0186	
BC	0.047	1	0.047	1.45	0.2950	
Residual	0.13	4	0.033			
Lack of Fit	0.099	3	0.033	1.03	0.6033	not significant
Pure Error	0.032	1	0.032			
Cor Total	5.38	9				

¹ inference for linear mixtures uses Type I sums of squares.

- The Model F-value of 32.15 implies the model is significant. There is only a 0.25% chance that an F-value this large could occur due to noise.

- Values of "Prob > F" less than 0.0500 indicate the model terms are significant. In this case A, B, C, AB, AC is significant model terms. Values greater than 0.1000 indicate the model terms are not significant.
- If there are many insignificant model terms (not counting those required to support hierarchy), model reduction may improve your model.
- The "Lack of Fit F-value" of 1.03 implies the lack of Fit is not significant relative to the pure error. There is a 60.33% chance that a "Lack of Fit F-value" this large could occur due to noise. Non-significant lack of fit is good -- we want the model to fit.

- **Table 15:** R-squared Calculations for CBR response

Std. Dev.	0.18	R-Squared	0.9757
Mean	2.97	Adj R-Squared	0.9454
C.V. %	6.08	Pred R-Squared	0.8233
PRESS	0.95	Adeq Precision	15.105
-2 Log Likelihood	-15.00	BIC	-3.49
		AICc	10.00

- The "Pred R-Squared" of 0.8233 is in reasonable agreement with the "Adj R-Squared" of 0.9454; i.e., the difference is less than 0.2.
- "Adeq Precision" measures the signal to noise ratio. A ratio greater than 4 is desirable. Your ratio of 15.105 indicates an adequate signal. This model can be used to navigate the design space [34-35].

3.3.4 Coefficient Estimates and Model Equations for CBR

The component coefficient estimate, degrees of freedom, standard error, variance inflation factor (VIF), and final equation terms of L_pseudo component computation results for the CBR response are presented in Tables 16-18. Standard error is the standard deviation with respect to the model coefficient estimate. It is the regression coefficient representing the change in expected response (y) per unit change in a (x) provided all other factors remain constant. In addition presented in the result is the 95% CI High and low law which presents the condition when this result gives 0 that means that the coefficient of 0 could be true, which indicates that the term is not significant [50].

Table 16: Model Coefficients Calculation Results for CBR response

Component	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
A-geogrid	2295.35	1	610.11	601.42	3989.28	33791.62
B-water	4.42	1	0.16	3.97	4.87	2.99
C-soil	3.44	1	0.16	2.99	3.90	3.40
AB	-2434.36	1	626.83	-4174.73	-693.99	13432.33
AC	-2400.69	1	626.78	-4140.90	-660.48	16104.96
BC	0.66	1	0.55	-0.86	2.18	1.96

Table 17: Final Equation in Terms of U_Pseudo Components

	*A	*B	*C	*AB	*AC	*BC
Sqrt(CBR) =	2295.35	4.41742	1.44353	2434.36	2400.69	0.660659

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels of the factors are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients [51].

Table 18: Final Equation in Terms of Real Components

The equation in terms of actual factors can be used to make predictions about the response for given

	*Geogrid	*Water	*Soil	Geogrid*Water	Geogrid*Soil	Water*Soil
Sqrt(CBR) =	8.88E+05	-1.79E+02	-1.78E+00	-9.00E+05	-8.88E+05	2.44E+02

levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor and the intercept is not at the center of the design space [34-35].

3.3.5 Diagnostics plots

The regression diagnostics are utilized for the verification of regression model assumptions and state if there are observations with substantial or undue influence on the analysis using the studentized residual which is the quotient of the residual and its predicted standard deviation [52]. Outlier is a group of data which differs significantly from other observations due to measurement variability or as an indication of experimental error. However, the studentized residuals are used essentially as outliers' detectors. Studentizing the residuals maps all different normal distributions to a single standard normal distribution. Diagnostic statistical tests were carried out with respect to the response variable which includes; normal probability test, predicted vs. residual, run plot, vs. residuals, predicted vs. actual, and box-cox power transformation [53].

3.3.6 Normal Probability Plot

The normal probability computation plot indicates whether the residuals or error functions follow a normal distribution, thus following the straight line or near the line of fit. Some portion of the data points may be scattered with normal data distribution of the residuals. Definite patterns such as an "S-shaped" curve plot imply that a transformation of the response will produce better analysis results [54]. Normal probability plots for the model response variables are presented in Fig. 10.

3.3.7 Residuals vs. Predicted

This is a plot of the residuals versus the ascending predicted response value which tests the assumption of constant variance as presented in Fig. 11. The plot should be a random scatter (constant range of residuals across the graph). Expanding variance observed from the plotted results indicates the need for a transformation. The result shows an expanding variance which indicates the need for a transformation. The scattered plot was near the zero studentized residual points with the maximum and minimum of 7.45332 and -7.45332 for the CBR target response [55].

Design-Expert® Software
Sqrt(CBR)

Color points by value of
Sqrt(CBR):

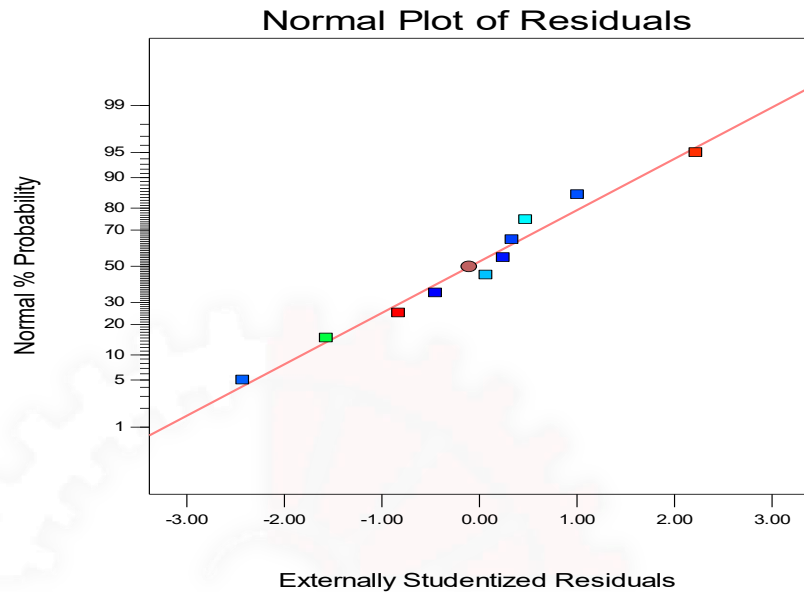


Fig. 10. Normal Plot of Residuals for CBR response

Design-Expert® Software
Sqrt(CBR)

Color points by value of
Sqrt(CBR):

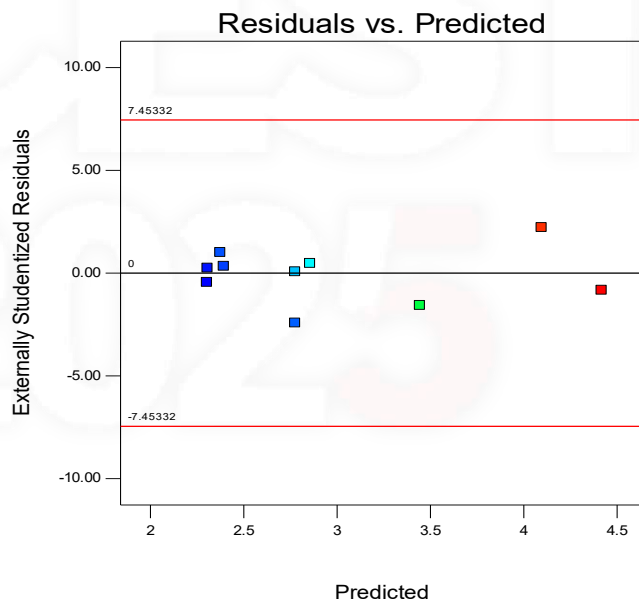


Fig. 11. Residuals vs. Predicted for CBR response

3.3.8 Residuals vs. Run Computation Plot

This diagnostic statistic shows a plot of the externally studentized residuals on the y-axis versus the run order of experiments on the x-axis. Lurking variables are investigated which may have influenced the response parameter during the experiment in this statistical computation as presented in Fig. 12. The plot shows the studentized residuals with respect to the experimental runs are close to the line which indicates a time-related variable lurking in the background [56].

Design-Expert® Software
Sqrt(CBR)
Color points by value of
Sqrt(CBR):
4.349
2.266

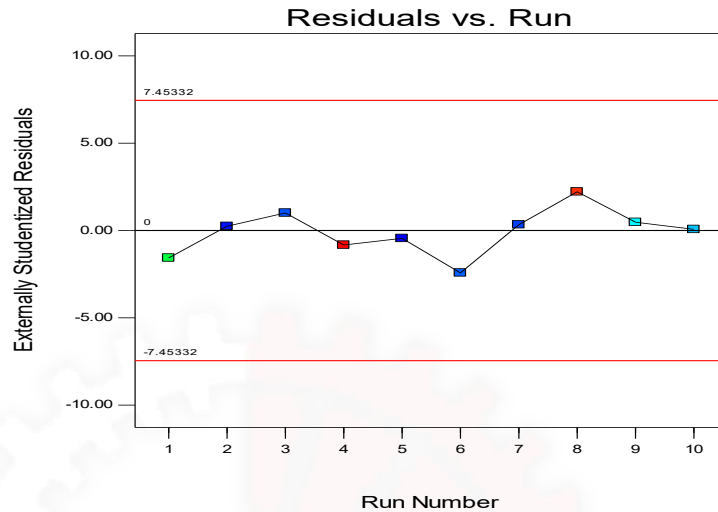


Fig. 12: Residuals vs. Run

3.3.9 Predicted vs. Actual

A graph of the predicted response values versus the actual response values. The purpose is to detect a value, or a group of values, that are not easily predicted by the model. Predicted vs. Actual plots for CBR output responses are presented in Fig. 13. The result obtained from the plotted graph shows a strong correlation between the experimental and the model predicted values [34-35].

Design-Expert® Software
Sqrt(CBR)
Color points by value of
Sqrt(CBR):
4.349
2.266

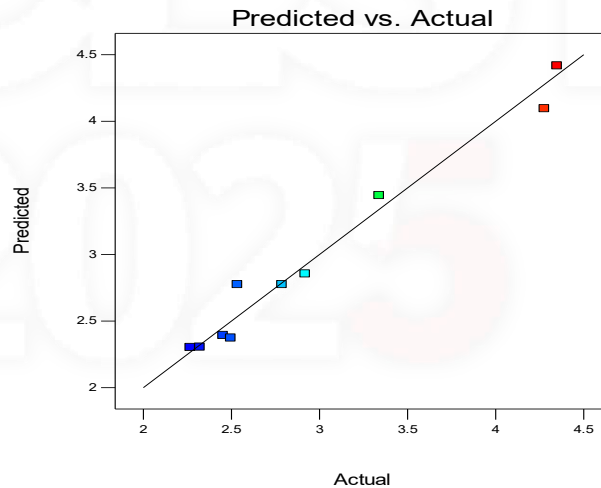


Fig. 13: Predicted vs. Actual CBR response

3.3.10 Box-Cox Plot for Power Transforms

This plot provides a guideline for selecting the correct power law transformation. A recommended transformation is listed, based on the best lambda value, which is found at the minimum point of the curve generated by the natural log of the sum of squares of the residuals as presented in Fig. 14. If the 95% confidence interval around this lambda includes 1, then the software does not recommend a specific transformation. This plot is not displayed when either the logit or the arcsine square root transformation has been applied [57]. The result presents the best point of 2.08752 for the residuals sum of squares which

showed the current and best lambda at 0.5 and -0.44, respectively at high and low confidence interval (C.I.) of 1.14 and -3.43 respectively.

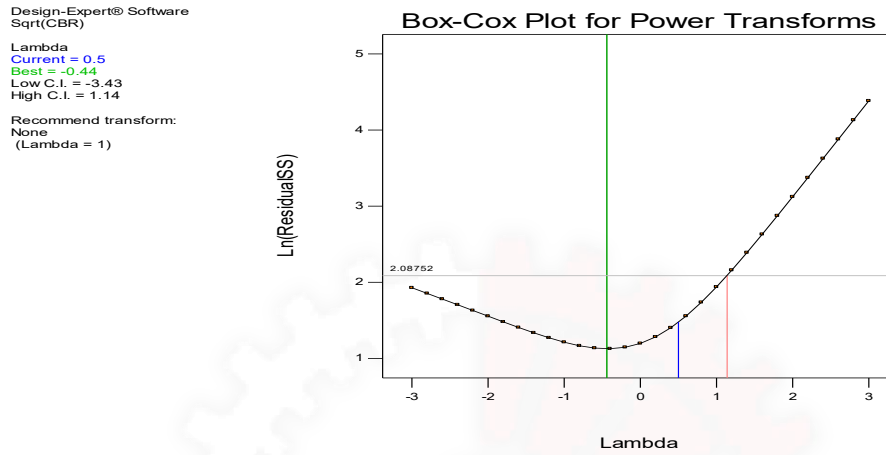


Fig. 14. Box-Cox Plot for Power Transforms

3.4 Statistical Influence Computation plots

These statistical values provide measures of the influence, potential or actual, of individual runs. The graphical plots provide a better perspective on whether a case (or two) “sticks out” from the others. The statistical influences were evaluated through the Cook’s distance, leverage vs. experimental run, and DFFITS statistics vs. experimental run. The results are presented in graphical plots which provide a better perspective on the data points [58].

3.4.1 The Cook’s distance

The Cook’s distance is commonly used for the determination of the data point statistical influence while conducting ordinary least squares regression analysis. The influential points which are particularly worth for validity checks and to show the planes of the feasible experimental design space where better performance can be achieved as presented in Fig. 15. The plotted result indicates that the Cook distance scores for the CBR response are mostly within 0 and 1 while experimental point number 1 were observed to be dispersed outside an positioned between 1.2 and 1.4 [59].

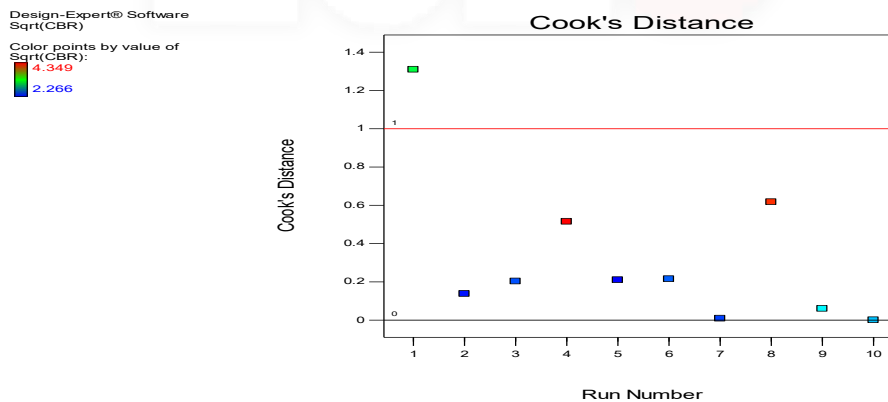


Fig. 15: Cook’s distance for CBR response

3.4.2 Leverage vs. Experimental Run

Leverage measures how much each of the experimental points influences the model goodness of fit. A point with a leverage of 1.0 indicates that the model performance exactly fits the observation at that point. Moreover, points with leverage results greater than 2 times the average are generally regarded as having high leverage [60]. The average leverage is the number of terms in the model divided by the number of experimental runs in the design as shown in Fig. 16.

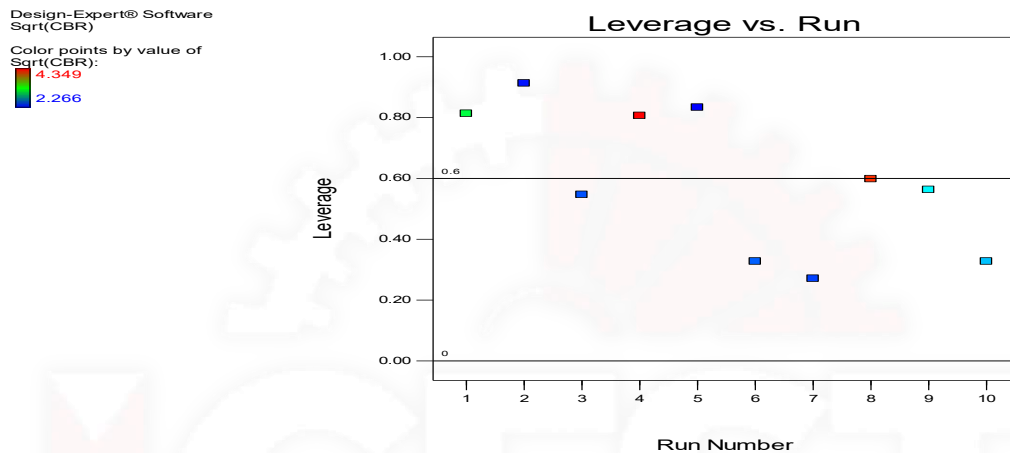


Fig. 16: Leverage vs. Run

3.4.3 DFFITS vs. Runs

DFFITS is a diagnostic statistical tool which shows the interactions of the influential experimental points in a regression analysis computation. It is the change in the estimated value for experimental point derived in regression when that point is left out and also the product of the leverage factor and externally studentized residual shown in Fig. 17. The plotted results indicate DFFITS points with respect to the experimental runs lie very close to the zero points within the boundaries of ± 2.32379 for the CBR output responses. Experimental run no. 1 and 8 were also observed to be situated outside the limits at about DFFITS of about -3 and 3 respectively [61].

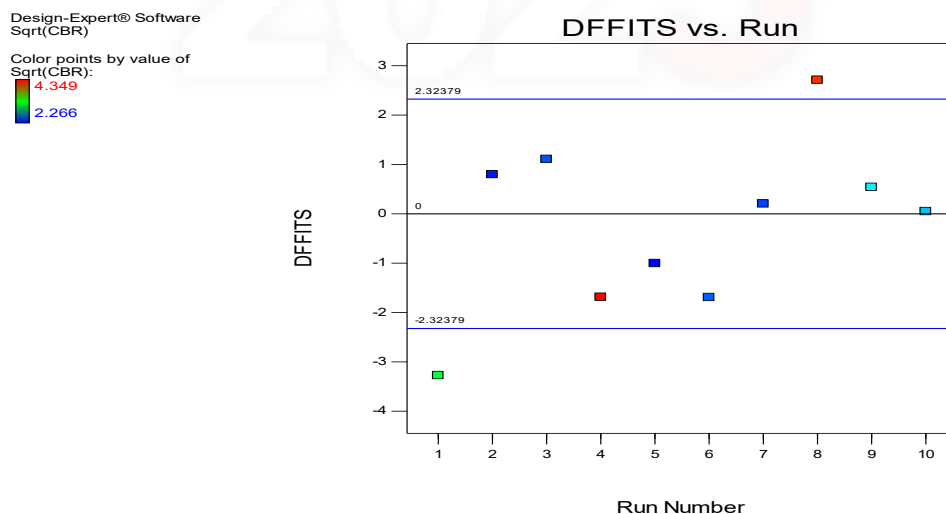


Fig. 17: DFFITS vs. Run for CBR Response

3.4.4 Diagnostic Plots and Influence Statistics Summary Report

The summary report of statistical diagnostic plots and influences showing the actual and predicted results, leverage, lambda values, internally and externally studentized residuals with respect to the generated standard experimental run, and order of the response output as shown in Table 19. The box-cox power transformation computation results showed the best lambda value of -0.44, 95% CI Low and high values of -3.43 and 1.14, respectively, for the response function [36-37].

Response	CBR				Transform:	Square Root	Constant:	0.000	
Diagnostics Case Statistics									
Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residual	Externally Studentized Residual	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	3.34	3.44	-0.10	0.813	-1.342	-1.568	1.3091	-3.2741	10
3	2.50	2.37	0.12	0.547	1.005	1.007	0.203	1.106	9
5	2.27	2.30	-0.037	0.833	-0.502	-0.449	0.210	-1.004	8
7	2.45	2.39	0.059	0.271	0.380	0.335	0.009	0.204	7
8	4.28	4.10	0.18	0.598	1.577	2.221	0.617	2.7101	6
10	2.79	2.77	0.012	0.327	0.079	0.068	0.001	0.048	5
6	2.53	2.77	-0.24	0.327	-1.628	-2.426	0.215	-1.693	4
4	4.35	4.42	-0.069	0.806	-0.862	-0.827	0.515	-1.688	3
9	2.92	2.86	0.063	0.563	0.529	0.475	0.060	0.540	2
2	2.32	2.31	0.015	0.913	0.281	0.246	0.138	0.796	1

Table 19: Summary Report of the Influence and Diagnostic Plots for CBR response

^1 Exceeds limits.

Box-Cox Power Transformation

Constant k	95% CI Low	95% CI High	Best Lambda	Rec. Transform
0.000	-3.43	1.14	-0.44	None

3.5 Numerical Optimization

Numerical optimization was carried out after statistical influence and diagnostic computation using desirability function. Desirability is simply a mathematical method to derive the optimum proportion of the mixture factor levels with respect to the response function; it is an objective function that ranges from

zero outside of the limits to one at the goal. The numerical optimization finds a point that maximizes the desirability function. The characteristics of a goal may be altered by adjusting the weight or importance. For several responses and factors, all goals get combined into one desirability function. The value is completely dependent on how closely the lower and upper limits are set relative to the actual optimum. The goal of optimization is to find a good set of conditions that will meet all the goals, not to get to a desirability value of 1.0. For each criterion fixed values ranging from 0 and 1 are defined such that the desirability function scale satisfies the following conditions of $0 \leq d(y_i) \leq 1$; 0 results indicates one or more criteria are outside their acceptable limit while 1 implies the solution obtained lie exactly at the acceptable response limits [62].

For the first condition, a maximized response which indicates that a larger value is derived and thus the desirability function are represented with the Eqn. 11.

$$d(y_i) = \begin{cases} 0 & y_i < L \\ \left(\frac{y_i - L}{T - L} \right)^{r_i} & L \leq y_i \leq T \\ 1 & y_i > T \end{cases} \quad (11)$$

For the second condition, a minimized response which indicates that a minimum or lesser value is desired and thus the desirability function is represented in Eqn. 12.

$$d(y_i) = \begin{cases} 0 & y_i < T \\ \left(\frac{U - y_i}{U - T} \right)^{r_i} & T \leq y_i \leq U \\ 0 & y_i > U \end{cases} \quad (12)$$

Finally, for this condition, the target response which indicates the best value (response) and the desirability function for this case is presented in Eqn. 13.

$$d(y_i) = \begin{cases} 0 & y_i < L \\ 0 & y_i < U \\ \left(\frac{U - y_i}{U - T} \right)^{r_i} & T \leq y_i \leq U \\ \left(\frac{y_i - L}{T - L} \right)^{r_i} & L \leq y_i \leq T \end{cases} \quad (13)$$

Where; T is the target or actual (experimental) value, y_i is the model predicted value of the i th response, L is the lower limit or lowest acceptable results or values, r_i is the weighted function of the i th desirability function and U is the maximum or highest acceptable results or values. Based on the given conditions presented in the equations above, a multi-response numerical optimization is executed through which the optimum mix combination is maximized through the weighted geometric mean of individual desirability function $d(y_i)$ from the feasible composite space [63]. Through this optimization process, a model with equal weight is then adopted through the composite desirability by using the mathematical equation of the form, where n is the total individual number of responses in Eqn. 11.

$$D = [d(y_1) \times d(y_2) \times d(y_3) \dots \times d(y_n)]^{1/n} \quad (11)$$

3.5.1 Optimization Overview

The optimization module searches for a combination of factor levels that simultaneously satisfy the criteria placed on each of the responses and factors. To include a response in the optimization criteria, it must have a model fit through analysis or supplied via an equation-only simulation. After statistical diagnostic tests and analysis, numerical and graphical optimization is carried out through which an appropriate ratio combination of factor levels which simultaneously satisfy the criteria (maximize, minimize, in range, equal to and target) for each of the predictors and response parameters with the imposition of the formulated single component constraints as presented in Table 20 where maximize and In range criteria were assigned to the response and predictors parameters respectively [64].

Table 20: Optimization Criteria Definition

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:geogrid	is in range	0.0005	0.002	1	1	3
B:water	is in range	0.098	0.15	1	1	3
C:soil	is in range	0.848	0.9	1	1	3
CBR	maximize	5.13527	18.9128	1	1	3

The mixture optimization solution is presented in Table 21. In the desirability function computation, the solution with the highest score is preferentially taken as the optimal solution. A desirability criterium score of 1.0 and optimal ratio 0.002:0.098:0.9 for the fraction of geogrid, water and soil, respectively [34-35].

Table 21: Optimization Solutions

Number geogrid		water	soil	CBR	Desirability	
1	0.002	0.098	0.900	19.546	1.000	Selected
2	0.002	0.105	0.893	19.112	1.000	
3	0.002	0.103	0.895	19.244	1.000	
4	0.002	0.100	0.898	19.429	1.000	
5	0.002	0.107	0.891	18.933	1.000	
6	0.002	0.099	0.899	19.480	1.000	
7	0.002	0.106	0.892	19.005	1.000	
8	0.001	0.118	0.881	6.039	0.207	

3.5.2 Optimization Ramps and Bar Graph

Ramp presents a graphical view of each optimal solution; the optimal factor settings are shown with red points, the optimal response prediction values are displayed in blue, the responses with models, but no goals are shown in gray. The Factor Tool is used to control which solution is shown in the graph area. Stepping through the list of solutions is a good way to explore how the factor settings affect the response. The optimization ramp and bar graph for the optimal solution is presented in Fig. 18. Desirability value of 1.0 was calculated for the mixture component variables and the response variables, which indicate a robust model prediction of the mechanical behavior of soil-geogrid blend [65].

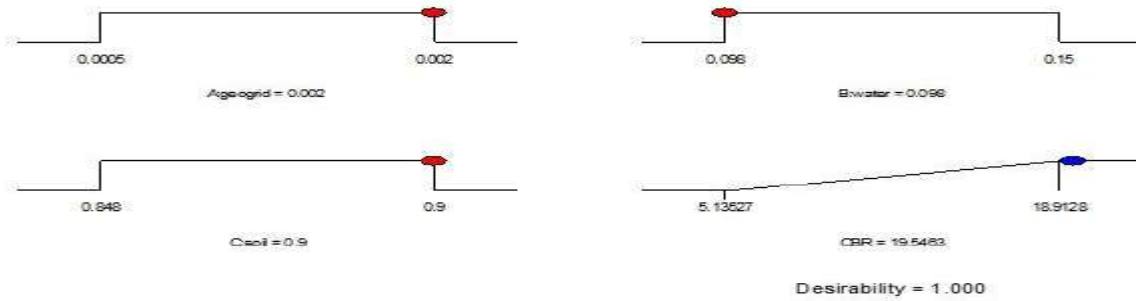


Fig. 18: Optimization Ramps

3.5.3 Optimization Trace Plot

Trace plots are used to evaluate all mixture components effects in the factor space, where the essence of this plot is to investigate sensitivity of the response function compared to the deviation from the formulation close to the reference blend. The trace Cox plot using U_pseudo coding units on the x-axis for the CBR response is presented in Fig. 19. The results indicate that mixture component 'B' which is geogrid produces the dominant effect in the mixture [66].

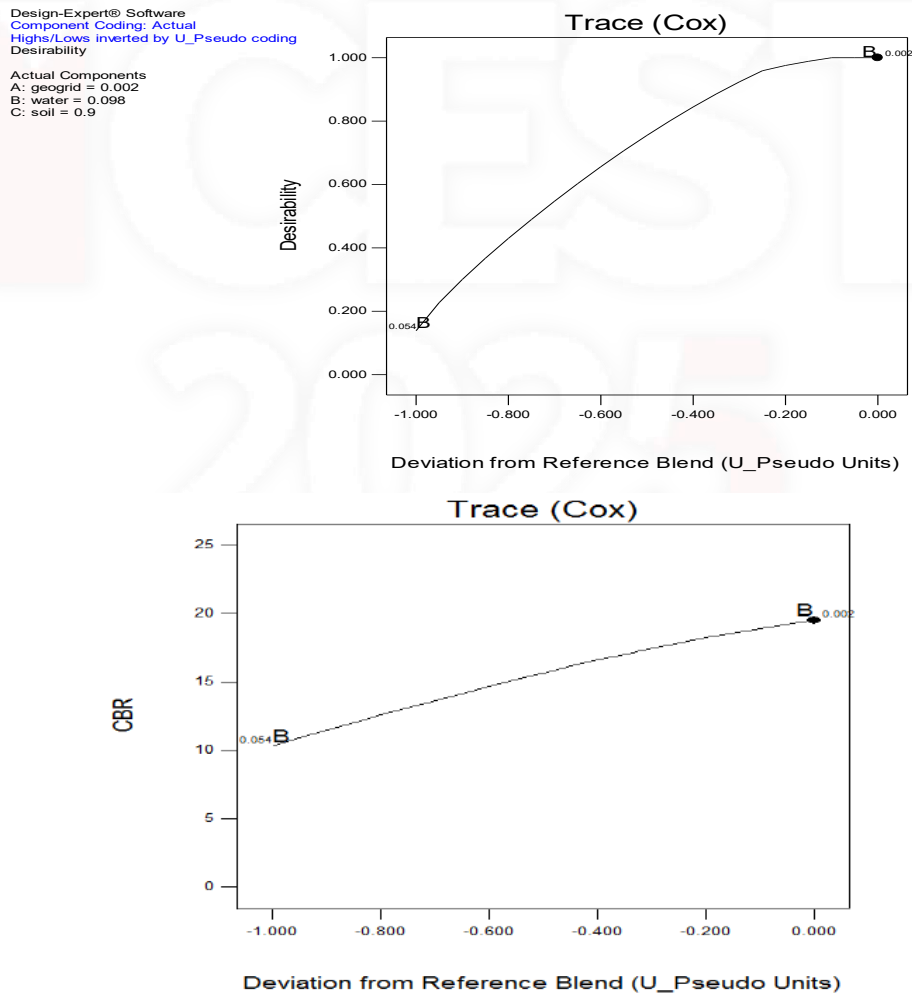


Fig. 19: Trace Cox Plot

3.5.4 Optimization Contour Plot

The contour surface plot is an essential technique utilized for the functional points' visualization of the feasible experimental region through iteration solution of mixture optimization. The contour plots for the optimal solution for the design points for CBR ranging from 5.13527 to 18.9128 and the desirability points from 0 to 1. The plots are presented in Fig. 20, which shows the three edges of the contour plot triangle representing the vertices of the three component's mixture simplex with -0.05, 0.098, and 0.848 coefficients for obtained for geogrid, water and soil respectively [67-68].

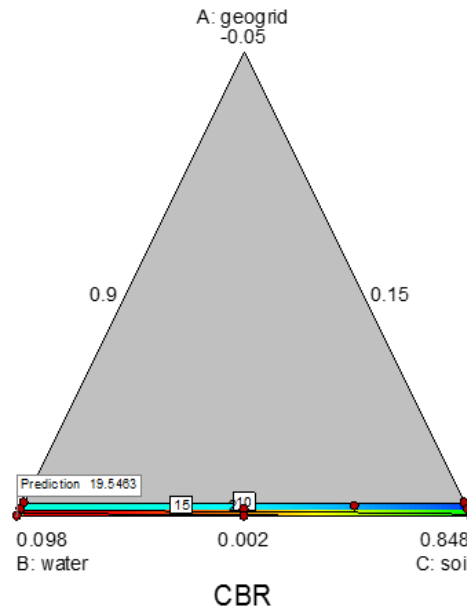


Fig. 20. Contour Plots for the Optimal Solution

3.5.5 3D Surface Plots

Three dimension surface plots are the diagrammatic presentations of the three mixture components relationships with respect to the response variables. The 3D plot for the optimal solution with respect to the desirability function showing the response surface for the corresponding points for the three mixture ingredients of soil, water and geogrid are presented in Fig. 21 showing the optimal CBR response of 19.546% and a desirability score of 1 [69].

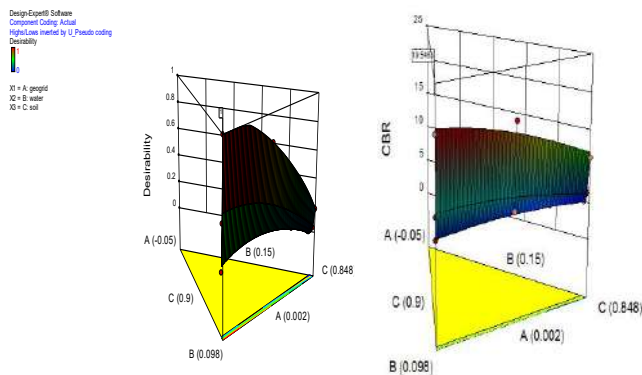


Fig. 21: 3D Plot for the Optimal Solution for CBR Response and Desirability Function

3.6 Post Analysis and Model Simulation

The post-analysis result presents the confirmation report at the confidence interval of 95 %, the descriptive statistical computation of the EVD model predicted results, and with the imposition of the sum to one constraint [34-35].

3.6.1 Point Prediction Results

For post analysis and model validation, Point Prediction computation is conducted, which uses the models fit during analysis and the factor settings specified on the factors tool to compute the point predictions and interval estimates as shown in Table. 22. The predicted values are updated as the levels are changed and the results indicate Predicted Mean and Median of 19.5463 and 19.5136 respectively.

Table 22: Point Prediction

Response	Predicted Mean	Predicted Median	Observed	Std Dev	SE Mean	CI for 95% low	Mean 95% CI high	99% of 95% low	Population 95% TI high
CBR ₂₆₃	19.5436	19.5136	-	1.59716	N/A	15.769	23.7295	8.80462	34.4286

3.6.2 Coefficient table

The coefficient table showing the factor level combination optimization coefficients of the black cotton soil-CKD blend is presented in Table 23. The special quartic and quadratic models were simultaneously adapted for the complex mixture optimization computation, where the former was used for UCS response modelling while the later was for CBR response modelling [70]. From the legend column in the presented result, p-values less than 0.01 are very significant and color coded red; p-values less than 0.05 but greater than 0.01 are significant and color coded green; p-values less than 0.10 but greater than 0.05 are marginally significant and color coded blue; p-values greater than or equal to 0.10 are considered insignificant and color coded black [34-35].

Table 23: Coefficient Table

Response	A	B	C	AB	AC	BC
sqrt (CBR)	2295.35	4.41742	1.44353	2434.36	2400.69	0.660659
p =	0.0008	0.008	0.0008	0.0178	0.0186	0.295
Legend	P <.01 .01<= P <.05 0.5<= p <.10 p >=.10					

3.7 EVD Model Simulation

This is the final phase of the model validation process whereby we replicate a life situation in what we have modelled to guide designers, contractors, and operators on how the developed EVD model will perform. The essence of the model simulation is also to show that the validation achieved during statistical inference and diagnostics can be achieved in the real life situation or applicability phase of the developed mixture model. Analysis of variance and Student's t-test statistics were further deployed to determine the statistical significant differences between the obtained simulated model results and the actual experimental values [71-72]. The computed simulated model results and the experimental results are presented in the plotted graph in Fig. 22.

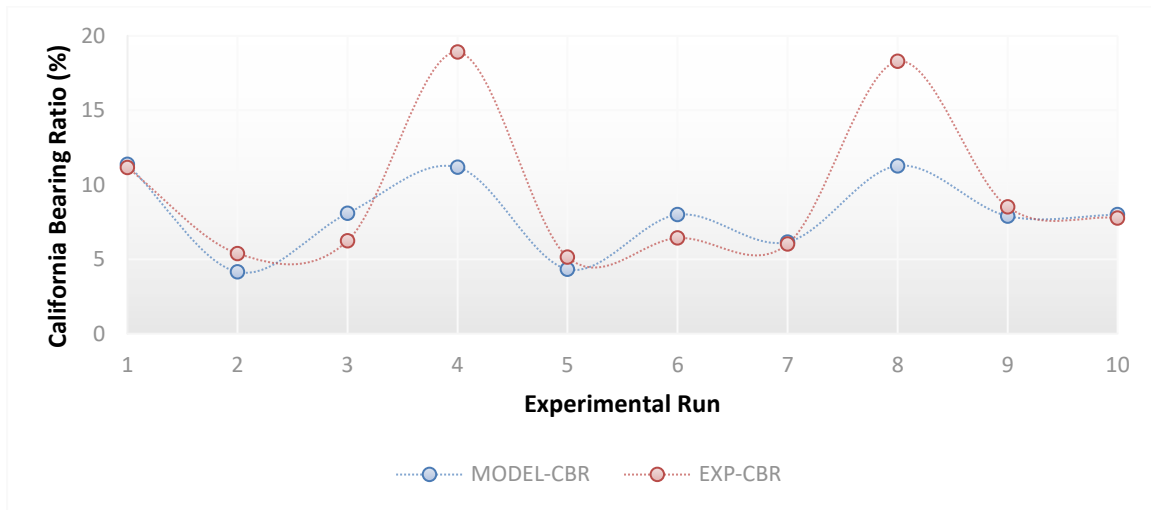


Fig. 22. Plot of Simulated EVD Model and Actual Results

The statistical test results to compare the two sets of means at a confidence interval of 95%, namely; the EVD model results and actual laboratory values and is presented in Tables 24-25. From the ANOVA computation results, P-value of 0.475329, F-critical of 4.413873, and F-value of 0.532, which indicates that there is no significant difference between the actual and EVD model results because obtained p-value > critical value (0.05). Similarly, the results obtained using student's t-test computation showed P(T<=t) two-tail of 0.234265, t-Stat of -1.27492, and Pearson correlation score of 82.6% which signifies excellent model performance which is also in agreement with the model validation results obtained by Alaneme et al. [39].

Table 24: ANOVA Test Results

Groups	Count	Sum	Average	Variance
MODEL-CBR	10	80.40141	8.040141	7.098755
EXP-CBR	10	93.81338	9.381338	26.74096

ANOVA Table Results						
Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8.994051	1	8.994051	0.531568	0.475329	4.413873
Within Groups	304.5574	18	16.91986			
Total	313.5515	19				

Table 25: t-Test: Paired Two Sample Means

	MODEL-CBR	EXP-CBR
Mean	8.040141	9.381338
Variance	7.098755	26.74096
Observations	10	10
Pearson Correlation	0.826	
df	9	
t Stat	-1.27492	
P(T<=t) one-tail	0.117132	

t Critical one-tail	1.833113
P(T≤t) two-tail	0.234265
t Critical two-tail	2.262157

4. Conclusion

From the foregoing mixture optimization research on the adaptation of the extreme vertex design method to evaluate the mechanical properties of an expansive clayey soil-geogrid mixture as a means of achieving mechanical stabilization to make the problematic soil suitable for construction work, the following conclusions can be drawn.

The research process involved the determination of the soil general engineering characteristics through experimental methods to obtain the test soil's general engineering behavior and classification. The obtained experimental results signify high swelling potential and plasticity property with AASHTO classification of A-7 and unsuitable for geotechnical work. I-optimal design was utilized to explore the constrained factor space for the derivation of the run of experiments and mixture proportions formulation at the edges, center, interior, and vertex of the simplex. The mixture ingredients are constrained by imposed restrictions on the sign of inequalities at the upper and lower region of the factor space to a subregion of the equilateral triangle formed as a result of three component mixture simplex through the q-vertices with regular sides of (q-1) dimensions where q is the total number of mixture ingredients. I-optimality and D-optimality of 0.39093 and 1747.474, respectively, were obtained with G-efficiency of 64.8%.

Data generated from experimental responses derived from the laboratory with the mixture components proportions formulation were utilized for analysis of variance (ANOVA), statistical fit test, statistical influence and diagnostic test computation using Design expert and Minitab 18 statistical software which provides an analytical toolbox for the simulation and analysis of the mixture experiments for test soil stabilization using geogrids; incorporated in the toolbox are statistical tools and techniques like fit summary, analysis of variance (ANOVA), statistical fit test, model equations formulation with coefficients estimation, diagnostic plots utilizing externally studentized residuals for regression model assumptions validation, Box-cox for power transformation, influence plots expressing the cook's distance and leverages vs. Run evaluation, trace plots using cox plot and contour plots.

The graphical and numerical optimization process which finds the mixture components combinations which satisfy the criteria placed on the mixture components and the corresponding response parameters was further conducted; the computation is based on the model fitness evaluation through statistical analysis and equation simulation using desirability function. A desirability score of 1 was calculated as the optimal solution with the optimal combination ratio of 0.002:0.098:0.9 for geogrid, water, and soil, respectively; and an optimum output response of 19.546% for CBR output parameter.

The laboratory response obtained from this research study on expansive soil mechanical properties improvement using geotextile materials showed significant improvement in the soil's strength property at about 0.2% by volume of geogrid. Furthermore, the model simulation was carried out using the generated coefficients and compared with the actual laboratory results using Student's t-test and ANOVA. The obtained statistical results indicated a good correlation of 82.6% between the two data sets.

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Development and Performance Evaluation of a Locally Fabricated Multi-Mould Wood Cement Composite Vibrating Table Machine

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Abstract: The quality and functionality of wood-cement boards are significantly influenced by factors such as air bubbles, voids, weak spots, and component segregation. Improving the functionality and enhance the performance of vibrating table, which is crucial for ensuring the optimal formation of the boards produced was the focus of this study. The design of a multi-mould vibrating table was refined to provide uniform, unidirectional vibration, and uses electric and manual drive mechanisms. Key components of the system include an electric motor, springs, a top plate serving as the platform, a stand frame, and an unbalanced eccentric assembly. The vibrating table, equipped with a 1.64 kg eccentric mass, was capable of producing ten composite tiles simultaneously. Operating at a frequency of 1500 rpm and with an amplitude of 0.4 mm, the system achieved an average production rate of 1020 Roman tiles per hour. The refined vibration process resulted in wood-cement boards that were non-porous, homogeneous, and well-consolidated, surpassing the quality of conventional boards. Performance testing of the produced boards revealed significantly improved properties, with superior consistency and durability. The enhanced vibrating table functionality contributed to a more efficient and reliable production process, ensuring the creation of higher-quality wood-cement composite tiles. This advancement not only improves the physical attributes of the tiles but also boosts overall production efficiency, making it a valuable innovation in the manufacturing of wood-cement boards.

Keywords: Cola nitida sawdust, Fiber-cement Tiles, Multi-mould vibrating-table, Machine design

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Introduction

One of the most exciting developments in material development is the use of natural fibre in cement-bonded tiles to create materials with unique properties from those of currently available tiles [1]. According to [2], these composites present a viable solution to many of the challenges faced by conventional construction materials, particularly in terms of sustainability and affordability, as opposed to conventional construction materials like concrete and steel, which have negative effects on environmental degradation due to their high carbon footprint and energy-intensive production processes. Cement serves as the binder, and natural fibre acts as reinforcement to support structural load while demonstrating strength and stiffness. The adoption of natural fibre cement bonded composites corresponds with global trends toward green building initiatives and eco-friendly materials [3]. Many developed and developing nations are focusing on reducing reliance on synthetic fibres and non-renewable resources in construction, recognising the potential of natural fibres in sustainable infrastructure development [4]. Natural fibre cement bonded composites also provide extra benefits such as enhanced thermal insulation, acoustic performance, and resistance to cracking, making them particularly suitable for a lot of application such as internal and external wall panels, ceilings and roof tiles in residential and commercial buildings. Also, these materials contribute to waste reduction by utilising agricultural by-products, thereby supporting circular economy principles [5] natural fibre cement bonded composites contribute to environmental sustainability in the aspect of reducing carbon emissions associated with cement production. The cement industry is one of the largest sources of CO₂ emissions globally, and adding natural fibres into cement composites can significantly reduce the amount of cement required per unit volume, leading to lower emissions. More so, the use of biodegradable and recyclable materials aligns with global sustainability goals, promoting a shift toward greener building practices [6]. Additional factors contributing to the present trend towards wood-cement composite include its superiority over unreinforced concrete in terms of its fundamental engineering qualities of ductility, energy absorption, and crack resistance. These characteristics guarantee many infrastructure projects that improve users' quality of life a long and

trouble-free service life. [7]. Furthermore, asbestos has been successful substituted, the use of natural fibres in cement-bonded composites has raised awareness of research on wood-fibre cement composites due to their toxic contents and detrimental health impacts [8]. However, many researches had proved the resourcefulness in this material development, hence, materials produced were void of micro and macro cracks weak points, void-spaces, air bubbles, and separation of the different ingredients of the composite were totally eliminated through the innovative technology that is available in the country but the production process is tedious, and time consuming due to low level of technological development by producing a composite board one after the other. Therefore, it is necessary to give researchers a way to advance and conduct rational study on methods for producing wood fiber-cement composites. By improving and properly putting, shaping, consolidating, and compacting the slurry, this issue can be reduced. The goal of this study was to make the current vibrating table a multi-mould, multi-purpose machine that would greatly increase production rates, be operated both manually and electrically, lower production costs, and complete base vibration of the top plate to guarantee the production of non-porous, homogenous, and well-consolidated boards with improved properties.

2. Method

2.1 Detailed Design Considerations of the multi-mould Vibrating Machine

The multi-mould vibrating table was designed using the proper design characteristics and concepts as outlined by [9]. The availability of materials, design parameters, and performance criteria served as the basis for the design analyses. The machine's parts are

- i. Table top
- ii. Electric motor
- iii. Pulley
- iv. Eccentricity assembly (eccentric mass, shaft, bearing)
- v. Spring
- vi. Frame
- vii. Belt

Component design for the vibrating machine table top. Given that a typical Roman roof tile weighs roughly 4.5 kg. Producing ten (10) tiles at once is the focus, then, 50 x 30 mm moulds were made to hold approximately, 10 kg of 6 mm tile. Therefore, using the volume, mass, density relationship, a square piece of dimensions was chosen. The table's dimensions was selected based on (a 2 x 5 layout of moulds) = 1525 x 925 mm

Expected mass of composite mixture and moulds = 45kg.

The total expected composite load on the table = 441.45N.

Mass of the table top = volume × density

Self-weight of table top = $m \times g$

(Equation 1 + Equation 2) = 112.17N

... 1
... 2

Combined weight of the table top and composite load = 441.8N + 112.17N = 553.62N

A 3hp motor with 1500rpm was selected for power transmission to the shaft pulley via a v-belt

Pulley

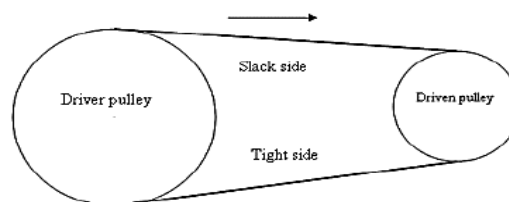


Figure 1. Sketch of a pulley system

$$\text{Volume of the pulley} = \pi r^2 h \quad \dots \quad 3$$

$$= 7.7 \times 10^{-5} m^3$$

Where, (r, radius = 0.06m, width of the pulley = 0.02m)

$$\text{mass of pulley} = \text{volume} \times \text{density} \quad \dots \quad 4$$

Where, (density of mild steel $\rho = 7860 \text{ kg/m}^3$)

$$= 1.78 \text{ kg}$$

$$\text{The weight of pulley} = \text{mass of pulley} \times \text{acceleration due to gravity} \quad \dots \quad 5$$

$$= 17.46 \text{ N}$$

$$\text{Speed of pulley} (N_2) = \frac{N_1 \times D_1}{D_2} \quad \dots \quad 6$$

Where, (N_1 = Speed of electric motor, D_1 = diameter of pulley on motor, D_2 = diameter of pulley on shaft)
= 875 rpm

Eccentricity assembly

The eccentricity assembly is made up of three parts namely; The eccentric mass, the shaft and the bearings.

i. The eccentric mass

An eccentric mass of 0.25 kg was selected to achieve the desired amplitude of 0.4 mm at the speed of 875 rpm.

ii The shaft

The shaft is a metal rod that rotates to avail the machine with the vibration needed via the electric motor. The shaft by the nature of work it is subjected to, bending moment is the critical form of stress caused by the eccentric mass and pulley.

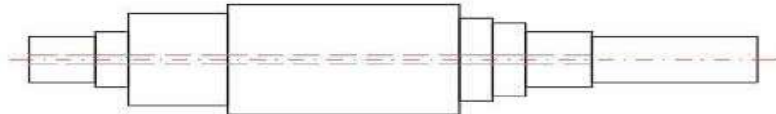


Figure 2. Sketch of a shaft

$$\text{Weight of eccentric mass} (P) = m \times g \quad \dots \quad 7$$

$$= 2.45 \text{ N}$$

$$\text{Bending moment due to eccentric mass, } (M_{ecc}) = \frac{P \times L}{4} \quad \dots \quad 8$$

$$= 0.6125 \text{ Nm}$$

$$\text{Bending moment due to pulley load, } (M_{pulley}) = F_{pulley} \times L_{pulley} \quad \dots \quad 9$$

$$= 6.984 \text{ Nm}$$

$$\text{Total Bending moment, } (M) = M_{ecc} + M_{pulley} \quad \dots \quad 10$$

$$= 7.5965 \text{ Nm}$$

$$\text{Torque generated by power transmitted from motor, } (T) = \frac{P_m}{2\pi f} \quad \dots \quad 11$$

$$= 14.24 \text{ Nm}$$

$$\text{The equivalent twisting moment } (T_e) = \sqrt{M^2 + T^2} \quad \dots \quad 12$$

$$= 16.14 \text{ Nm}$$

$$\text{Using maximum shear stress theory, } T_e = \frac{\pi}{16} \times \tau \times d^3 \quad \dots \quad 13$$

$$\text{minimum shaft diameter, } d \geq \sqrt[3]{\frac{T_e \times 16}{\pi \times \tau}} \quad \dots \quad 14$$

$$\text{Mass of shaft} = 2.47 \text{ kg; Weight of shaft} = 24.23 \text{ N}$$

Where, P_m is the power transmitted from motor, L is length of shaft, F_{pulley} is weight of pulley, L_{pulley} is the distance between the pulley and shaft midpoint, τ is the maximum shear stress of the shaft
 $\geq 9.37 \text{ mm}$

A shaft with diameter of 20 mm was selected for multi-mould vibration table

The bearings

Two ball bearings of inner diameter of 20 mm and outside diameter 42 mm with an allowance of 0.1 mm was selected off shelf. Mass of bearing = 0.508 kg, Weight of bearing = 4.984 N

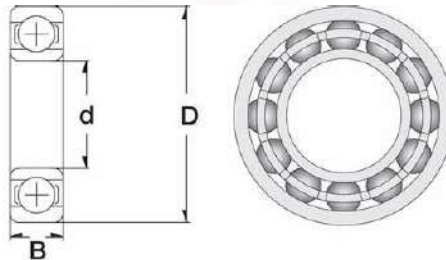


Figure 3. Sketch of a bearing

Spring

Total load on spring = load on table + weight of table top + pulley weight+ weight of shaft + weight of eccentric mass + weight of bearing ... 15
 Total load on spring = 602.744 N



Figure 4. Sketch of a spring

Taking a factor of safety of 2;

Design load = $602.744 \text{ N} \times 2 = 1205.488 \text{ N} = 1206 \text{ N}$, hence, Four springs are to be used for the multi-mould vibrating table.

Therefore, the design load on each spring = $\frac{1206 \text{ N}}{4} = 301.5 \text{ N}$

$$\text{Shear stress } (\tau) = \frac{8FD}{\pi d^3} \quad \dots \quad 16$$

Where, F = allowable design load, D = spring mean diameter, d = spring wire diameter

$$= \frac{8 \times 301.5 \times 40}{\pi \times 4^3} = 479.85 \text{ Nmm}^{-2} = 479.85 \text{ MPa}$$

The allowable strength of this spring (525MPa) > 371.58MPa. Hence it is suitable for the design

Frame

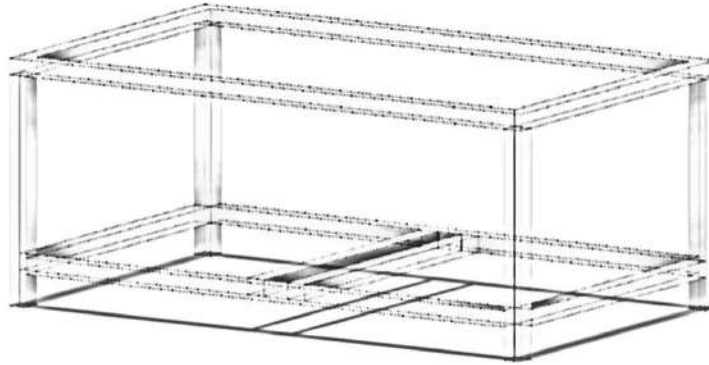


Figure 5. Sketch of the Frame

Beam of frame design

Total load on beam = load on table + weight of table top + pulley weight+ weight of shaft + weight of eccentric mass + weight of bearing + weight of spring ... 17

Total load on beam = 618.32N

Considering a factor of safety of 4, the design load = 2473.28N

The design load on each beam is 1236.64N, Since it's a UDL (w) = 0.8678KN/m

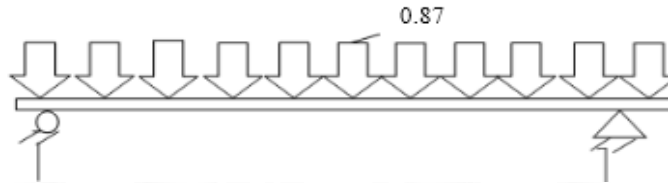


Figure 6: Loading behaviour of table top of the multi-mould vibrating machine

$$\text{Maximum Bending Moment } M_{max} = \frac{wL^2}{12} \quad \dots \quad 18$$

$$= 0.1468 \text{ KNm}$$

$$\text{The allowable bending moment of beam, } M_{all} = Z \times \sigma \quad \dots \quad 19$$

$$\text{Where, } Z \text{ is the section modulus of the beam, } \sigma \text{ is yield strength}$$

$$= 5.2075 \text{ KNm}$$

Since M_{all} (5.2075 KNm) > M_{max} (0.1468 KNm) hence, the beam design is safe under bending criteria

$$I = \frac{bd^3}{12} \quad \dots \quad 20$$

$$= 5.2083 \times 10^{-7} \text{ m}^4$$

$$\text{Maximum deflection } \Delta_x = \frac{wL^3}{384EI} \quad \dots \quad 21$$

Where, w = force per unit length on each beam, L = length of beam, E = Young Modulus of the material,

$$I = \text{moment of Inertia}$$

$$= 0.062 \text{ mm}$$

$$\text{Allowable deflection limit for the beam, } (\Delta) = \frac{L}{240} \quad \dots \quad 22$$

$$= 5.9375 \text{ mm}$$

Since Δ (5.9375 mm) > Δ_x (0.062 mm), hence, the beam design is safe under deflection criteria

Column of frame design

Total load on column = load on table + weight of table top + pulley weight+ weight of shaft + weight of eccentric mass + weight of bearing + weight of spring + weight of beams ... 25

Total load on column = 649.32 N

Considering a factor of safety of 4, then, Total load on column = 649.32 N x 4

The design load = 2597.28 N

Four columns are used in the design, therefore the design load per column = 649.32 N = 0.649 KN

Rankine's formula for Crippling load was determined

$$W_{cr} = \frac{\sigma_c \times A}{1 + \alpha \frac{l^2}{k^2}} \quad \dots \quad 26$$

$$W_c = 641.2 \text{ KN}$$

Where, k is radius of gyration, l is length of column, σ_c is the crushing stress of mild steel, α is Rankine's constant, A is the area of column.

Comparing the crippling load with the design load; 641.2 KN > 0.649 KN, hence, The column is very stable

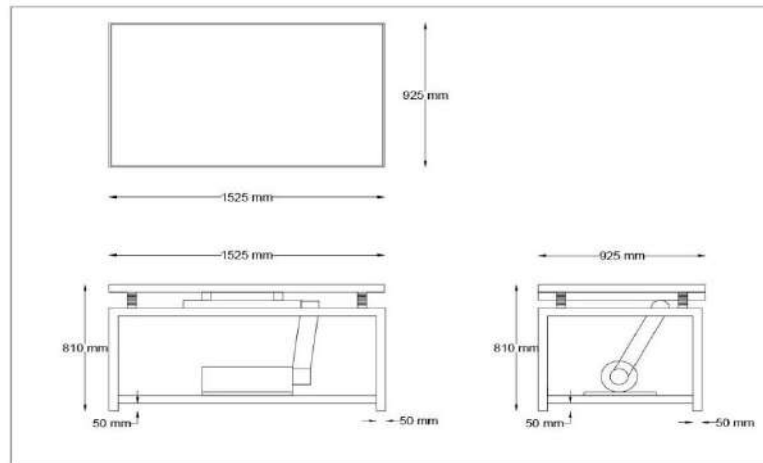


Figure 8. 2D Sketch of the Vibration Table



Figure 9. Exploded view of the Vibration Table



Figure 10. 3D view of the Vibration Table

2.2. Reason for Design Parts

Table 2. Weight of some components of the Vibration Table

S/N	Component	Mass (Kg)	Weight (N)
1	Table Top	11.434	112.17
2	Pulley	1.78	17.46
3	Shaft	2.47	24.23
4	Bearings	0.508	4.984
5	Eccentric mass	0.25	2.45
6	Springs	1.5876	15.574
	Total	18.030	176.868

Table 3. Material selected for multi-mould vibrating table

S/n	Name of component	Material selected	Reason(s) for selection
1	Table Top	Mild Steel	Cost effective, high strength, good weldability
2	Electric motor	Induction motor	meets the power requirement for the machine
3	Pulley	Mild Steel	High strength, corrosion and wear resistance
4	Eccentricity assembly		
	i) Shaft	Mild Steel 1045HR	Fatigue resistance, high torsional strength
	ii) Bearing	Deep groove ball bearing	High radial load capacity, low friction
	iii) Eccentric mass	Mild steel	High strength to weight ratio, availability
5	Spring	Mild steel	High strength
6	Frame	Mild steel	High strength, cost effective
7	Belt	Rubber	High strength, cost effective, good weldability.
			High elasticity, wear resistance

To prevent failure due to excessive yielding and failure during the machine's life cycle, the requisite design characteristics, such as the size and strength of the building materials, were evaluated and taken into account when choosing different machine parts. Table 1 lists the machine's parts along with the estimated masses for each.

2.3. Fabrication Process

The machine was fabricated at the Faculty of Technology University of Ibadan Technical Support Unit (TSU) workshop. The stages involved in the machine fabrication are presented thus

Marking out

The dimensions of the parts are measured and marked out on the material as shown in Plate 1a. The marking out process starts with the table top of 1524.6 x 924.6 mm with 2 mm thickness from iron plate while, the table top frame were gotten from angle iron of 40 x 40 mm and 925 mm length for the table length and table width was gotten from angle iron 40 x 40 mm and 1525 mm length. Six pieces of 50.8 mm (2-inch) pipes of 812.6 mm length, four 50.8 mm (2-inch) pipes of 1422.4 mm length and four 50.8 mm (2-inch) pipes of 607 mm length were marked out to be used for the frame.

Cutting

The marked-out materials were cut using a high-power grinder into the desired dimensions as shown in Plate 1b. The iron plate is the only material that was cut using a gas blow torch as shown using Plate 1c.

Welding

The cut-out parts were aligned according to the design. Arc welding was used for the tacking and was examined carefully for its square-ness. Full arc welding as presented in Plate 1d was then used for joining the parts together, hence, frame of the vibration table was developed.



a. Marking out b. Cutting using an angle grinder c. Cutting using a gas blow torch d. Welding process

Plate 1. Fabrication Process

Assembling

The frame was assembled to meet the design specifications as shown in Plate 2a. The shaft was aligned with the bearing which was then bolted to the base of the table top. The table top was connected to the frame through four springs which are bolted at the top and bottom. The Electric Motor was placed on the base of the frame to align with the design. It was then bolted to the frame as shown in Plate 2b. The shaft pulley was bolted to the shaft as shown in Plate 2b. The eccentric mass was also welded to be attached to the shaft as shown in Plate 2c. The machine was then sand, primed and painted.



a. The frame shaft b. Bolting of the electric motor to the frame c. Bolting the pulley to the

Plate 2. Assembly Process

2.4. Materials collection and processing

The materials used for the production of the composite board are, *Cola nitida* sawdust, Sand, Portland cement, (with the trade name “Dangote cement”), and potable water. The *Cola nitida* sawdust was obtained from Bodija plank market. The Portland cement “Dangote cement” was bought off the shelf, whilst the Sand was packed from drainage and potable running tap water was obtained from the wood composite workshop, Department of Wood Products Engineering.

The material preparation was done according to [10]. The *Cola nitida* sawdust was air-dried prior to sieving with a 2 mm sieve. The Sand was also sieved using a 2 mm then the materials were batched in accordance to the experimental design and kept inside polythene nylon for the material not to adsorb moisture. The fiber material was weighed and batched into (0.9, 1.8, 2.7)g, cement (90)g, and sand (180)g, respectively.



Plate 3. Batched materials

2.5. Performance Evaluation

A multi-mould vibrating machine capable of vibrating ten (10) (50 x 30 x 0.6 mm) moulds mm at once was developed from locally sourced materials. Plate 4, presents the developed machine multi-mould vibrating machine. The developed machine was evaluated with ten (10) (50 x 30 x 0.6 mm) moulds of composite slurry was vibrated at different timing. The materials were dry mixed manually inside a mixing bowl until a homogenous mixture was achieved, The cement/sand ratio was 1:2 for the specimen and the fibre content was 5, 10, and 15% by mass of cement. The required 45 ml volume of potable water was added according to the experimental design and the entire contents were mixed until an acceptable level of homogeneity was achieved. The slurry was poured on a polythene sheet built with the mould in ten flat moulds of 50 x 30 x 0.6 mm on the vibrating table (Plate 3) and spread to cover the entire area inside the mould and levelled. The top plate was then vibrated for the stated seconds {control (no vibration), manual, 2, 4, and 6 min} as presented in the experimental design table. Three samples of each group were produced according to standard procedure. After 24 hours the tiles were de-moulded and was moist cured for a period of 24h, 7, 14, and total of 28 days.



Plate 4. The Developed Vibrating Machine

Table 4. Experimental design for the composite mix

Vibration	Sample	Cement (g)	Sand (g)	<i>Cola nitida</i> sawdust(g)	Water (ml)
No vibration	A	90	180	0.9	45
	B	90	180	1.8	45
	C	90	180	2.7	45

Manual	D	90	180	0.9	45
	E	90	180	1.8	45
	F	90	180	2.7	45
2 mins	G	90	180	0.9	45
	H	90	180	1.8	45
	I	90	180	2.7	45
4 mins	J	90	180	0.9	45
	K	90	180	1.8	45
	L	90	180	2.7	45
6 mins	M	90	180	0.9	45
	N	90	180	1.8	45
	O	90	180	2.7	45



Plate 4. Mixing of dry materials



a: Filling the mould



b: Composite mix in mould



c: Curing in water

Plate 5. Composite production process

2.5.1. Physical Properties Test

Density test

This is determined by calculating the mass-to-volume ratio of each test piece that has the same moisture content. Density was determined using Equation (1).

$$\text{Density, } \rho = \frac{\text{mass}}{\text{volume}} \quad \dots 1$$

Water Absorption (WA) Tests

Samples were submerged in water, and after 2, and 24 hours, the water absorption weight of the samples was measured on an electronic weighing balance as presented in Plate 6a. The amount of water that the composite tile could absorb after being submerged for two hours was determined, according to ASTM C642-06. The percentage of water absorbed for these specimens were determined using Equation 2.

$$\text{Water Absorption (\%)} = \frac{W_f - W_i}{W_i} \times 100 \quad \dots 2$$

Where, W_i – Initial weight before soaking; and W_f – Final weight of each sample

Thickness swelling test

Samples were submerged in water, after 2, and 24 hours, the thickness swelling of the sample were assessed using a micrometre screw gauge as shown in Plate 6b. The purpose of this dimensional analysis test was to measure the effect of the sample's immersion in water for a predefined period of time on its thickness. By measuring the differences before and after immersion in water, a micrometre screw gauge was employed to assess the impact of water on the tile's thickness. The thickness swelling in percentage

for these specimens using Equation 3.

$$\% Ts = \frac{T_f T_i}{T_i} \times 100 \quad \dots \quad 3$$

Where T_i – initial thickness of the board, T_f – final thickness of the board



a: Water Absorption Test



b: Thickness Swelling Test

Plate 6. Physical properties determination

Porosity Tests

The test for porosity was done in accordance with ASTM7063/D7063M-11. Equation 4 was used to determine the specimens' porosity in percentage.

$$\% \text{ Porosity} = \frac{W_u - W_k}{W_u - W_a} \times 100 \quad \dots \quad 4$$

Where: (W_u = mass of specimen in air W_k = mass of dry specimen W_a = mass of specimen under water Flexural Strength)

2.5.2. Mechanical Properties Test

The mechanical properties test, which included the Modulus of Elasticity (MOE) and the Modulus of Rupture (MOR), was conducted in compliance with ASTM D1037 utilising a universal testing equipment with a 600 kg capacity.



Plate 7. Flexural Test on UTM Machine

3. Results and Discussion

3.1. Physical Properties

Density

The produced composite density, the samples vibrated for 6 minutes recorded the highest average of 1863 kg/m³, while those without vibration had the lowest average of 1662.9 kg/m³. This indicates that mechanical vibration significantly improves particle packing and compaction, thereby increasing density. It was noted that as the vibration time increases there is an increase observed in the density of the

composite boards, though samples with higher sawdust content showed slightly lower values overall. This inverse relationship between fibre content and density agrees with the understanding that organic fillers are less dense than cement matrix materials, as emphasized by [11]. Proper vibration, as applied in this study, allowed for more uniform slurry compaction and minimised entrapped air, leading to denser, more consolidated boards.

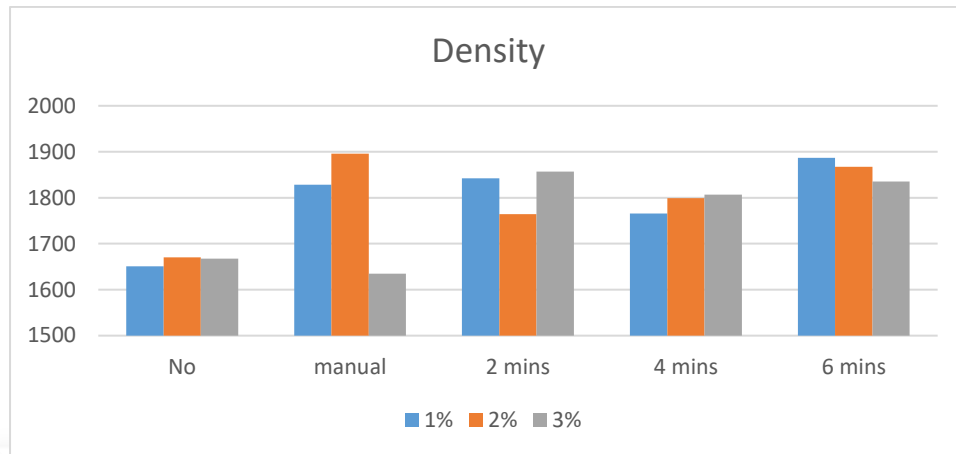


Figure 11. Densities of samples treatments with different vibrations

Water absorption

Samples subjected to vibration (2 minutes, 4 minutes, and 6 minutes) generally exhibit lower water absorption compared to samples with no vibration or manually vibrated. This suggests that vibration reduces the composite tiles ability to absorb water over time. Longer vibration durations (e.g., 6 minutes) do not consistently result in lower water absorption compared to shorter durations (e.g., 2 minutes). For example, at 1% *Cola nitida* sawdust composition, 2 minutes of vibration (Sample G: 4.88% at 2 hours, 5.30% at 24 hours) shows slightly lower absorption than 6 minutes of vibration (Sample M: 5.16% at 2 hours, 5.34% at 24 hours). This indicates that vibration duration does not have a linear relationship with water absorption reduction. In addition, all samples show an increase in water absorption from 2 hours to 24 hours, indicating that water absorption is time-dependent. However, the rate of increase is generally lower for vibrated samples.

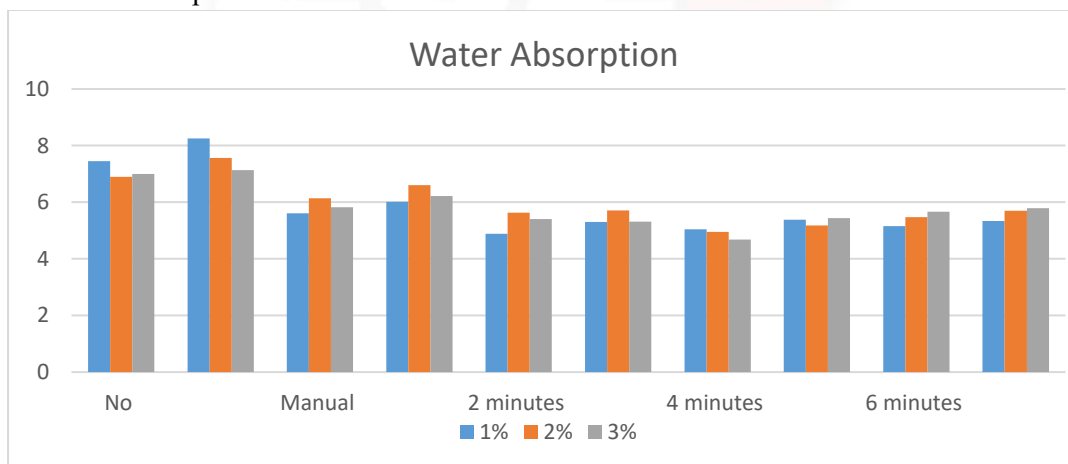


Figure 12. Water absorption of samples treatments with different vibrations

Thickness swelling

Samples subjected to vibration with the fabricated vibration table (2 minutes, 4 minutes, and 6 minutes) showed lower thickness swelling (0.3%) compared to samples with no vibration (0.5%) and samples manually vibrated (0.4%). This indicates that vibration reduces thickness swelling in the composite tiles. Although it was observed that the duration of vibration (2 minutes, 4 minutes, or 6 minutes) does not affect the thickness swelling, as all vibrated samples show the same thickness swelling (0.3%) regardless of the duration, this suggests that even short durations of vibration are sufficient to minimize thickness swelling.

It was also observed that *Cola nitida* sawdust composition (1%, 2%, or 3%) does not influence thickness swelling under any condition as all samples within a given treatment group (no vibration, manual, or vibrated with the vibrating table) show the same T.S%, regardless of composition. In addition, thickness swelling remained constant between 2 hours and 24 hours for all samples, indicating that swelling stabilizes within the first 2 hours and does not increase over time.

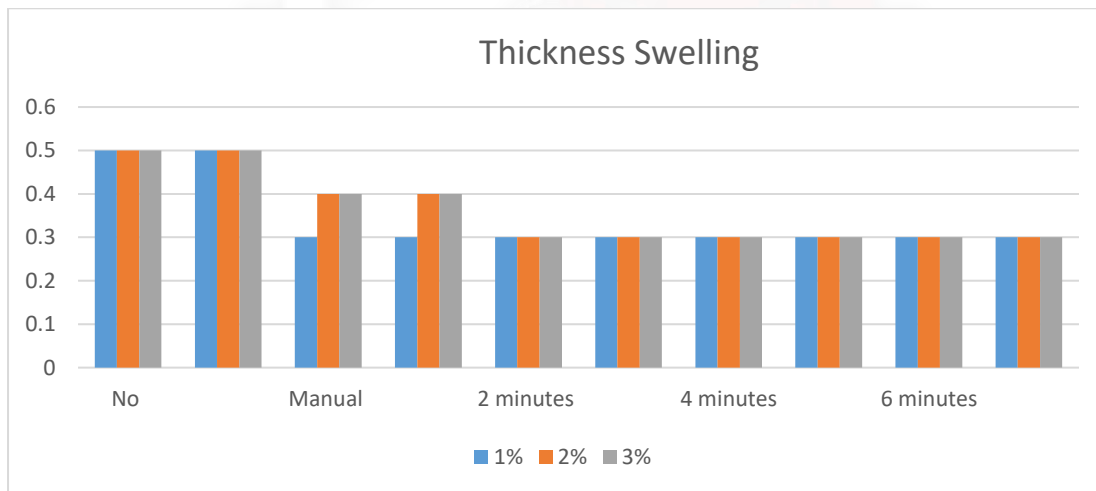


Figure 13. Thickness swelling of the sample treatments with different vibrations

Porosity

There is around 20% trapped air in the slurry in the mould prior to vibrating. In order to strengthen the bond strength and reduce concrete permeability, vibration first compacts and consolidates the concrete particles. Next, it removes trapped air and weak places. By rearranging aggregate particles, the pressure waves produced by the vibration lessen friction between them. Large spaces, or honeycomb, were therefore removed. According to [12], compressive strength is reduced by roughly 3% to 5% for every percent of air in the slurry when the water to cement ratio is kept constant. In contrast to the vibrated samples, this was also seen in the samples within the group (no vibration, manual). By solidifying the concrete composite, the vibrating process improves the mechanical properties of the samples.

3.2. Mechanical properties

The modulus of elasticity (MOE) increased significantly with vibration, peaking at 247.24 GPa in the 6-minute vibrated samples with 2% sawdust composition. Samples with no vibration had the lowest MOE (90.78–104.04 GPa), revealing the impact of vibration on stiffness. Vibration promotes fibre alignment and stronger fibre matrix bonding, which are critical for stiffness in composite systems. It was also observed that MOE increased with vibration time, though not linearly across fibre contents. This

reinforces the idea that optimal vibration helps eliminate voids, reduce fibre agglomeration, and enhance internal structure, all of which contribute to improved elastic response. The modulus of rupture (MOR) followed a similar pattern, reaching its highest value of 727.82 MPa at 6 minutes of vibration and 2% fibre composition. This demonstrates enhanced bending resistance due to improved matrix cohesion and fibre dispersion. Samples without vibration yielded the lowest MOR values (427.04–492.90 MPa), highlighting the effect of voids and weak fibre-matrix interfaces. The slight dip in MOR observed at 4 minutes (e.g., 588.78–617.11 MPa) may be linked to inconsistencies in machine performance or fibre clumping. As supported by [13], uniform compaction is essential in reducing stress concentration zones and improving load-bearing capacity in fibre-cement composites.

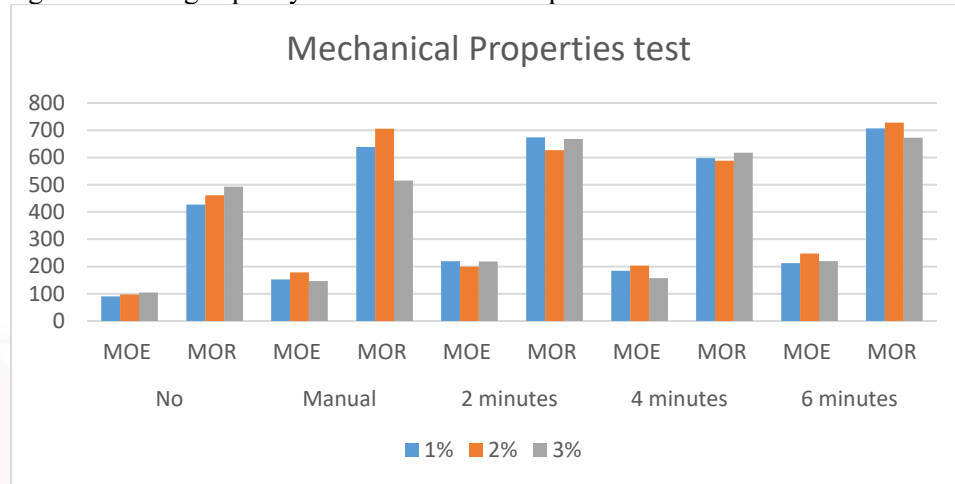


Figure 14. Mechanical properties of the sample treatments with different vibrations

4. Conclusion

In accordance with fundamental engineering concepts, a cement composite roof tile vibrating machine with ten of moulds of 50 x 30 x 0.6 mm that is operated both manually and electrically and can support a load of 100 N at an amplitude of 0.4mm and a frequency of 1500 rpm was developed. On average, it could produce roughly 1020 Roman tiles every hour. The developed vibrating table produced tiles with better qualities compared to the conventional tiles by significantly increasing the rate of production, improving compaction, and removing voids.

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Developing Sustainable Forest Practices for Bio-material Production to Serve as Alternative for Industrial Growth

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Abstract: The rapid depletion of wood resources due to continuous harvesting and deforestation has necessitated the exploration of alternative materials to support industrial growth. This paper examines the potential of bio-materials, particularly bamboo, as viable substitutes for wood in industrial applications, highlighting the role of sustainable forest practices in their development and utilization. Bamboo, with its fast-growing rate, high strength properties and versatility, offers an eco-friendly and cost-effective alternative to wood products. However, its industrial adoption in Nigeria faces challenges such as inadequate processing equipment, limited local innovation and low awareness of its economic potential. Reflected in this paper is the importance of sustainable forest practices to ensuring the availability of bio-materials while preserving biodiversity. It also emphasizes the need for localized equipment development and skills training to overcome barriers to efficient bio-material production. By integrating sustainable forest practices with innovative equipment and policy support, The State can unlock the industrial potential of bio-materials, reduce deforestation and drive economic growth. This paper can serve as a framework for stakeholders to advance sustainable forestry and bio-material development as key pillars of a resilient and green industrial future.

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1. Introduction

The dearth in the volume of wood available for structural and non-structural application has become a cause of worry for investors to the fate of wood supply in future. When harvesting wood from the forest, little or no attention is given to non-wood products such as bamboo amongst others as it is often disregarded and destroyed [1]. Incessant deforestation has caused considerable reduction in the quantity of wood available for large scale production of wood merchandise [2] which had led to a mandatory necessity to augment wood with materials such as bamboo and the likes [3]. It is pertinent, that to achieve a sustainable solution to the above stated challenges requires a collaborative effort. Stake holders, researchers and industries must come to a round table, playing a part to improve the economy.

The adequate utilization of bio-materials such as bamboo, rattan, and others to serve as supplement for wood and other industrial purposes in Nigeria is hindered by the unavailability of equipment to process them [4]. Though there is an increasing demand for their products, they remain the difficulty to meet these needs. It is particularly worse for small scale operators in Nigeria with the negative impact of harsh economy on the sector. Yet the necessity for products manufactured from these alternatives to wood is not diminishing. Consequently, developing the local capacity for these bio-materials through sustainable forest allocation and practice, development research, training of personels, design and fabrications of machines are many ways to mitigate the cost inflicted dislocation in the area and foster a growing economy.

1.1 An Overview of Bio-materials

Bio-materials are materials designed and developed to interact with the human body. They are bioactive materials and easily interact biologically. These materials are generally biodegradable and reduce carbon footprint when used for production. Example of forest bio-materials aside wood are bamboo, rattan, and other non-woody plants. With the current depletion in the nations wood resources, it is critical to look at alternatives with special attention to bamboo growing and developments.

2. Bamboo

Bamboo is the common name for member of a particular perennial, giant, woody grass belonging to the group angiosperms and the order monocotyledon, of the sub-family of bambusoideae. It is made up of about 1,200 species within 50 genera [5,6]. Pandey and Ashby [7,8], Bamboo has a fast growth rate of 4-6 years of planting to reach maturity with a growth rate of 4 feet a day [9,10,11]. According to Anokye et al. [12] bamboo height ranges from a few centimeters to over 30 meters, with a stem (culm) diameter of 3 mm to over 25 cm. Bamboo occupies a total area of approximately 36 million hectares of land which is 3.6% the average total forest area of the world. It is naturally found in the tropical and subtropical zone and originating from countries in Asia; India, China, Indonesia, Myanmar and Vietnam [13]. In Africa, the total bamboo area is about 2.7 million hectares or 7% of the total bamboo area in the world (Fig 1), with about 40 species including *Arundinaria alpine*, *Bambusa vulgaris* and *Oxytenanthera abyssinica* [14,15]. Among these, *Bambusa vulgaris* is indigenous to Nigeria.

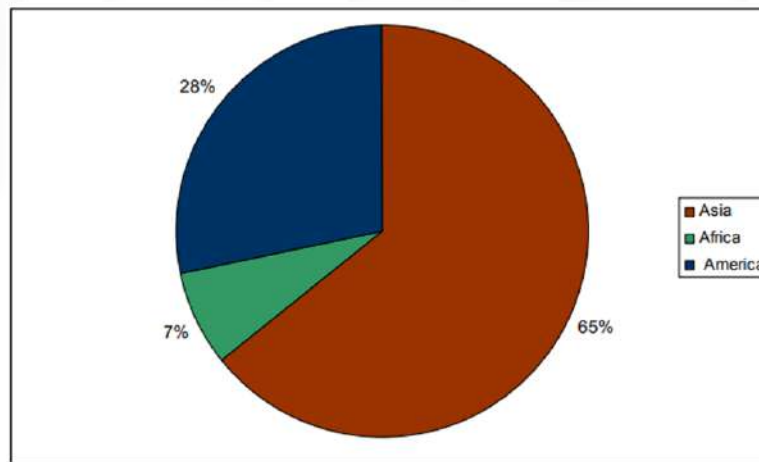


Fig 1: Contribution of world bamboo resources by continent Source: [15]

2.1 Bamboo Utilization

Bamboo has been reported to be among engineering materials ever used by mankind [9,2]. In previous times, the use of bamboo in its crude form applied only for yam staking, fence making, handcrafts, improvise local beds, studs, scaffolding and similar applications. But recently, several applications are reported in many developed countries such as China, Japan and Asian continents [16,17,18,19]. Bamboo is deployed for utilization as a supplement of wood in structural and furniture making industries [3,20,11]. In India, more than 30 types of bamboo panel products exist, some of bamboo only and others of bamboo in combination with wood, other lingo-csellulosic materials and inorganic materials have been developed [21]. Developing countries such as Nigeria are not left out in the recent developments and research work aimed at harnessing bamboo for different innovative products, even though the process is slow.

[22] discussed the use of bamboo for environmental restoration by applying it in a variety of purposes including furniture making. The proper harnessing of bamboo if not hampered, will afford alternative viable source of income and enterprises for large, medium and small-scale entrepreneurs including the rural poor. [23] discussed the growing rate of bamboo development and its application as an engineering material in the construction industries of developing countries. The report recorded twelve other avenues to which bamboo can be applied for constructional purpose with recommendation to create awareness. The afore mentioned studies are similar to that carried out by [24] in Beijing Forestry University, China. In their work, they detailed the potential of bamboo as a source of income and better livelihood for rural communities. The significance of bamboo from a universal standpoint, giving particular consideration to its economic, social and ecological values, was discussed. Observations were that bamboo is very abundant, known all over the world, and use in countless application. According to the reports, it is a profitable business that could liberate rural dwellers from poverty if adequate skills and good business marketing values are applied.

2.2 Bamboo in Nigeria

In Nigeria, research has shown that bamboo is widely distributed throughout the country. Results of findings by INBAR [25], Onilude [6], Ogunwusi and Onwualu [26] prove the extensive availability and distribution of *Bambusa vulgaris* in Nigeria. According to Ogunwusi and Onwualu [26], Ogun, Oyo, Osun, Ondo, Edo, Delta, Rivers, Akwa-Ibom, Cross-River, Abia, Ebonyi, Enugu, Anambra and Imo States have high percentage distribution of about 10% of natural vegetation while the least found state in the country are around 3% of natural vegetation (Fig 2). According to Adewole and Bello [27], *Bambusa vulgaris* Schrad is an open-clump type of bamboo species that matures between 3-4 years. Recorded reports of Anon [28], Bansal and Zoolagud [29], Xiaobo [30], Adewole and Olayiwola [31] present *Bambusa vulgaris* as suitable for the production of innovative items for both commercial and domestic use. *Bambusa vulgaris* is also reported to share excellent properties such as adequacy of strength, versatility and beauty in both natural and finished states with wood [32,33,13], making it an adequate substitute in producing household items to enhance rural livelihood in a developing country like Nigeria [17].

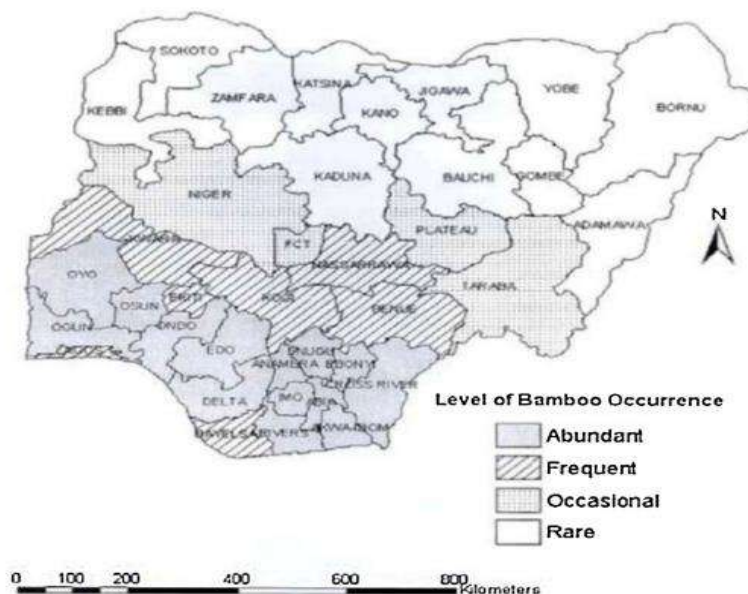


Fig 2. Nigeria Map indicating levels of Natural Bamboo Distribution **Source:** [1].

3. Engineered Bamboo

Engineered (mostly laminated) bamboo is a recent concept-based material used in developed countries for furniture making, floor tiles, balustrades, and decorative crafts [34]. It is one amongst the over 1,500 industrial applications and uses of bamboo [26]. The utilization of bamboo for industrial purpose is limited by its circular shape and hollow form dimensions. Hence the need to convert bamboo into laminated board to meet many service requirements especially for furniture [35]. This involves gluing together of bamboo strips to form rectangular boards by flattening bamboo culms and gluing them in masses to form a bonded composite similar to that of laminated lumber [36,35]. The absence of chemical extractive in bamboo as is with wood makes it easy to be glued together [37,34]. The finished product of bamboo laminates, take the form and shape of planks and beams depending on the producer's desire. Different researchers have investigated on the techniques for processing bamboo [36,38,35,39].

There are various studies on bamboo laminate reported in literature across the world. An estimated number of 28 laminated bamboo products that merge wood and other organic materials have been reported [40,12]. One of the first recorded work on bamboo laminate was in 1989 when Chu, in his article titled "Bamboo board" and described a product that was similar in layup to plywood. Other published works examined the prospective of substituting bamboo laminate in place of wood because of its availability and excellent properties [12,34]. Lin [19] researched on how to make use of bamboo laminate, showing the characteristics of bamboo laminate, and exploring ways of the development of new composite material design. In Indonesia, Sulastiningsih and Nurwati, [35] reported that bamboo laminates provide an alternative to wood in appearance when used for furniture, interior design and as a building material. American researchers, Mahdavi et al. [34] recommended bamboo as economically, environmentally, and structurally beneficial to use as a wood alternative.

Developing countries such as Ghana and Kenya have recorded research on the performance of laminated bamboo [14,34]. It is not a different case in Nigeria as studies of bamboo and the use of bamboo laminate revealed that it is indeed suitable for the production of innovative items for both commercial and domestic use [31,26,27]. Laminated bamboo has been affirmed by researchers to be limited in use by nothing. It can be used for chairs, desks and other furniture. In fact, it can be utilized as efficiently as laminated wood, with the advantage that bamboo laminates are much lighter in weight and the manufacturing process is much the same as for conventional plywood [40,42,5,12]. According to Correan et al., [43] and Pereira and Faria [44] the manufacture of Bamboo laminate can be summarized as present in Fig 3 and 4.

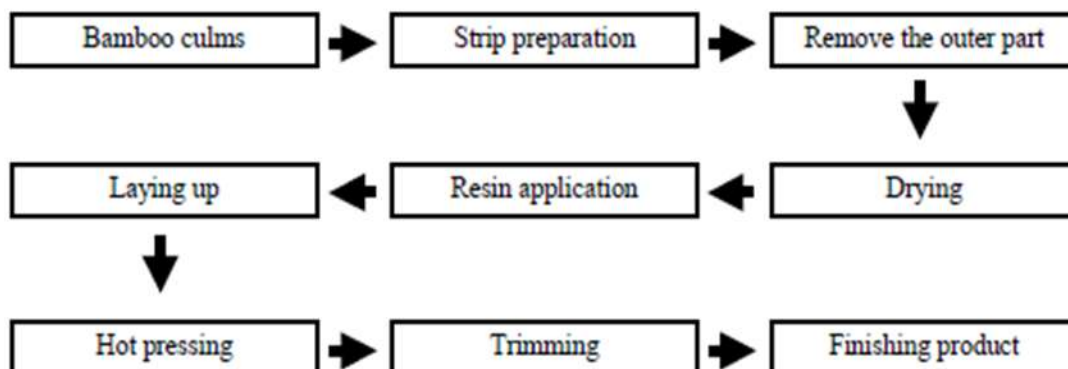


Fig 3: The Flow Chat of Bamboo Laminate Production. Source: [45]

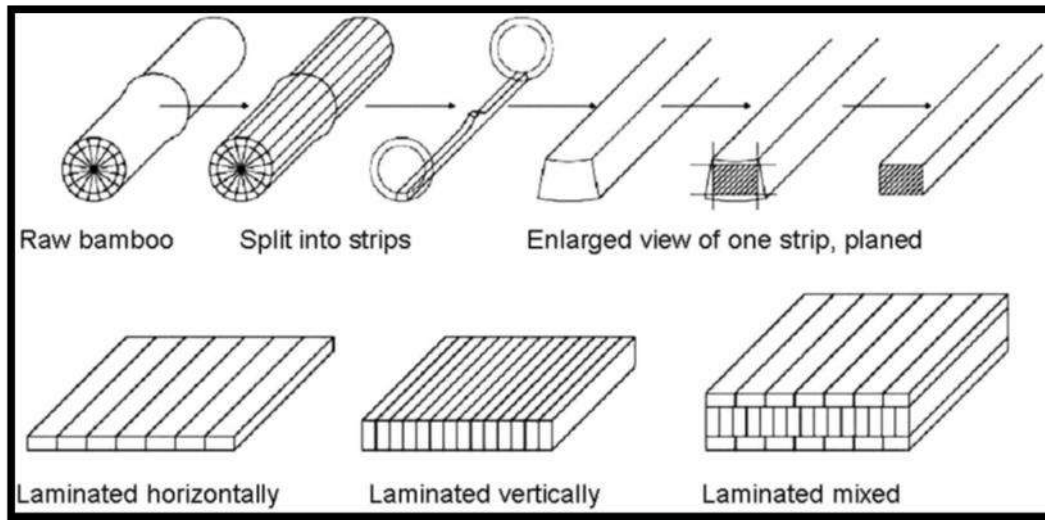


Fig. 4: Manufacturing process of laminated bamboo lumber using bamboo strips Source: [14]

3.1 Strength Properties of Engineered Bamboo

Bamboo laminates strength properties must be investigated for the laminate to serve as a structural material. The strength properties of bamboo laminate are affected by various parameters surrounding the production of the laminated bamboo board such as: species of bamboo used, type of glue or adhesive, number of layers for the bamboo board and treatment among others [35]. Several reports on the strength properties of bamboo laminates abound by scholars. [35] investigated the physical and mechanical properties of *Gigantochloa apus* and *Gigantochloa robusta*. The results showed that strength properties of bamboo decreased as number of layers increased. The bonding capacity was higher in *G. robusta* than *G. apus*, and the boards were suitable for furniture production, interior design and building materials. [10], analysed the tensile strength properties of *Dendrocalamus strictus* bamboo laminate. The test results obtained showed resemblance to the properties of teak wood and could apply for beams and column among other building materials.

Pande and Pandey [46] documented the strength properties of different tested bamboo composites board researched by the Indian Plywood Industries Research and Training Institute (IPIRTI) from 1983 to 2008. Stating the significance of successful commercialization of those products in India. Chaowana et al. [45] determined the strength performance of bamboo laminate (*Dendrocalamus sericeus*) to ascertain its bonding properties and suitability as raw material use for manufacturing. The conclusions on this report did not clearly state the suitability or non-suitability of the produced bamboo laminates. Echavarria et al., [47] investigated the mechanical performance of glulam beams reinforced by bamboo in order to improve the flexural strength and ductility of glulam beams. The results showed that considerable improvements in strength and stiffness were obtained.

Developing countries such as Ghana and Kenya have recorded research on the performance of laminated bamboo under point load with results that its flexural strength was higher and showed better load carrying capacity than its cypress beams counterpart and also when used also in carvings [14,34]. Adewole et al. [2], investigated the suitability of producing parquet laminate from *Bambusa vulgaris* Schrad harvested in Nigeria. Laminated bamboo was subjected to test and properties documented. Table

1 to 3 show Strength Properties of Bamboo Laminates from different researchers. Continuous research in the strength properties and utilisation of bamboo is necessary to improve and foster its development.

Table 1: Physical and mechanical properties of laminated bamboo boards

Property	A ₁		A ₂		ANOVA		
	B ₁	B ₂	B ₁	B ₂	A	B	AB
MC (%)	13.07 (1.16)	13.68 (0.34)	12.81 (1.57)	12.67 (0.71)			
Density (g cm ⁻³)	0.75 (0.01)	0.75 (0.01)	0.71 (0.02)	0.72 (0.03)	**	ns	ns
TS (%)	2.47 (0.29)	3.00 (0.74)	4.08 (0.69)	3.75 (0.68)	*	ns	ns
LE (%)	0.11 (0.01)	0.17 (0.02)	0.07 (0.01)	0.10 (0.01)	ns	ns	ns
MOR (kg cm ⁻²)	969.39 (94.04)	462.44 (53.22)	895.34 (123.46)	393.68 (47.59)	ns	**	ns
MOE (× 10 ³ kg cm ⁻²)	102.29 (8.14)	96.77 (8.53)	100.03 (4.97)	74.10 (10.84)	ns	**	ns
CS (kg cm ⁻²)	564.79 (66.39)	518.76 (16.04)	571.98 (51.40)	503.17 (35.58)	ns	*	ns
BS (kg cm ⁻²)	40.77 (3.64)		55.82 (4.39)				
Delamination (cm)	0		0				

Each value was the average of four specimens except for bonding strength which had eight specimens. Numbers in parentheses represent one standard deviation; MC = moisture content; TS = thickness swelling; LE = linear expansion; MOR = modulus of rupture; MOE = modulus of elasticity; CS = compression strength; BS = bonding strength; A = bamboo species; A₁ = *Gigantochloa apus*; A₂ = *G. robusta*; B = number of layers; B₁ = three layers; B₂ = five layers; ns = not significant; * = significant at p < 0.05 ; ** = highly significant at p < 0.01.

Source: Sulastiningsih & Nurwati [35]

Table 2: Properties of some bamboo panel products Source: Anokye *et al.*, [12]

Types of bamboo product	Density (kgm ⁻³)	MOR (Nmm ⁻²)	MOE (Nmm ⁻²)
Bamboo Mat board (India)	766	51	3678
Bamboo Mat board (China)	850	93	na
Bamboo Curtain board (China)	850	121	12500
Bamboo Strip board (Vietnam)	815	124	9600
Bamboo Strip board (China)	780	113	na
Bamboo Parallel glulam (China)	850	167	11500

Note: na = not available

Table 3: Strength Properties of some bamboo Laminates

Source: Pandey [7]

Property	Vertical laminate			Horizontal laminate (MUF)
	UF	MUF	PF	
Density (kg m^{-3})	728	745	796	782
MOR (N mm^{-2})	122.5	149.1	145.2	164.4
MOE (N mm^{-2})	12028	16570	16800	17300
Compressive strength (N mm^{-2})	61.7	84.7	96.0	87.9
Block shear strength (N mm^{-2})	11.89	12.8	12.7	9.65
Screw withdrawal strength (N)				
Face	4,999	4,006	4,683	3,235
Edge	2,333	3,659	3,216	5,375

4. Sustainable Forest Practices

The need to examine various strategies that support the sustainable production of bio-materials in Cross River State which are viable substitutes for wood resources in industrial applications are discussed. It is necessary for governments, academics and industries to find their role and contribute collaboratively to the development of the state.

4.1. Forest Allocation and Management Strategies

The state should allocate her land, implementing controlled harvesting and regenerative planting cycles to balance resource extraction with forest replenishment. Management practices such as selective harvesting and rotational planting particularly of fast-growing species like bamboo, ensuring that harvested areas regenerate quickly and remain productive. Furthermore, afforestation and reforestation efforts help to restore depleted forest areas, increasing the availability of bio-materials while improving the ecosystem.

4.2 Conservation Techniques

Industries in collaboration with forest management agencies and researchers can collaborate to develop sustainable techniques and conservative methods to maintain forest health. This will prevent soil degradation and support essential bio-material production. Soil management techniques such as erosion control and controlled burning if implemented will maintain soil quality and help plantation to thrive. In areas where bamboo is planted, controlled clearing and selective removal of mature stalks will allow younger shoots to flourish, ensuring endless supply of resources without depletion. Adequate soil monitoring is a necessary practice that informs the management of nutrient levels and manage or completely mitigate erosion.

4.3 Policy and Regulatory Support

Government policies and regulatory frameworks will go a long way to enforce sustainable forestry practices and encourage the use of alternative bio-materials. Effective policies and support from the Government can foster responsible harvesting practice and incentivize the cultivation of bio-materials such as afore discussed. The Cross River State Government by introducing policies that promote bio-material production could mitigate pressures on wood utilization and reduce deforestation. Government subsidies, tax incentives, and grants for sustainable forest management can drive industry compliance

and stimulate investment in bio-material, contributing to industrial growth in an environmentally friendly way.

4.4 Community Involvement

Community engagement plays a pivotal role in promoting sustainable forest practices. In Nigeria, where local communities often depend on forest resources for their livelihood, their involvement in sustainable practices will foster stewardship and ensure long-term forest viability. This could be achieved by offering training and incentives, communities can be empowered to manage bio-materials like bamboo in a way that benefits both their local knowledge of sustainable harvesting techniques and fosters a culture of conservation, where forests are seen as renewable sources for economic advantage.

5. Equipment Development

The development and availability of appropriate machinery for processing bio-materials like bamboo is crucial to realizing their potential as sustainable industrial resources. In Nigeria, the lack of specialized equipment poses a barrier to efficient bio-material production, particularly for small scale producers who could benefit most from bamboo and similar alternatives. It is therefore imperative to discuss the equipment required, local innovation possibilities and the importance of skills training in supporting sustainable bio-material industries below.

5.1 Current Equipment Limitations

In Nigeria, bamboo processing machinery is often unavailable or cost prohibitive, limiting the country's capacity to fully utilize bamboo and other bio-materials for industrial purposes. Traditional equipment used in wood processing is generally unsuitable for bamboo, as bamboo's hollow, cylindrical structure and unique fiber composition requires specialized machinery. Furthermore, the cost of importing and maintaining advanced processing equipment is prohibitive, especially for small and medium enterprises (SMEs) looking to enter the bio-material market.

5.2 Types of Equipment Needed for Bio-material Production

Several types of machinery are essential for processing bio-material at an industrial scale. For bamboo, this includes debarking machines, splitters, slicers and lamination presses to process bamboo into viable forms such as laminated boards and panels. These machines allow bamboo to be converted into standardized sizes and shapes suitable for structural application, furniture product, and other uses. Drying and treatment units are also needed to enhance bamboo's durability, making it more resistant to pests, moisture and environmental attacks.

5.3 Local Innovation and Manufacturing

Developing indigenous equipment tailored to the specific needs of Nigeria's bio-material industry could provide a cost-effective alternative to expensive imported machinery. Partnership between local universities, research institutions and industries could foster innovation, resulting in affordable, durable and efficient machinery for bio-material production. For instance, machines specifically designed for bamboo processing could be manufactured locally using readily available resources, reducing costs and dependence on imported machinery. This approach could create employment opportunities and strengthen Nigeria's industrial base.

5.4 Training and Skill Development

Even with access to appropriate equipment, skilled operators are essential for effective and safe machinery use. Training programs focusing on equipment operation, maintenance and safety are vital to building a sustainable bio-material industry in Nigeria. Collaboration with educational institutions such as University of Cross River State, Calabar and the University of Calabar, vocational training centers such as Calabar Technology incubation Centre and West African Construction and Fabrication Academy, Calabar can provide the technical knowledge required to operate and maintain bamboo processing machinery, ensuring quality production and extending the lifespan of equipment. Additionally, ongoing skill development initiatives can adapt to technological advancements, maintaining Cross River's competitiveness in bio-material production.

5.5 Future Prospects and Recommendations

Going forward, several actions can help fully integrate bio-materials into Cross River's industrial sector:

- i. **Increased Research and Development:** Continued research into bio-material properties, such as bamboo's strength and durability, can unlock new applications and enhance its competitive advantage over traditional wood.
- ii. **Enhanced Policy Support:** Government policies that promote sustainable forestry, provide subsidies for equipment development, and incentivize local production of bio-material products can drive industry growth.
- iii. **Public Awareness Campaigns:** Educating consumers and industries on the environmental and economic benefits of bio-materials like bamboo can increase market demand, encouraging more investment in bio-material production.
- iv. **International Collaboration:** Collaborating with countries with established bio-material industries, such as China and India, can facilitate technology transfer, knowledge exchange, and joint research opportunities, accelerating Nigeria's bio-material industry.

6. Conclusion

The potential of bio-materials like bamboo to serve as sustainable alternatives to traditional wood products offers an exciting pathway for industrial growth in Cross River State and Nigeria at large. Sustainable forest practices, combined with the development of suitable equipment and effective community involvement, can transform the bio-material sector into a cornerstone of Nigeria's sustainable industrial future. It requires a unified approach among stakeholder – governments, institutions, communities, and industries to prioritize sustainable forest practices and invest in equipment and skills for bio-material processing. Nigeria can build a robust bio-material sector that reduces deforestation, supports local economies, and contributes to a sustainable, greener future. It is essential for all stakeholders to commit to this vision, as it holds the promise of both economic resilience and environmental sustainability for generations to come.

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Track B:

Environmental Sustainability and Scientific Innovations for a Digital Economy

Waste management and Public Health in Nigeria: A Study of Ebonyi State Environmental Protection (EBSEPA) Activities in Selected Towns

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Abstract: This study evaluates the impact of public administration on the operational effectiveness of the Ebonyi State Environmental Protection Agency (EBSEPA) in managing solid waste across five major towns in Ebonyi State. Increasing urbanization, population growth, and escalating waste generation, prompted the research in identifying major gaps in infrastructure, policy implementation, and public engagement in the agency's waste management activities. The study adopts a human capital theoretical framework and utilizes a stratified survey method to assess types of waste generated, level of community awareness, availability of waste infrastructure, and health implications of poor waste disposal. The findings reveal that although EBSEPA is moderately effective in urban centers like Abakaliki, faces significant operational deficiencies in rural and semi-urban areas due to inadequate infrastructure, poor enforcement, and low public awareness. Indiscriminate dumping and limited health surveillance contribute to respiratory, waterborne, and vector-borne diseases across the state. The study concludes that strengthening public administration through decentralization, funding, public education, and community inclusion is critical to enhancing EBSEPA's performance and achieving sustainable environmental governance in Ebonyi State.

Keywords: Public administration, waste management, environmental protection, EBSEPA, health implications

1. Introduction

Today, due to rapid industrialization, increase in population and urbanization, the generation, disposal or management of waste has proved to be a major environmental and public health issue. Urban waste management today has become an intractable environmental problem that can be likened to a monster staring everybody on the face. The unprecedented rapid increase in human population created several environmental problems leading to growing concerns with wide range effect on social behaviour, economy and overall developmental efforts. In Nigeria today, between the pressing environmental and public health issues are the problems of solid waste generation, control and disposal. Although the problem of solid waste disposal is as old as man's existence that is inextricably linked to the generation of waste, the truth is that in many cities, it has become so intractable that even the government is overwhelmed [1]. For Onwughara et al., [2], Urban Solid Waste (USW) covers a broad range of materials including garbage, refuse from factories, commercial refuse, construction and demolition debris, dead animals and abandoned vehicles, food particles, plastics, bottles, polythene material (nylon bag), metallic objects, furniture/wood material, paper and some other unclassified wastes. Rodgers [3] submits that waste management is a systematic control of the generation, storage, collection, transportation, separation, processing, recovery and disposal of waste.

Waste management remains a critical challenge in many developing regions, including Ebonyi State, Nigeria. The gory sights of solid waste dumped in parts of our public space tends to destroy the aesthetics

(beauty) of the environment, and affected the people's health when decomposed to produce provoking odour or contaminating our drinking water. This no doubt, causes avoidable epidemics. This prompted the federal government of Nigeria to promulgate decree 58 for the establishment of Federal Environmental Protection Agency (FEPA) on 30th December, 1988 [1], and the National Policy on Environment formed to secure for all Nigerians a quality of environment adequate for their health and well-being Momodu et al. [1].

Prior to the creation of Ebonyi State in 1996, Abakaliki urban was faced with myriad of environmental problems ranging from inadequate environmental education and awareness campaign to poor personal and environmental hygiene. Every street was adorned with heaps of refuse while rivers, in Abakaliki urban were converted to dumping arena for domestic wastes and human excreta [4]. Generally, in Ebonyi State, environmental degradation resulting from land, forest and water have been reported, resulting in persisting poor crop yield from cultivated lands, disappearance of forests and forest resources; water bodies and sometimes salination of drinking water [5]. It was in response to the foregoing realities, that Ebonyi State government set up the Ebonyi State Environmental Protection Agency (EBSEPA) on 6th December, 1996, to clean, protect and conserve the environment. While it cannot be denied that for quite some time, Ebonyi State Environmental Protection Agency (EBSEPA) has always embarked on some routine clearance of waste, especially in the capital city (daily, weekly and monthly), the intractable nature of urban wastes always noticeable in Abakaliki urban leaves much to be desired. This has been the reason why the commonly repeated experience is a simple transfer of refuse from one point to another in open trucks to some undesignated sites where they are either burnt or buried [2] and, [6].

The problem of solid waste generation, control, especially, disposal or simply, management, has continued to be a threatening global and environmental health issue but more pronounced in Nigeria's major urban centres caused by indiscriminate heaps of solid wastes from the environment. This is despite the continuous government and individual efforts including daily, weekly or monthly environmental sanitation. Waste disposal habit of the people, lack of experienced and skilled manpower, inadequate/lack of modern plant and equipment, among others, militate against any waste management effort/strategy in Nigeria, particularly in Ebonyi State major towns. The areas of Abakaliki, Afikpo, Ishiagu, Ishieke, and Uburu have witnessed increasing health complications linked to indiscriminate waste disposal. This study investigates the extent to which the Ebonyi State Environmental Protection Agency (EBSEPA) curtails the tide of indiscriminate waste dumps in these areas and proposes actionable solutions to enhance its effectiveness.

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1.1 EBSEPA and public administration activities

Solid waste management is an integral part of public administration with successive Governments in Nigeria applying different approaches in a bid to eradicate the scourge [7]. The agency responsible for

waste and refuse management, and sanitation in Ebonyi State is EBSEPA. Public administration plays a crucial role in the management and operations of environmental protection agencies like the EBSEPA whose functions include policy formulation, implementation, regulation, and oversight, all aimed at ensuring sustainable environmental management, resource allocation, and regulatory enforcement. Empirical evidence underscores the significant influence of public administration on EBSEPA's activities through legislative supports, resource allocations, regulatory enforcements, inter-agency collaborations, and public engagements. Public administration shapes the effectiveness and reach of EBSEPA's environmental protection efforts in Ebonyi State by providing empirical studies into these relationships [7,8].

Therefore, the main objective of the study was to assess the impact of public administration on the activities of Ebonyi State Environmental Protection Agency (EBSEPA) in five towns in Ebonyi State. Specifically, the study investigates the types of waste generated and their composition, EBSEPA strategies on waste management, and the extent of indiscriminate solid waste disposal/dumps on health complications suffered by the people in these areas.

Research questions and hypothesis: The research questions for the study are:

- i. What are the types and composition of waste generated in these areas?
- ii. What are the strategies and provisions of Ebonyi State Environmental Protection Agency (EBSEPA) on waste management in the State?
- iii. What extent does indiscriminate solid waste disposal/dumps contributed to health complications suffered by the people in these areas?

The following research hypotheses were put up for analysis:

- i. The types and composition of waste generated affects the roles of EBSEPA in these areas.
- ii. The strategies and provisions of EBSEPA on waste management are adequate.
- iii. Indiscriminate solid waste disposal/dumps contributed to health complications suffered by the people in these areas

This study is beneficial to State government by documenting the perceptions of public administration in solving environmental problems, which is useful for environmental policymaking and implementation, the host communities, and every other stakeholder in the waste management industry and contributions to improve the social and health wellbeing of the people.

1.2 Conceptual and empirical reviews

The relationship between humans and nature was transformed from one based on responsibility, restraint and reciprocity to one, based on unrestrained exploitation. This exploitation of nature according occurs in two phases; the first phase occurs when nature's wealth was considered freely available and the second phase occurs after rapacious exploitation has created degradation and scarcity [9]. The management of natural resources only became important in order to maintain continued supply of raw materials for commerce and industry. As the limits of nature's ability to renew is violated, real scarcity is created, soils loose fertility, forests disappear, water and air are polluted. From this analysis, most problems of environmental degradation are natural disasters caused by man in his attempt to create limitless growth and consumption.

Nigeria's environment is facing increasing threats from natural disasters, like desertification, drought, erosion, and flooding, all of which are exacerbated by human activities. There are visible signs of

environmental degradation in the depletion and pollution of the natural resource base including land, forest, and water upon which all life depends. Traditionally in Ebonyi State people settled along riverbanks, because the lands were fertile, rivers were sources of aquatic foods and rivers afforded them some kind of protection from invading enemies. There were rules on how to protect rivers from pollution including prohibiting farming near rivers, use of masquerades and people to guard springs during dry seasons, prohibiting washing cloths directly in the streams and prohibiting the use of gamalin 20 poison for fishing. Today natural water sources are polluted; streams and rivers are silting up and most drinking water sources taste salty. The impact of these activities includes salination of the soil, pollution of the rivers and wells making them unsafe for drinking.

The rapid urbanization and lack of adequate waste management infrastructure in Ebonyi state have led to the accumulation of waste in urban areas, posing serious health and environmental risks. The Ebonyi State Environmental Protection Agency (EBSEPA) plays a pivotal role in managing waste and mitigating its adverse effects. However, challenges persist that hinder its efficiency and interventions.

1.3 Framework for analysis

Human capital theory proposed by Arthur Lewis in 1954 was used as framework for analysis [10]. Human capital is directly related to human development and effective and efficient uses of the wealth of nation, and so, where there is human development, the qualitative and quantitative progress of a nation or any part thereof is inevitable. According to this theory, the principal source of productive capacity rests in the capacity of the people. The theory was relevant to this study in that it was an avenue to open new vistas in making environmental resources less harmful and more useful through proper management. It also uncovered the reasons for the dismal performance of government even through EBSEPA operations. This will surely give room for concerned stakeholders in environmental policymaking and implementation to fashion out new strategies that would be adopted.

2. Method

2.1 Research design

Survey research method was used in this study for it is suitable for gathering precise information and drawing possible conclusions from the analysis of the information. It enables the selection of population samples and discovery of relative incidence distribution and interrelations of variables as evident with suitable findings.

2.2 Study areas and sample size

This study focused on five (5) towns of Abakaliki, Afikpo, Ishiagu, Ishieke, and Uburu among the towns in Ebonyi State. The population of the study comprise of the entirety of the people that make up the towns and communities within the local government. For this study, the population is made up of 400 people randomly selected from each town as indicated in Table 1. The sample size for this study was determined using Yamane's formula for sample size determination according to equation (1) [11] and represented in Table 1:

$$n = \frac{N}{1 + N(e)^2} \quad (1)$$

Where n = Sample size, N = population, 1 = constant, e = error limit (0.05).

Table 1. Population and sample size distribution of sample area

S/N	Group	Population	Sample size	Percentage
1.	Abakaliki	106	83	26.61
2.	Afikpo	93	75	22.94
3.	Ishiagu	80	66	20.18
4.	Ishieke	66	56	16.51
5.	Uburu	55	48	13.76
	Total	400	328	100.00

2.3 Sampling technique

The sampling technique adopted for this study is stratified random sampling technique in which the sample respondent population were selected randomly from the study fields within the State. This technique enabled the researcher to minimize bias while picking those who met the purpose of this research. Following the determination of sample size, distribution of questionnaires was done based on stratified random technique. Four hundred (400) respondents were selected randomly from the towns in proportion of sample sizes to fill in the questionnaire.

2.4 Data sources and instruments of data collection

The sources of data collected were through two sources: primary sources and secondary sources. The primary sources of data were through responses obtained from the administration of questionnaire distributed to the respondents in the study areas. The questionnaires were structured using open-ended dichotomous and multiple-choice question. Secondary data are relevant information not specifically designed for the purpose of the study but are readily available. The secondary data sources include scholarly journals, conference papers, articles, books, textbooks, thesis, and the internet. The instrument used for data collection are questionnaire focused on four research questions about which respondents' opinions were sought. Random oral interviews were used to confirm the responses of the respondent's answers to each question.

2.5 Data sources and instruments of data collection

Sourced data relating to responses from respondents' perspectives were used to evaluate the relationships between the dependent variables (waste management) and the independent variables (public administration). The method of data presentation in this study is the frequency tables while the analyses were done using simple percentages. The presentation of data was done using research questions and questionnaires, while conclusions were drawn from the evaluation of the research questions.

3 Results and Discussion

1.1 Types and composition of waste generated in the sample towns

The types of waste generated in each of the towns were obtained through the analysis of the sources and composition of the waste samples and represented in Table 2. The types and composition of waste generated in each of the town varied based on the socioeconomic activities, population density, and cultural practices of each area.

Table 2: Solid Waste Generated from the Sample Towns

Composition of wastes	Categories of waste
Polythene bags, sachet water bags, worn-out clothes, ash, worn-out footwear, rubber items, plastics, vegetables etc.	Residential
Sawdust, wood residues, leaves, straws	Agricultural
Stone dusts, e-wastes, can, bottles, used cartons/cardboard boxes	Industrial
Food scraps, polythene bags, sachet water bags,	Residual food
Worn-out tyres, can, bottles, used cartons, cardboard boxes	Institutional
Metallic materials, tile debris	Miscellaneous

Types of wastes generated in Abakaliki include domestic, industrial, construction and E-Waste. The compositions of these wastes are either organic or non-biodegradable. The city's status as the state capital leads to higher waste generation due to increased population and industrial activities. In Afikpo, the wastes are mainly from Agricultural activities, Domestic and commercial composing of organic and non-Biodegradable. Types of waste generated in Ishiagu include mining, domestic, and industrial composing of inorganic and organic materials. Mining activities within this town dominate the waste profile, leading to significant environmental concerns. The types of waste generated in Ishieke and Uburu respectively are, domestic, agricultural, educational and salt production wastes. Due to their proximities to Abakaliki, the waste composition is due to spill-over urban activities. The types and composition of waste in these towns reflect the economic activities and cultural practices prevalent in each area. Poor waste management practices in these areas often lead to pollution, especially in mining areas like Ishiagu and salt-producing regions like Uburu. The result revealed that a greater percentage of the wastes emanated from the residential sector (58%), follows by commercial wastes (19%), then industrial (9%), and institutional (5%), while other miscellaneous sectors account for (1.5%) (Figure 1).

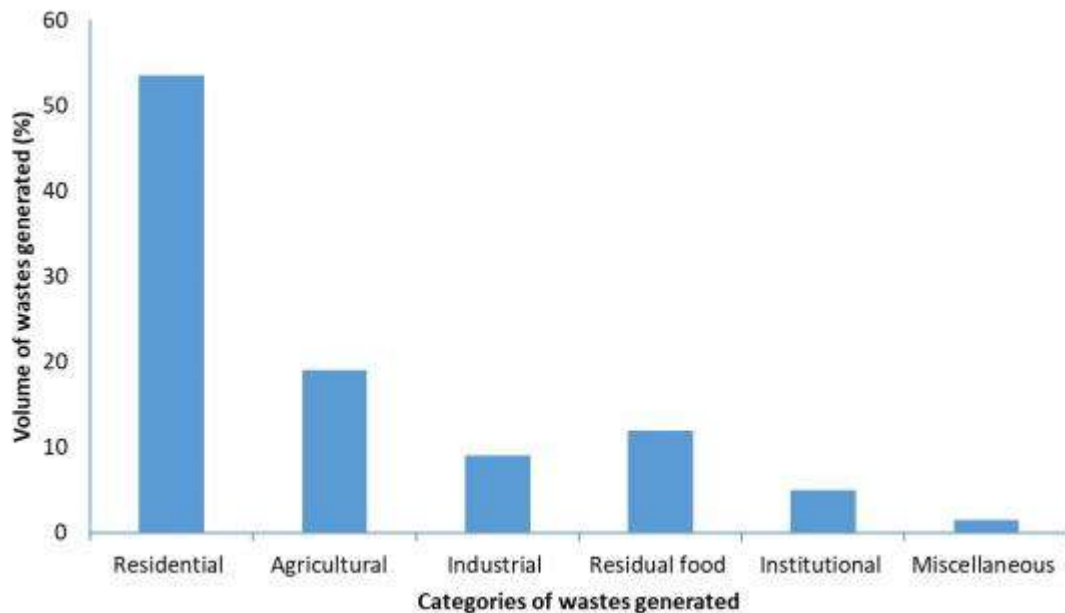


Fig. 1: Solid waste generated from the sample towns

1.2 Awareness of EBSEPA presence in the sample towns

The study (Figure 2) revealed that most of the respondents are aware of the activities of EBSEPA; the government designated waste management authority. Awareness varied due to differences in the agency's outreach efforts, the nature of environmental challenges, and the level of public engagement in each area. The level of awareness Abakaliki is High (41.36%) being the state capital, the host town of EBSEPA's headquarters, ensuring visibility, regular environmental campaigns, such as clean-up drives and waste management programs, are more frequent in the city.

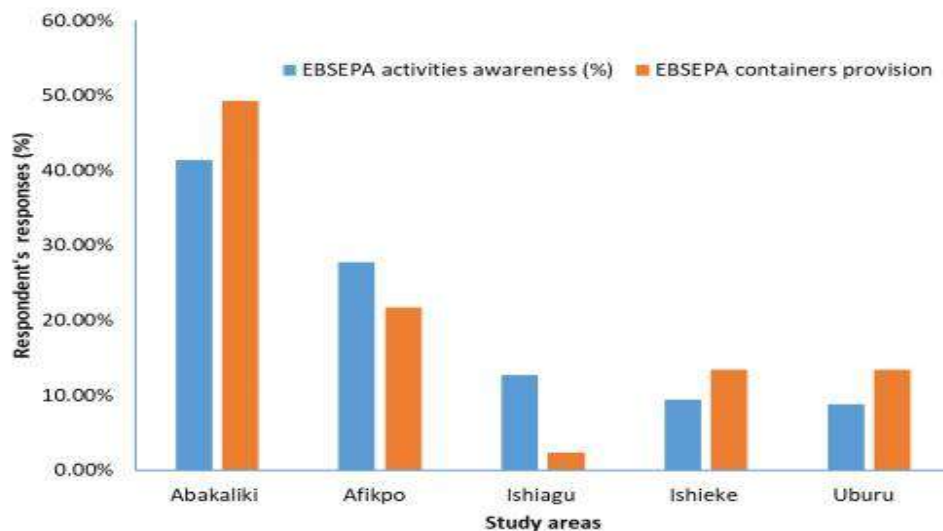


Fig. 2. Responses on awareness and container provision in the sample towns

The level of awareness in Afikpo is moderate (27.76%) being a major town with substantial agricultural and commercial activities, necessitating EBSEPA's involvement. Ishiagu awareness level was low to moderate (12.70%) because of the EBSEPA campaign focus on mining activities on addressing environmental degradation. Ishieke awareness level is low (9.42%) due to the town's proximity to Abakaliki and the presence of the educational institutions in the area. Awareness level in Uburu is low (8.76%) due to the limited attention from EBSEPA the traditional salt production activities often addressed by local methods rather than agency intervention. While awareness of EBSEPA is relatively high in urban centers like Abakaliki, it diminishes in rural and semi-urban areas like Uburu and Ishiagu. Strengthening outreach efforts, infrastructure, and community engagement is critical to improving the agency's visibility and effectiveness across Ebonyi State.

1.3 Provision of EBSEPA containers in the sample towns

Figure 3 gives the perception of the residents interviewed on the provision of containers for waste collection services in each town. The availability of EBSEPA containers for waste collection are scanty and obviously not adequate in each of the towns, except within Abakaliki town, which is the State capital. Respondents' observation indicated that despite the availability of EBSEPA collection containers in some of the designated locations, the waste is thrown in a random manner and these heaps of waste then blocks free access to the EBSEPA collection containers. In other towns like Ishiagu, Ishieke and Uburu, the waste is stock piled indiscriminately at available open spaces provided either by individuals or at nodal points for open burning to reduce its volume periodically.

The study revealed that despite the high level of awareness of EBSEPA activities, the government designated waste dumpsites within these areas not regularly checked and evacuated by EBSEPA staff. However, observations revealed that these wastes are either manually and randomly evacuated after a very long time or left unattended to, depending on the area where located. The EBSEPA's framework of operation lacks digital tools such as GIS and IoT, which has led to manual and reactive approaches, characterized by irregular monitoring, inefficient waste collection schedules, and poor enforcement of environmental regulations. For instance, studies highlight that in towns like Ishiagu and Uburu, where industrial and salt-production wastes are prevalent, waste is often dumped indiscriminately without proper tracking or timely evacuation, worsening environmental degradation and health risks. From this study, it is obvious that indiscriminate dumping of waste around these sites are due to unchecked dumping, illiteracy, human factors among others, which could degenerate as more illegal dumping were made.

A recent study by [12] emphasized the importance of longitudinal environmental governance analysis to evaluate the sustainability and effectiveness of environmental agencies over time. The study evaluates EBSEPA's impact at a specific point in time but does not assess changes or improvements over multiple years. This short-term focus fails to track policy continuity, sustainability of waste management practices, or the evolution of environmental indicators across Ebonyi State. This nonchalant attitude of the EBSEPA staff towards monitoring and evacuation of these solid wastes in towns where their presence is felt could result in negative effects manifesting in environment pollution, road encroachment, air pollution, health, and in residential land encroachment constitute a knowledge gap.

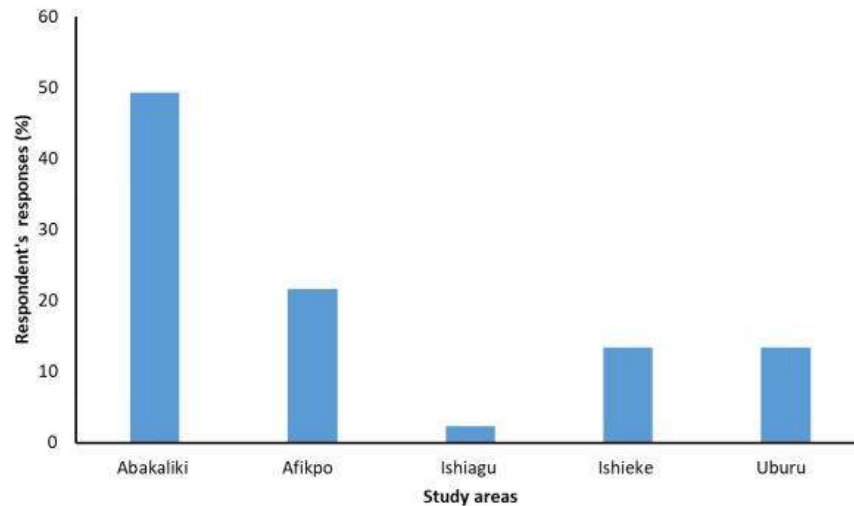


Fig.3. EBSEPA provision of containers in sample towns

The effectiveness of the EBSEPA in curbing indiscriminate waste dumping in the areas are influenced by factors such as infrastructure availability, public awareness, enforcement capacity, and community participation. In Abakaliki, EBSEPA effectiveness is moderately high being the state capital, and benefiting from the concentration of EBSEPA's resources, such as waste collection trucks and enforcement personnel. Effectiveness of EBSEPA in Afikpo is moderate due to community engagement programs that fostered some level of awareness about proper waste disposal. The EBSEPA effectiveness is relatively low in Ishiagu and Ishieke communities with little efforts in regulating mining-related wastes and little access to waste collection services. Uburu received limited interventions by EBSEPA with increased indiscriminate dumping of waste from salt production activities due to inadequate regulation, poor infrastructure for waste collection and widespread dumping. The general factors affecting effectiveness of EBSEPA in these locations include limited infrastructure, poor public awareness campaigns, cultural practices and economic constraints. While EBSEPA has made notable progress in curbing indiscriminate waste dumping in urban centers like Abakaliki, its effectiveness is limited in rural and semi-urban areas such as Uburu and Ishieke.

Addressing the challenges of infrastructure, public awareness, enforcement, and community engagement is critical to enhancing EBSEPA's capacity to manage waste across Ebonyi State. insufficient community participation and behavioural analysis was another gap identified by the study. Chukwuma and Ibrahim [13] found that behavioural change campaigns and community co-management strategies were far more effective than top-down enforcement in improving waste practices in south-eastern Nigeria. The study highlighted community awareness but does not explore behavioural drivers of improper waste disposal or how participatory governance and local ownership can enhance EBSEPA's effectiveness. These limits understanding of the socio-cultural factors affecting waste management compliance.

Again, limited technological and data-driven waste management framework constitute another research gap. Umeh *et al.*, [14] assert that integrating GIS, IoT sensors, and mobile data platforms in urban waste management enhances route optimization, monitoring, and transparency in Nigerian states. These tools are particularly crucial for regions with diverse waste profiles and varying levels of

urbanization, such as those found across Ebonyi State. Despite growing global recognition of digital technologies in urban waste management, Ebonyi State Environmental Protection Agency (EBSEPA) is yet to adopt digital technology platforms like mobile communication to access real-time updates on waste services, waste tracking and monitoring [13]. The study does not incorporate or assess the role of digital tools, geospatial data, or waste tracking technologies in EBSEPA operations, however, it a way of improving operational efficiency, accountability, and community engagement. This represents a significant operational gap that hampers the efficiency and transparency of the agency's activities. This is a significant omission given the global and national shift toward data-driven environmental governance. In modern environmental governance, GIS platforms provide spatial data essential for mapping waste generation hotspots, optimizing collection routes, and identifying illegal dumping sites. When integrated with IoT-based smart sensors, real-time data on bin fill levels, collection frequency, and waste volume can drastically improve responsiveness and resource allocation [14]. The lack of such participatory platforms further distances EBSEPA from the communities it serves.

1.4 Health implications of wastes on the people in the sample towns

The study evaluated the likely common health issues prevalent in each of these areas by listing likely suffered health conditions in the questionnaire. The common Health implications and causes identified within the study areas are represented in Table 3, while the responses from these areas were used to categorize the results of health implications on the people in these areas as shown in Figure 4. A higher percentage of the respondents (34%) agreed that Respiratory conditions e.g. cough; asthma and bronchitis are most prevalent in these areas. Other results showed that waterborne diseases contributed 28%, followed by Vector-borne diseases (22.1%), Skin infections (9.2%), and mental illnesses, which accounted for 6.7%. These results were due to the indiscriminate dumping of waste constitute severe health implications for humans due to the harmful chemical elements. These heaps of solid wastes also serve as good breeding grounds and hideouts for reptiles, rodents, and other dangerous insects such as mosquitoes and flies. In addition, open burning of waste within the city generate serious greenhouse gases and other hazardous gases that pollute the air within the vicinity.

Table 3. Health Complications, Causes and Responses Within the Study Towns

Health complications	Causes
Respiratory diseases	Burning of waste in open dumps
Waterborne diseases	Leachate from improperly managed dumpsites
Vector-borne diseases	pests such as rats, flies, and mosquitoes
Skin infections	Direct contact with waste, especially hazardous materials
Mental health Issues	Unmanaged dumpsites due to foul odours, unsightly surroundings

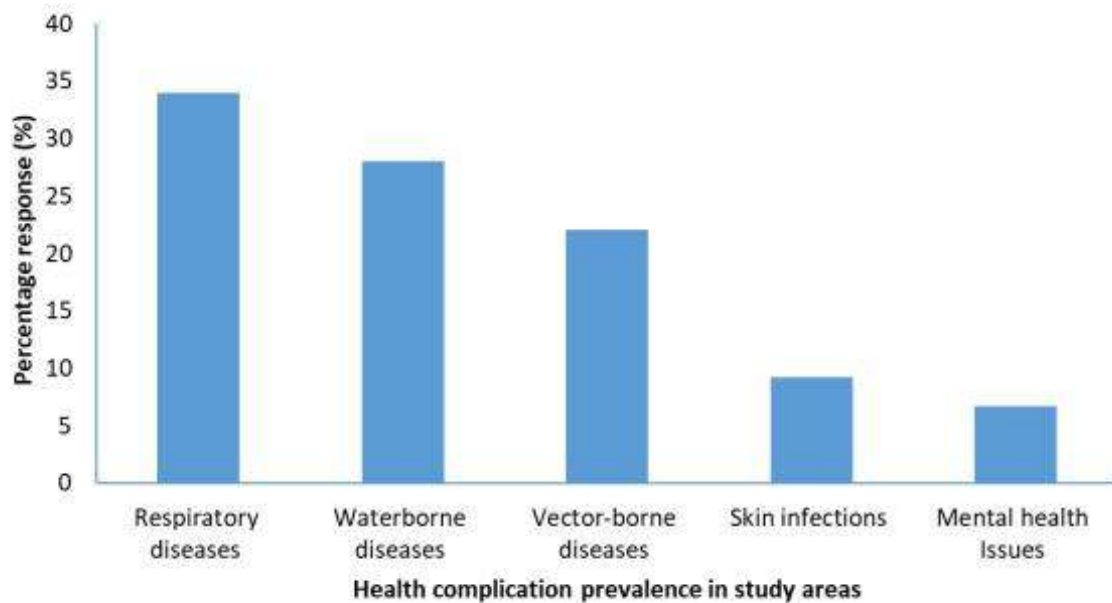


Fig.4. Health complication responses within the study towns

The improper management of waste has significant health implications for residents of these towns arising from the accumulation of various types of waste resulting in public health hazards. The health implications of waste are significant and multifaceted, affecting physical and mental health, economic stability, and overall quality of life (Table 4). Addressing these issues requires a comprehensive approach involving improved waste management infrastructure, public education, stricter enforcement of environmental regulations, and active community participation.

Table 4. The health implications of waste in the sample towns

Town	Health implications	Notable risks
Abakaliki	Respiratory problems, vector-borne diseases, food contamination	Disease outbreaks, health risks
Afikpo	Waterborne diseases, skin infections, air pollution	Increased exposure to pesticides and fertilizers
Ishiagu	Heavy metal poisoning, silicosis and lung diseases, cancer risks	High levels of environmental and health challenges
Ishieke	Infectious diseases, rodent infestations, mental health issues	Health risks from urban waste
Uburu	Salt production waste, skin and eye irritations, water scarcity	Worsening health outcomes

1.5 Waste Governance Challenges in Nigeria

These findings offer a robust empirical foundation for assessing the challenges confronting waste governance in Nigeria's urban and semi-urban environmental management systems. The diversity of these wastes—ranging from residential and agricultural to industrial and institutional—observed across Ebonyi State exemplifies the widespread lack of waste segregation and context-specific disposal strategies that characterizes many Nigerian municipalities. The absence of structured waste categorization mechanisms has led to a predominance of mixed solid waste, which constitutes over 70% of municipal waste in Nigerian cities and significantly hampers recycling and waste-to-resource processes [15]. Operational inefficiencies in the activities of the Ebonyi State Environmental Protection Agency (EBSEPA) are particularly evident in its limited effectiveness outside the state capital. While EBSEPA exhibits moderate functionality in urban centers such as Abakaliki, its impact in rural and semi-urban locations remains minimal due to infrastructural deficits, inadequate enforcement mechanisms, and low levels of public awareness. This pattern is not unique to Ebonyi State. Similar disparities are reported in other Nigerian states. For example, the Lagos State Waste Management Authority (LAWMA) maintains relatively efficient operations in central districts but faces logistical challenges in suburban regions such as Ojo and Ikorodu [16]. This urban-rural divide in service delivery underscores a systemic nationwide imbalance in environmental governance.

A pervasive cultural perception that positions waste management solely as the responsibility of government authorities contributes to the widespread practice of indiscriminate dumping. Studies by Chukwuma and Ibrahim [13] underscore the critical role of behavioural change communication and community co-management strategies in improving waste disposal practices. The uneven levels of public awareness about EBSEPA—high in urban areas but considerably low in peripheral towns—point to a broader failure of participatory governance. This deficiency is exacerbated by the limited integration of environmental education into Nigeria's school curricula and local government public orientation efforts, thereby stalling the development of environmental literacy among citizens [17].

Moreover, the study identifies a strong correlation between poor waste management and adverse health outcomes. In towns with limited EBSEPA presence, residents are disproportionately affected by respiratory ailments, waterborne diseases, vector-related illnesses, and mental health challenges. These health risks are compounded in flood-prone cities such as Ibadan, Enugu, Port Harcourt, and Makurdi, where waste-clogged drainage systems facilitate the spread of communicable diseases [18].

A critical operational gap identified in the study is the absence of digital technologies in EBSEPA's waste management framework. The reliance on manual systems has led to inefficiencies in route planning, delayed waste collection, and inadequate monitoring. This digital shortfall reflects a broader national governance challenge, where most state and federal environmental bodies lack access to smart technologies. As Umeh et al. [14], argue, the integration of mobile data platforms, sensors, and Geographic Information Systems (GIS) is imperative for real-time waste tracking, route optimization, and enhancing transparency in waste management systems.

Policy and administrative challenges further compound Nigeria's waste management crisis. The current centralization of environmental governance has limited the ability of state-level agencies to coordinate effectively with local councils. This disconnect, coupled with fragmented policy implementation and insufficient funding, has resulted in overlapping mandates and service delivery failures. Although the National Policy on Solid Waste Management (2018) was formulated to address these issues, its implementation has been undermined by weak enforcement mechanisms, inter-agency conflicts, and lack of political will. To bridge these gaps, a comprehensive national reform agenda is

essential—one that promotes decentralization, smart governance, increased public sector investment, and community-based waste audits. Based on the objectives outlined and the research outcome on the impact of public administration on the activities of Ebonyi State Environmental Protection Agency (EBSEPA), the following conclusions and recommendations were made:

4 Conclusion

Based on the objectives outlined and the research outcome on the impact of public administration on the activities of Ebonyi State Environmental Protection Agency (EBSEPA), the following conclusions and recommendations were made:

Conclusions:

1. Waste generated in the selected towns include domestic waste, commercial and industrial waste, agricultural mining waste and salt production waste. Most of these wastes consist of both biodegradable and non-biodegradable components.
2. Strategies and provisions of EBSEPA on waste management include regular (daily/weekly/monthly) waste clearance (mainly in Abakaliki) and public environmental awareness campaigns. However, the implementation is inconsistent across various towns. Urban centers like Abakaliki benefit more from EBSEPA's resources, while semi-urban and rural areas like Ishiagu, Ishieke, and Uburu suffer from neglect. There is a notable shortage of infrastructure (e.g., waste bins, collection trucks), infrequent monitoring, and poor enforcement of regulations.
3. Health complications such as respiratory issues, waterborne diseases, vector-borne diseases, and skin infections and mental health issues. The worst-affected areas include Ishiagu and Uburu, where industrial and salt-production wastes are poorly managed.

Recommendations:

1. Conduct town-specific waste audits to design tailored waste segregation and recycling strategies.
2. Decentralize EBSEPA operations to improve service delivery in underserved areas. To enhance EBSEPA's impact, the capacity of public administration must be improved through adequate funding, provision of sufficient waste bins and ensure regular collection to discourage indiscriminate dumping, recruitment and training of skilled environmental officers, increased community engagement and inclusion in environmental policy formulation and execution.
3. Improve health surveillance systems to monitor disease outbreaks linked to poor sanitation.

By implementing these recommendations, the State government can improve the effectiveness of public administration in waste management and promote a cleaner and healthier environment for the citizens of Ebonyi State.

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Sustainable Energy Generation from Agricultural Waste: A Review

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Abstract: The increase in agricultural production has resulted in increased quantities of livestock waste, agricultural crop residues, and agro-industrial by-products. A review of agricultural wastes, such as palm oil and other wastes, is valuable because of their contribution to environmental degradation and the need to convert them to value-added products, such as renewable energy, to reduce their impacts. This paper reviews the available renewable biomass resources that can enable developing countries, including Nigeria, to overcome their current energy challenges. The palm oil industry generates a large quantity of waste, making its disposal a challenging task. Apart from a few isolated cases where palm kernel shells (PKS) and palm fruit fiber serve as sources of fuel for cooking, they are usually dumped in open fields and water ponds, which negatively impacts the environment. Renewable energy produced from agricultural waste will add to the national system in view of the exhausting nature of fossil fuel resources coupled with the challenges of environmental degradation.

Keywords: Sustainable energy, Agricultural wastes, palm oil wastes, palm kernel shell, Biomass

1. Introduction

Agricultural waste is residue from the growing and processing of raw agricultural products, such as fruits, vegetables, meat, poultry, dairy products, and crops. Biomass resources include wood waste, agricultural residues, municipal waste, animal waste, waste from food processing and consumption, aquatic plants, and algae. These are renewable resources whose utilization has received great attention owing to environmental considerations and the increasing demand for energy worldwide [1]. In the realization of renewable sources of energy, agricultural waste is emerging as a promising resource because it is cheap and abundant compared to depleting fossil resources and increasing environmental concerns. These resources represent a huge underexploited capital of energy, which can meet much of the growing energy demand at a cost far less than those of conventional fossil fuels if given the attention and consideration they deserve. Research has been conducted in the field of alternative energy sources. This has received the attention of the United Nations Climate Panel, which aims to reduce greenhouse gas emission 'by 50-80% by 2050 [2]. To achieve this target, it has become necessary to shift the dependency from fossil fuels to renewable energy sources. The potential of agricultural waste to help meet global energy demand has been widely recognized in recent years (Ben-Iwo et al., 2016) [3]. It is expected to be one of the most important renewable energy sources in the near future. The palm oil industry, for example, generates a large quantity of waste, making its disposal a challenging task. Depending on the type of agricultural waste, when combusted, the chemical energy in the biomass is released as heat that is used to produce steam, which in turn can be used to either drive turbine electricity production or provide heat to industries and homes.

The Nigerian government has made efforts toward renewable forms of electricity in previous years, but despite these plans, there has been no significant addition of renewable energy to the national system. Among the many types of agricultural waste, oil palm waste is a major contributor to energy production in Malaysia, which is one of the primary palm oil producers in the world. This study reviews the available biomass resources that can be used in the production of renewable energy to enable developing countries, including Nigeria, to overcome their current energy challenges. The use of these

agricultural wastes as sources of energy could help reduce waste volume and minimize over-dependency on non-renewable energy (fossil fuels). The conversion of these renewable energy resources is desirable because of their contribution to environmental degradation and the need to convert them into value-added products, such as renewable energy, to reduce their impacts. The expansion of agricultural production has naturally resulted in increased quantities of livestock waste, agricultural crop residues, and agro-industrial by-products. The generation of agricultural waste will continue to increase globally as developed and developing countries continue to enhance their farming systems. It was estimated that approximately 998 million tonnes of agricultural waste will be generated globally, with organic waste comprising 80% of the total solid waste on any farm [4].

According to a study by Kishimba [5] on the potential of energy from agricultural waste (sugarcane waste) in Tanzania, the largest sugar factories in Tanzania cultivated over 17,000 hectares of sugarcane farms and produced 125,000 tonnes of sugar per annum after processing 1,300,000 tonnes of sugarcane. In the process, the factories produced approximately 40,000 tonnes of molasses, which were exported, and approximately 455,000 tonnes of bagasse as waste. From an environmental and economic perspective, the disposal of such agricultural waste is not only hazardous but also a waste of resources when renewable energy is not produced from them, and most of the activated carbon used in industries for various adsorptive purposes is imported [6]. Biomass Feedstocks in Nigeria Generally, the sources of biomass include wood, energy crops, agricultural residues, industrial wastes; sawmill residues, and animal wastes. The major agricultural crop biomass feedstocks in Nigeria are millet, yam, cassava, sorghum, rice, groundnut, oil palm, sugarcane, and soybeans [7]. An estimate in 2001 reported that the total number of cattle, sheep, goats, horses, pigs, and poultry in Nigeria was 245 million, which produced 0.78 million tons of animal waste daily [8]. The estimated crop and crop residue outputs for Nigeria in 2004 are shown in Table 1. Nigeria has yet to fully harness them to play a significant role in electrical energy production, biogas, biofuel, and the production of other value-added products. Nigeria is endowed with abundant quantities of each of these agricultural waste resources, which should be an important energy source for rural households, agricultural production, and rural industries. Based on statistics, Nigeria produces approximately 227,500 tonnes of fresh poultry and pig waste daily, and if fully utilized, the quantity will be equivalent to 6.8 million m³ of biogas production per day [9]. Waste from livestock activities includes solid waste, such as manure and organic materials, and liquid waste, such as urine, which can generate pollutants, such as hydrogen, sulfide, and methane, with their characteristic offensive odor. Pollution caused by livestock production is a serious problem because many farms are close to residential areas. This conversion of livestock waste to value-added products, such as renewable energy, biogas, and biofuel, will help prevent the negative effects on the human population that lead to frequent complaints.

Table 1: Estimated crop and crop residue in Nigeria

Resource	Crop Production (tonnes)	Crop Residue (tonnes)
Oil palm	1,000,000	400,000
Cowpea	30,000,000	4,050,000
Groundnut	20,800,000	6,000,000
Sugar Cane	800,000	300,000
Cassava	45,000,000	29,000,000
Sweet Potato	3,000,000	2,000,000
Yam	33,500,000	22,000,000
Cocoyam	2,000,000	1,500,000
Millet	8,000,000	1,000,000
Maize	7,500,000	3,000,000
Rice	4,600,000	1,800,000
Potato	1,000,000	600,000

Sorghum	11,000,000	2,500,000
Plantain	20,500,000	9,450,000
Cashew	1,800,000	300,000
Coffee	2,000,000	400,000

Source: Akorede *et al.* [8].

1.1 Palm Oil Wastes

The oil palm industry is a major aspect of the agricultural sector in Malaysia and Nigeria. Malaysia is endowed with substantial potential in this regard and has replaced Nigeria as the chief producer since 1971 [7]. According to Wikipedia [10], for each tonne of crude palm oil produced from fresh fruit bunches, approximately 6 tonnes of palm fronds, 5 tonnes of empty fruit bunches, one tonne of palm kernel endocarp, 250 kg of palm kernel press cake and 100 tonnes of palm oil mill effluent (POME) are produced. The infiltration of palm oil waste, such as POME, into groundwater has constituted a threat and detrimental effects on the survival of the ecology, aquatic life, and food chain [11]. The widespread contamination of the atmosphere and surface water due to palm oil industrial operations has increased the aesthetic concerns of most environmentalists. Moreover, the revolution of palm oil mill effluent in microbiological science has attracted much attention, which is attributed to its abundance and low commercial value. Sandhu *et al.* [12] reported the prominent role of palm oil effluent in the composting process for increasing soil fertility. Ahmad *et al.* [13] had through palm oil processing discovered carotenes in POME which is the most important vitamin A that protects against blindness, skin disorder, toxin, flu infection and strengthening of immunity level. Moreover, biogas and biofuel technologies are now widely used to convert organic biomass materials into gaseous and liquid states, respectively. Biofuels are manufactured by esterification of renewable oils, fats, and fatty acids and have become a growing area in fulfilling the pressing need for renewable energy [14].

Palm Oil Waste Generation and Disposal in Nigeria Oil palm, otherwise known as *Elaeis guineensis*, is the most important species of the *Elaeis* genus in the family of *Palmae*. It is planted in West Africa, especially Nigeria, and most tropical countries of the world, including Malaysia, Indonesia, and Thailand [15]. The oil palm industry has been recognized for its contribution to economic growth and development in Nigeria. Notwithstanding, Parveen *et al.* [16] observed that it also contributes to environmental pollution due to the production of large quantities of waste products during the extraction process. Mohamed and Yusup [7] observed that during palm oil processing, more than 70% (by weight) of the processed fresh fruit bunch was left over as oil palm waste, consisting mainly of extracted fiber and palm kernel shells. Palm kernel Shell (PKS) are the shell fractions left over after the nut has been removed after crushing in an oil palm mill. This agricultural waste is abundant in Nigeria with the development of the palm industry, especially in the southern part of the country, and has great potential for recycling to obtain many products [17]. In Oyo State, Nigeria, there is an annual estimate of the availability of 3,500,000 kg of fruit bunches, 2,250,000 kg of oil-pressed fibres, and 1,750,000 kg of palm kernel shells (Vogel, 2002) [24], which are the major biomass in the oil palm industry [18]. There is a surplus of these by-products in the palm oil value chain, but their utilization is extremely negligible. Apart from a few isolated cases where they serve as a source of fuel for cooking, PKS is usually dumped in open fields and water ponds, which negatively impacts the environment. According to Kolade *et al.* [19], palm kernel wastes, especially PKS produced from small- and medium-scale industries, pose serious environmental pollution in Nigeria.

The palm oil industry generates a large quantity of waste, and its disposal is a challenging task. In palm oil mills, fresh fruit bunches are sterilized, after which the oil fruits are removed from the bunches. The empty fruit bunches are left as residues, and the fruits are pressed in an oil mill to separate the kernel from the press cake. The palm kernels are then crushed, and the kernels are taken to a separate mill, where they are pressed. In tropical palm oil plantations, almost 70% of the fresh fruit bunches are turned into waste in the form of empty fruit bunches, fibers, shells, and liquid effluent (palm oil mill effluent). Therefore, the production of renewable energy from palm kernel shells could be a value addition to palm oil processing, which is a veritable economic activity in Southeastern Nigeria [20]. Specifically, it can be converted to value-added products such as bio-oil, bio-diesel, bio-ethanol, biogas (or methane), or energy to generate additional profit for the palm oil industry [21]. The problem associated with the burning of these solid fuels is the emission of dark smoke, which results from partially carbonized fibrous material due to incomplete combustion [22]. The use of palm kernel shells (PKS) in Generating Renewable Energy and Other Value-added Products Press fiber and palm kernel shells generated from palm oil mills are traditionally used as solid fuels for steam boilers to run turbines for [23] electricity production. This is desirable in view of the fact that other sources of energy needed to be sought through the use of agricultural waste to avert the problem of deforestation in the course of using woody biomass to generate electricity [24].

It is practiced in countries such as Malaysia, Indonesia, and Thailand, where most palm oil mills in the region are sufficient in terms of energy, resulting in an increasing demand for PKS, which serves as a means of its disposal. These leading palm oil producers in the world are even limiting the export of PKS to ensure the supply of waste materials for renewable energy projects to decrease dependency on fossil fuels. For example, many developers in Indonesia have expressed interest in building palm-kernel-shell-fired power plants for electricity generation. The principal methods of thermochemical conversion of agricultural waste for the generation of electrical energy, activated charcoal, and other products are combustion in excess air, gasification in reduced air, biochemical conversion, and pyrolysis in the absence of air, with direct combustion in excess air being the most applied procedure, as shown in figure 1. The heat generated by the direct combustion method must be exploited immediately for heating or power generation. In addition to the obvious problem of low efficiency, this approach also leads to undesirable ash buildup [25]. The large amount of CO₂ produced as a byproduct of combustion is also a significant disadvantage, unlike the biochemical method, which has little impact on the environment. An advantage of thermochemical conversion is that it is not feedstock-specific and can even process a combination of feedstocks. Thermochemical processing of agricultural waste uses heat and catalysts to transform plant polymers into biofuels and other useful products.

The biochemical conversion of agricultural waste into biofuels and other valuable hydrocarbons can be performed using biochemical routes such as fermentation and anaerobic digestion. Biofuels are liquids or gases produced from agricultural waste that can be burned to obtain energy. Unlike thermochemical processing, biochemical processing of agricultural waste uses enzymes and microorganisms for the same purpose. This is why biochemical conversion is often referred to as a 'matured' technology. Although thermochemical processes occur faster than biochemical conversions, which take days to complete, some agricultural waste must undergo a suitable biological treatment and dry digestion before being subjected to biochemical conversion [26]. A good example is chicken feathers, which are composed of more than 90% keratin (insoluble protein) and have great potential for

biogas production. However, they must undergo pretreatment prior to biogas production because of their recalcitrant nature [27]. This characteristic of chicken feathers and sheep wool limits their biological degradation, resulting in slow processes and low biogas production. This is why they undergo pretreatment to overcome their recalcitrant structure and make them accessible to microorganisms for improved biogas production [26]. Bioconversion of poultry feathers is an alternative method for improving the nutritional value of feather waste [28]. A novel feather-degrading microorganism (*Klebsiella* species) isolated from a poultry waste disposal site in India was able to degrade native feathers by keratinolytic activity [29], while *Bacillus subtilis* was found to degrade keratin in sheep wool [28] with varying amino acids derived from it. This ability to hydrolyze keratin, a rigid and strongly cross-linked protein in poultry feather and sheep wool waste, has made keratinase enzyme production from Agricultural Wastes (Pig Dung, Palm kernel shell, etc.) via thermochemical processes by microorganisms highly relevant to the biotechnological industry.

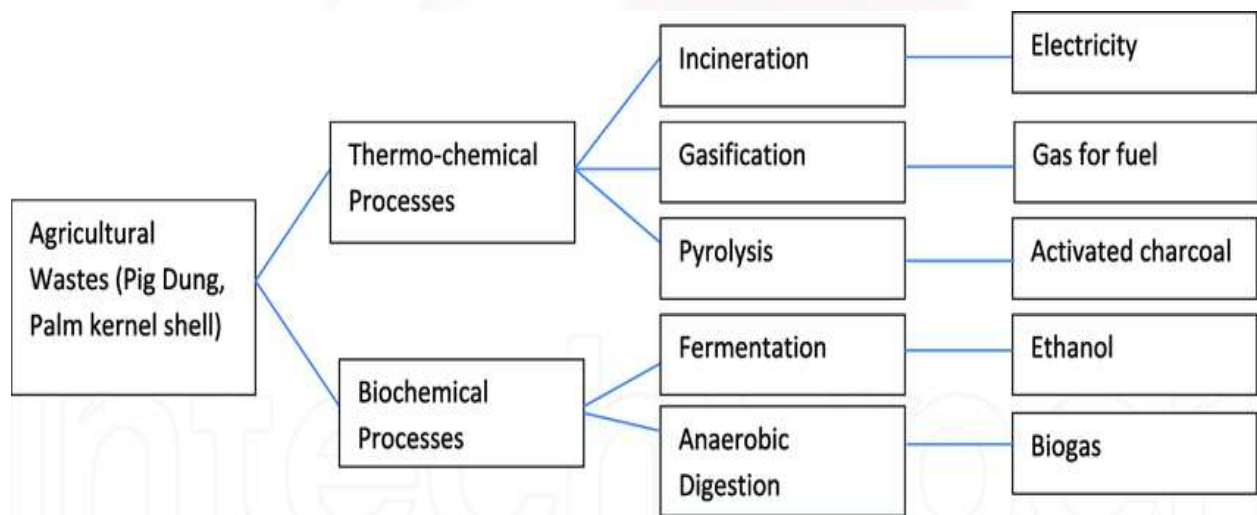


Fig 1. Method of converting agricultural waste to generate electricity and other value-added products using thermo-chemical and biochemical processes.

Source: Okey and Ogbu, [23]

1.2 Renewable Energy and Biogas Production using Agricultural wastes

Biogas is produced from agricultural waste through anaerobic digestion. The national energy supply in Nigeria is entirely dominated by fossil fuels, while renewable energy resources are grossly underutilized in the country despite their availability in reasonable quantities [8]. This overdependence on fossil fuels is a serious concern for the country because of its negative impact on the environment, coupled with the constant depletion of fossil resources. The burning of fossil fuels produces greenhouse gas emissions that cause global warming and pollutants such as soot, ash, and hydrogen sulfide [8]. Therefore, there is a need to conserve the environment from these pollutants, which has led to a global search for alternative energy sources. This is desirable in view of the fact that no country can witness any significant economic growth without meeting the primary energy requirements of its consumers and industries. Biogas produced from animal waste and other agro-waste is an excellent source of heat and electricity; hence, it has become a value-added product for farmers who earn extra income from it. Biogas production has a positive impact on the environment since less CO₂ is formed as opposed to when fossil resources are employed.

A clear example of this is when the combustion of coal is compared with agricultural biomass which is known for significant reduction of greenhouse gas emissions. Biogas as a renewable fuel is produced by anaerobic fermentation of organic material with the value of the substrate employed in the processing determining the quality of biogas or its methane content depending on its lignin and cellulose content ratio. The process as described in Figure 1 involves the utilization of microorganism for conversion of organic substrate in anaerobic environment to generate CO₂, biogas and impurities such as hydrogen sulphide [30]. The process involved in the conversion of animal waste to biogas and to electrical energy includes mixing of the waste to homogenize it, digestion of waste in an anaerobic digester, separation of sludge, biogas collection from digester and power generation from biogas [8]. In biogas production, agricultural wastes with high lignin content offer much energy or biogas when compared to cellulose biomass. Under normal conditions, biogas is expected to contain 50-70% methane, 25-50% Carbon dioxide, 1-5%Hydrogen, 0.3-3%Nitrogen and some traces of Hydrogen Sulphide with Methane (CH₄) being the only combustible component utilized in different forms of energy such as lighting, heating, transportation and in power generation using gas turbines [31].

Methane is the second most important greenhouse gas after CO₂ and a major product of biogas production; hence precautions should be taken to reduce methane emissions because of its effects on air quality and the ecosystem. The most commonly used substrates for biogas or methane fermentation process before were maize and sorghum [32] but due to their exorbitant prices, alternative sources such as agro-wastes are now exploited. This alternative biomass includes waste materials from food industries and farms which are not meant for human consumption. Other agricultural biomass used for renewable energy production includes straw or animal droppings, crops, perennial grasses and animal wastes [33]. Table 2 showed estimated energy potential from major agricultural crop residues in Nigeria from 2001-2006. It could be observed from Table 2 that cassava and yam peelings formed about 95% of the total processing residues.

Table 2: Average annual agricultural crops residues for bio-energy production in Nigeria (2001 - 2006)

Crop	Residue types (Gg)	Residue Amount	Energy (PJ)
Groundnut	Straw	1369.25	16.10
Maize	Stalks	5923.01	69.83
	Cob	1473.70	17.33
Cassava	Stalks	1052.54	12.38
	Peelings	7716.56	90.74
Yam	peelings	6372.83	74.93
Millet	Straw	4571.40	53.72
Sorghum	Straw	5304.86	62.39
Rice	Straw	2918.54	34.32
	Husk	806.37	9.48
Total		39,931.41	469.56

Gg=gigagrams (equal to10⁹g), PJ=petajoules (equal to 10¹⁵ J). Source: Lye and Bilsborrow (2013) [44].

In Poland, there is a strong focus on utilizing agro-wastes and by-products from food industries, energy plants, and farms for generating renewable energy. Consequently, many agricultural biogas facilities are strategically situated near large livestock farms to ensure easy access to substrate sources and to facilitate

the removal and use of livestock waste, such as poultry manure, to prevent environmental pollution. Recently, the number of poultry farms has grown, but urban expansion into these areas has led to more complaints from nearby residents [34] due to unpleasant odors and nuisance flies, which can lead to legal actions and potential farm closures. The odors from intensive poultry production are a significant annoyance to those living nearby and have caused health issues. Some of these odorous compounds can negatively impact both animal health and production efficiency. The odor, primarily resulting from the microbial breakdown of organic compounds in manure, is released into the air from buildings or external manure storage areas [35]. In addition to the offensive smell, gases like hydrogen sulfide and ammonia emitted by poultry manure can degrade air quality. The presence of such odors and fly populations in poultry production environments, caused by aerobic and anaerobic microbial activities within the litter [36], would not occur if poultry and livestock manure were used for renewable energy production. Biogas production itself enhances sanitation and reduces the risk of groundwater pollution, which is a concern with other waste management methods like direct field spraying [30]. The biogas production process ultimately results in electricity and heat, leaving behind post-fermentation residue that serves as a natural fertilizer for crop farming from which grains are produced and used to create animal feed.

4. Conclusion

Agricultural waste materials are renewable resources that have attracted considerable interest due to environmental concerns and the rising global energy demand. Biogas produced from palm oil residues and other agricultural by-products is an excellent source of heat and electricity. The processes involved in bioenergy production are considered environmentally sustainable and help mitigate the negative climatic and environmental effects linked to the use of fossil fuels, which are currently the main energy source. Biogas technology enables the creation of renewable energy from agricultural waste while also recycling nutrients within the waste as fertilizer, thus reducing harmful emissions that could negatively impact human health and ecosystems. If given proper priority, the generation of renewable energy from agricultural waste could make a significant contribution to the national energy grid in many developing countries, including Nigeria.

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A Critical Review of Women Exclusion in Agricultural Development Revolution: Contributions, Constraints, and Strategic Solutions

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Abstract: Abstract is compulsory. Women's roles in agricultural production system have been relegated as traditionally domestic contributors to reproductive tasks, despite their pivotal roles in agricultural systems across the globe; they remain systematically marginalized in decision-making, access to productive resources, technology adoption, and leadership. This paper investigates the multi-dimensional discrimination of women in agriculture, highlighting both structural and socio-cultural barriers that hinder their empowerment. Drawing on global and regional evidences, the study explores the historical and contemporary contributions of women to sustainable agricultural practices, emphasizing the exclusivity of women from male-centric agricultural tool and machine development, extension services, and agrarian governance. It concluded that women are regarded as passive recipients in the agricultural development trajectory despite their contributions to the development of the sector. The paper proposed gender-responsive reforms and implementation in the area of tool redesign and female-centric ergonomic considerations as agricultural technology advances. It further suggests an inclusive policy frameworks, capacity-building strategies, and public sector reforms to enhance women's recognition in agriculture. The study advocates for the mainstreaming of gender equity as a fundamental pillar for achieving sustainable productive agri-food systems.

Keywords: Gender inclusivity, empowerment, passive farmer, public sector reform, gender-responsive policy

1. Introduction

Gender encompasses both men and women, each with the potential to significantly contribute to food security and economic development. The roles of men in agricultural operations are distinctive, direct, and unambiguous; regarding men as the primary drivers of innovations and adopters of technology [1], while women roles are relegated as traditionally domestic contributors and passive recipients to reproductive tasks, such as food preparation, giving birth and caregiving, within agri-food systems [2]. Despite their substantial roles, women remain underrepresented in agricultural decision-making, technology development, policymaking and leadership [3,4,5]. Barriers such as limited access to resources, education, and entrenched social norms contribute to this gender exclusivity. Despite these contributions, women remain underrepresented in agricultural.

Research on agricultural mechanization confirms male dominance in technology ownership and use. For instance, in Nepal, only 4% of mini-tiller owners were women, and just 1% could operate the tillers due to societal perceptions, limited technical knowledge, and other responsibilities [6]. In Tanzania, mechanized maize shelling is largely male-driven due to limited training and societal expectations about women's technical capacities [7,8]. The study emphasizes the need for inclusive policies that address these gender-based barriers. Women are typically assigned labour-intensive, low-paying tasks such as weeding and post-harvest processing [9,10], leading to higher physical demands and increased stress.

Historically, women have been viewed as passive recipients of agricultural innovations. However, evidence highlights their active and transformative roles in sustainable agricultural practices, biodiversity conservation, and natural resource management [11,12]. Women play a vital role in shaping agricultural practices using agrobiodiversity and traditional knowledge systems, which are essential for food security and livelihoods [1]. However, global gender inequalities persist, particularly in access to land, inputs, finance, and decision-making platforms [13]. These disparities are further reinforced by societal underestimation of women's agricultural contributions [14].

Despite several conversations in public domain around gender equality, significant gender inequalities still persist towards women in every region of the world, manifesting in unequal distribution in governance, domestic care work, or denial on land ownership, or lack of equitable access to decision-making, and or unequal access to basic services, resource inputs, finance etc. [13]. In addition, there has been worrisome perceptions around under-appreciation of women's contribution in agriculture, which is consequential on the image of women's agricultural engagement and inclusivity, especially in the developing nations [14]. Different nations, communities, and geographical areas have different levels of gender imbalance towards women's empowerment [16], which make it an expression of perceptions about their roles, responsibilities, and relationships across different social groups [17]. This paper therefore examined the systemic barriers and institutional biases that limit women's participation in agricultural development and technological innovation, with a focus on gender-specific barriers in agricultural access, decision-making, and technology adoption, while proposing inclusive frameworks and policy solutions that foster gender equity and empowerment in the agricultural sector.

2. Method

This study adopted a qualitative narrative review approach, combining systematic structured search and inclusion criteria with critical synthesis to explore the exclusion of women in agricultural development and technology adoption. The review drew upon peer-reviewed journal articles, institutional reports, policy papers, and grey literature published over the last 15–20 years, with an emphasis on recent data (2010–2025). Relevant data were extracted manually, including authors, year, and location. The analysis involved thematic synthesis to identify recurring constraints, strategies, and gaps; comparative analysis to contrast regional trends, and critical reflection on limitations and research gaps in the existing literature.

3. Results and Discussion

3.1 Gender disparities and global perspectives

Despite increased global attention on gender equality, substantial disparities remain, particularly in agriculture. Empirical percentage statistics of gender-based research reported in literature on a regional or continental basis from bibliographic databases like Scopus, Web of Science, PubMed, Dimensions, and Google Scholar filtered by first author continent and study context spanning the last 15 years across the continents shown in Table 1.

Table 1: Percentage of regional gender-based research and institutional contributions

Region	% of gender-based research	Institutional contribution focus
North America	32–35%	Strong in the USA and Canada
Europe	28–30%	High in the UK, Germany, and EU-funded gender programs

Region	% of gender-based research	Institutional contribution focus
Asia	15–17%	Lower in the Southeast and East Asia, with rising trends in Southern Asia
Africa	6–8%	Development-focused on NGOs activities
South America	5–7%	Studies dominated by gender justice, reproductive rights, and indigenous women's
Oceania	2–3%	Mostly from Australia and New Zealand
Global outlook	5–7%	Includes comparative/global health, policy reviews, and UN-type reports

Source: [18].

The analysis highlights strong institutional contributions from North America (32–35%), especially USA and Canada, with high contributions from Europe (28–30%), and Asia (15–17%). The trends in Asia (15–17%) and Africa (6–8%) are on the increase; however, it is still lower in Southeast and East Asia. South America (5–7%) trails behind, with Oceania and multi-regional collaborations contributing even less (2–7%). This distribution suggests a pressing need to expand gender-focused agricultural research in underrepresented regions. The bulk of the research are development-focused, while gender justice, reproductive rights, and indigenous women's studies dominate the South America and the Oceania (3%) studies, and multiregional collaborations accounted for the balance. According to the World Bank [19], the global gender disparity in the agricultural sector stands at 67.2%. However, the research results were unequally distributed, with Sub-Saharan Africa and South Asia accounting for the majority of gender-focused agricultural studies—59% and 22% respectively—while Southeast Asia accounts for only 6% [20].

Globally, the push for gender equality in agriculture has gained policy-level recognition. SDG 5 of the United Nations 2030 Agenda prioritizes women's empowerment as a critical element of sustainable development [21]. While overall gender-based participation in research is increasing, inequality remains across geographies and subject areas in terms of publication outputs, citations, awarded grants and collaborations [18]. In India, patriarchal inheritance laws limit women's access to land despite their significant labour contributions [22] (Dharamshi, 2022). In Pakistan, women face greater barriers in decision-making, physical labour, and vulnerability to social risks [16]. Rural Nepal experiences persistent gender exclusion from smallholder farming [23]. In Southeast Asia, women may exhibit relatively higher household decision-making autonomy [24], but broader empowerment in leadership, asset ownership, and agricultural governance remains limited. In many developing nations, women represent over 60% of the agricultural labour force [25], yet they are consistently marginalized in resource allocation and policy design [26,27]. Women gender barriers also include restricted land tenure rights, limited control over financial assets, and cultural norms that dictate women's roles and access to agricultural services [28,29,30]. Many women are responsible for time-consuming tasks such as collecting water and fuelwood, reducing their capacity for productive engagement in agriculture [31,1].

Women's underrepresentation in the use of agricultural technologies and innovation ecosystems is another major constraint. Studies show that women have lower access to agricultural inputs, training, and extension services [32,33]. Beyond access and ownership, there seemed to be gender biasness more favourable to men in the deployment of agricultural technology, inputs, and information than women. Women have lesser access to farm inputs and technologies than men, which further increase the gender gap, and bring to the fore the question of inclusivity and exclusivity [33]. Gender inclusivity involves recognizing and addressing these systemic inequities, while gender exclusivity highlights the exclusionary design and deployment of agricultural technologies [34]. Gender exclusivity on the other hand, is

expressed by existential gender-based dichotomies in the historical emergence of technology innovations perceived to be driven consciously or unconsciously by men to exclude women, which undervalued or overlooked women's contributions in food production and value chain, thereby promoting gender inequality [34]. The significance of women's roles in agriculture has revived global discourse on equitable labour rights, access to productive resources, and recognition within food systems [35]. Women's economic participation is essential for overcoming poverty and improving food security in rural areas [36,37].

3.2 Global perspectives on women empowerment in agriculture

Women's empowerment in agriculture is increasingly viewed as a catalyst for sustainable food systems, improved household nutrition, and economic growth [38]. Women's role in the food management systems and ensuring adequate nutrition for all household members is significant, however, gender gaps regarding access to income and ownership of the productive resources in the rural sector are enormous [39,35]. Studies across developing regions confirm that when women have access to productive assets—land, credit, and technology—agricultural productivity and food security significantly improve [40,41]. For example, In Zambia, research indicates that public administration perpetuates gender inequality due to entrenched patriarchal systems and cultural biases, which, often confined their roles in care-related ministries such as Community Development and Social Services, and consequentially limiting women's participation in decision-making processes and limit their access to resources, ultimately affecting agricultural productivity and food security [42]. Nigeria situation is not different; women's empowerment through secure land rights and decision-making authority has been linked to increased productivity and food security [43]. Similarly, in Kenya, public policies enhancing women's roles in agriculture contributed to improved maize yields and better livelihoods [44].

Several national policies—including rural social protection programs and targeted agricultural services for women—have demonstrated positive outcomes when aligned with gender-sensitive institutional frameworks [45,46]. However, their effectiveness often depends on local socio-cultural dynamics, political will, and institutional responsiveness. Therefore, significant gaps remain in women's access to income and productive assets. In Zambia, cultural norms often restrict women to care-focused ministries, excluding them from key decision-making roles in agriculture [42]. This limits their influence on resource allocation and agricultural development. To address these barriers, comprehensive strategies must integrate gender empowerment across all stages of agricultural value chains—from research and extension to marketing and governance. Enhancing women's agency not only benefits household welfare and community resilience but also strengthens the overall sustainability of food systems.

Women contributions in agricultural development

Women continue to make impactful contributions to agricultural development, with their participation in agricultural innovation also rising, but varied greatly from region to region. Nevertheless, regardless of these variations, and women's active involvement in various agricultural activities recognizes and values their roles in designing equitable policies, enhancing productivity, and promoting inclusive growth within agrifood systems. Throughout history, women have played vital roles in agricultural systems, contributing to production, food security, environmental stewardship, and knowledge transmission. In early societies, women were responsible for managing home gardens, livestock, and developing indigenous farming practices like crop rotation and seed saving [47]. The noble and responsible rural woman still permeates many development initiatives, with the rural women being unwittingly appointed as caretakers of not only the household, but also farms and landscapes in some societies [47].

In the 20th century, women's participation in agricultural technology development had begun to gain recognition with organizations like the African Agricultural Technology Foundation (AATF) focusing on empowering women through agricultural technologies leading to the development of innovative solutions, such as labour-saving technologies and climate-resilient crops, which improves the livelihoods of women farmers, enhancing their productivity and income [48]. The growing feminization of agriculture—driven by male outmigration, conflict, and climate shocks—has led to women assuming multiple roles as cultivators, entrepreneurs, and resource managers [49]. Today, women involvement extends beyond

farming to include childcare, food preparation, water collection, and land stewardship. Despite this, women often remain concentrated in unpaid or low-wage roles, particularly in labour-intensive tasks. In Latin America and parts of Africa, the proportion of female-headed rural households is increasing, reinforcing women's roles in both subsistence and commercial farming. Organizations such as the African Agricultural Technology Foundation (AATF) promote labour-saving and climate-smart technologies targeted at women farmers. These interventions enhance women's productivity and income, reinforcing the link between gender-inclusive innovation and sustainable development.

Constraints to women participation in agriculture

Women face numerous structural and socio-cultural constraints that limit their full participation and recognition in the agricultural sector. These challenges are embedded in patriarchal and social-institutional constraints, discriminatory legal frameworks, and policy gaps that restrict women's access to land, finance, markets, training, and leadership roles. Beside the challenge of determining modalities for women inclusion in agricultural mechanization from the onset, women farmers face multiple challenges in adopting mechanization, despite its advantages of time, labour, and drudgery reduction in agricultural production. These constraints to its full adoption range from the low economic status of women, limited access to information about new agricultural technologies, men-centric designs and utilization, lack of technical knowledge of new technology designs, intra-household-role barriers, access to credit facilities, land holding or ownership practices.

Patriarchal and social-institutional constraints: Social-institutional constraints such as equal access to economic opportunities and productive resources (land, credit, technology, and market information etc.) faced by women make them more vulnerable in managing risks arising from economic shocks than men. African culture discriminates a lot against women and girls land inheritance owing to customary laws and patriarchal inheritance practices. The perception of the patriarchal society about women submission to men gained prominence from men, thereby excluding women from having some statutory rights such as landholder rights. Land ownership is skewed towards men, which restricts women's control over productive resources and decision-making power in agriculture [14]. This lack of secure tenure inhibits women's ability to invest in long-term productivity and restricts their access to the following provisions [36,50].

Access to credit facilities: Women farmers often have limited access to resources such as credit, seeds, and agricultural tools, and technology, which restricts their ability to practice modern and efficient farming techniques. They often struggle to obtain these agricultural inputs due to discriminatory banking practices, lack of collateral, and limited extension outreach. Without these resources, productivity remains low, and women are unable to scale their agricultural activities or improve household incomes [32]. Low economic status of women further limits their opportunities for broader participation in agricultural inputs sharing, ownership and control.

Technical knowledge of new technology designs: Women often face barriers of technologies frequently designed with male users in mind, neglecting ergonomic and functional considerations for women. These exclusions perpetuate systemic inequities and hinder women's full participation in agricultural modernization [7]. A lack of awareness and technical knowledge may hinder their ability to adapt and effectively utilize modern farming tools and techniques. Women farmers with limited access to training and technical knowledge may find it difficult to operate some new agricultural machinery and equipment with complex controls requiring specialized skills to operate effectively. Limited access to education and training opportunities hampers women's ability to adopt modern agricultural practices and technologies [7]. The ergonomic design of agricultural machines and equipment further pose challenges for women farmers, who may find it difficult to operate machinery too large, heavy, or cumbersome for their size and physical strength.

Information bridge: Despite women's greater need for extension services [51,52], they continue to face asymmetry knowledge obstacles, which limits their capacity to adopt new technologies, improve agricultural methods, hence constituting an information gap [53,54]. Women faced barriers of exclusions from agricultural information, poor knowledge of new agricultural technologies, lack of resource inputs,

limited opportunities for training and skill development, and markets in the value chain of agricultural development [7]. Furthermore, women farmers have limited access to information about new agricultural technologies and lack of technical knowledge to adopt and effectively utilize modern farming tools and techniques. Extension services and training programs are predominantly male-targeted and fail to accommodate women's needs or schedules. As a result, women are less likely to benefit from technological advancements or participate in innovation systems. Female extension agents are also underrepresented, further reducing outreach to women farmers [55].

Barriers of cultural norms and intra-household roles: Gender roles and cultural norms within rural communities may discourage women from operating machinery or engaging in activities perceived as traditionally male-dominated [56]. Women may face resistance, stigma, or discrimination when attempting to use agricultural equipment, limiting their access to these tools and technologies. Women face intra-household-role barriers in many countries, and negative socio-cultural perceptions associated with women agricultural machinery use. Deeply rooted social norms and cultural practices sometimes restrict women's involvement in decision-making processes within the family or community, limiting their influence on agricultural matters [56]. Women carry a disproportionate burden of unpaid household and care work, in addition to farming duties. The exclusion of women from decision-making and undervaluing of their involvement in agricultural labour deliveries constitutes serious feminist negative perceptions. These stereotypes limit women's mobility, access to markets, and public participation. Resistance to women's leadership and skepticism about their abilities persist across many communities [1]. Research over the decades has suggested that women farmers have been excluded from dominant agricultural systems due to their involvement in the informal economy, their contributions to inclusive development, and the gaps in the existing literature [37,57,58].

Climate change effects: Climate change disproportionately affects women [59], who are often responsible for securing water, food, and energy for their families. Changes in climate patterns can disrupt these responsibilities and increase their workload.

Representation in governance and policy-making: Women remain significantly underrepresented in agricultural institutions, cooperatives, and policymaking bodies. This lack of representation results in policies that often overlook women's needs and realities. Inclusive governance is essential for designing interventions that reflect the experiences of all stakeholders [26].

Strategies for gender-inclusive agricultural development

Addressing these challenges requires multi-disciplinary approaches that promotes women's rights, provides targeted support, and integrates gender considerations into agricultural technology, extension policies, and practices. According to the Africa Food Systems Summit 2024 [60], addressing gender inequality in agriculture extends beyond economic empowerment—it is essential for improving nutrition outcomes across entire communities. When women have equitable access to resources such as land, credit, and authority for decision-making, they are better positioned to ensure their families' nutritional needs are met. This has a direct impact on reducing malnutrition and enhancing health outcomes, particularly for children and other vulnerable groups. Some productive strategies include cultural integration, deployment of credit facilities and input initiatives, gender mainstreaming, inclusive innovative fee-for-service approaches, and introduction of gender technology assessment toolkits among others.

Cultural integration and inclusive extension and training: The force of cultural dynamism applied to social changes could help lower the barriers against land tenure system in areas where they are prevalent. Governments should prioritize legal reforms that ensure women's rights to land ownership and inheritance. Land registration systems must be inclusive and affordable, with legal protections to enforce women's tenure rights. Customary law should be harmonized with statutory law to promote gender equity in land governance [11]. Furthermore, it is necessary to particularly identify women as an integral part of the agricultural extension policy and develop gender-specific operational guidelines, which will direct the extension activities of women farmers. Governments and development agencies must promote inclusive extension services by hiring and training female extension agents, offering gender-sensitive curricula, and

designing programs that accommodate women's time constraints. Participatory approaches that involve both men and women in technology dissemination should be prioritized.

Deployment of credit facilities and input initiatives: Financial institutions must develop credit schemes tailored to the needs of women farmers, including group lending, mobile banking, and microfinance. Policies should incentivize banks to expand access for women through collateral alternatives, credit guarantees, and training in financial literacy. More robust credit facilities and input initiatives made available through farmers' cooperative societies and families could help reduce the poor economic status of women and enhance greater access. Efforts should focus more on strengthening women's access to credit resources, technological advancements, improvement in their participation by strengthening women's cooperative groups [61] and enhance decision-making process. The traditional women's groups and societies in the village could be organized and strengthened to increase women's access to extension services, credit facilities, agricultural inputs and even marketing services. In addition, efforts should be intensified in promoting gender-responsive extension services that are essential for realizing the full potential of agricultural extension in empowering women and advancing sustainable rural development including the provision of an understanding of intra-household gender norms and women's roles in household technology adoption [62].

Gender mainstreaming and educational training: Gender mainstreaming is a strategy put in place to reduce gender inequality by bringing about institutional change and empowering women in a reformed system as active participants, thereby redress systemic patterns of women's social exclusion [1], and reducing their disadvantaged position in agriculture. Mainstreaming gender is considered vital for transforming gender inequality in agrarian societies by addressing the acknowledged generic historical gender disparities; working towards a more inclusive and equitable agricultural innovation system that benefits all farmers, regardless of gender. Technological innovations are now providing a narrowing of the gender gap by enhancing women's participation through women-enabled satellite imaging systems, women operable drones, and mobile applications that could optimize crop yields, reduce waste, and improve resource allocation. Educational programs must address gender stereotypes and empower women through skills training, leadership development, and entrepreneurship support. Targeted initiatives that enhance women's voice in cooperatives, farmer associations, and policymaking platforms are essential to increase their influence in rural governance.

Women advocacy and information access: Effective advocacy and access to timely, relevant agricultural information are pivotal in addressing the systemic challenges faced by women in agriculture. Women's advocacy groups play a critical role in amplifying the voices of female farmers, influencing gender-sensitive policy reforms, and driving grassroots mobilization for resource equity and institutional accountability [33]. These organizations also bridge the gap between rural women and decision-making platforms, enabling the co-creation of solutions that reflect women's realities in farming systems. Information access, particularly through gender-responsive extension services and digital tools, enhances women's ability to adopt new technologies, access markets, and make informed decisions about agricultural practices. Research shows that access to extension services and mobile-based agricultural information significantly increases productivity among women farmers and reduces the gender yield gap [28,63]. In addition, there are digital extension services such as blockchain technology including those leveraging the Internet of Things (IoT) that could provide women farmers with access to agricultural information, markets, and financial services, enhancing their decision-making capabilities. However, persistent disparities in digital literacy, network infrastructure, and gendered norms around information use hinder equitable dissemination. Therefore, scaling women-led advocacy networks and investing in inclusive agricultural information systems—especially those tailored to low-literacy and remote contexts—are crucial for strengthening women's roles in agriculture and overcoming exclusionary barriers.

Introduction of gender-based technology assessment toolkits: The development of a 'lean' gender technology assessment adapted from the technology assessment toolkit, incorporating principles of human-centered design to identify practical, easy and quick-incorporated recommendations into

mechanization program activities could provide solution to technology knowledge of farmwomen [64]. This technology assessment toolkit include the design of user needs, dissemination (learning), adoption (access) and continued use (intra-household dynamics). The assessment was to meet women's practical needs and strategic interests, including providing financial resources (access to credit), accessible training for the low literacy farmers, and a resource list of service providers [7]. Evidences have further shown that developed women-preference agricultural tools and equipment have improved their usability and adoption [65]. These technological advances are not only increasing women's participation in agriculture but also improving their livelihoods, productivity, and overall well-being. There should be regular gender-based transformative technology assessment of machinery to tailoring agricultural technologies to women's preferences identify gender barriers and enablers to adoption of such agricultural technologies. Inclusive innovative fee-for-service approach also incorporates gender disparities in the mechanization of agriculture that restricted women's ability to participate in paid work outside the home, operate machines, including field-based agricultural works. This arrangement made all required implement for conservation agriculture (CA) accessible to smallholder farmers who no longer need to purchase capital-intensive machinery.

Climate adaptation: Climate adaptation strategies are increasingly recognized as critical levers for empowering women in agriculture, particularly in regions where climate change disproportionately affects female farmers due to their roles in managing water, food, and fuel resources. Women are often at the frontlines of climate vulnerability but are underrepresented in adaptation planning and implementation. Integrating gender-responsive climate adaptation approaches can both reduce vulnerability and enhance women's participation in agricultural decision-making, resource access, and technology use. Key solutions include the promotion of climate-smart agriculture (CSA) practices that are accessible and relevant to women, such as drought-tolerant seeds, water-efficient irrigation systems, and renewable energy-powered tools. These interventions help reduce time and labour burdens, enabling women to engage more actively in productive and decision-making roles within the agricultural sector [50, 66]. Additionally, involving women in climate adaptation policy frameworks and extension services ensures that their knowledge and priorities shape interventions. Gender-inclusive climate adaptation enhances women's adaptive capacity and catalyzes broader resilience building within rural communities [59]. However, challenges such as limited access to climate finance, information, land, and technology continue to constrain the full benefits of climate adaptation for women. Bridging these gaps requires targeted policies, investment in women's agricultural cooperatives, and participatory climate risk assessments that recognize and value women's knowledge and labour [64]).

Public sector reform and institutional accountability: Public institutions must adopt gender-mainstreaming frameworks and integrate gender equity indicators into performance assessments [67]. Gender focal points should be empowered with resources and authority to influence planning and budgeting processes. Inter-sectoral collaboration is key to aligning agricultural, social protection, and economic empowerment initiatives. The government should promote the implementation of gender equality initiatives and policies such as the National Gender Policy and the National Gender Policy and Strategic Framework [68] to create conducive environment for gender investment.

4. Conclusions

This study revealed a slow and uneven progress toward gender equality in agriculture despite numerous global commitments and development programs, especially in Sub-Saharan Africa and South Asia, which has continue to undermine productivity, equity, and sustainability of food systems. Women face numerous structural and socio-cultural barriers that limit their full participation and recognition in the sector. These challenges are embedded in patriarchal and social-institutional constraints, discriminatory legal frameworks, and policy gaps that restrict women's access to land, finance, markets, training, and leadership roles. In addition, women empowerment in agriculture is beyond social justice imperative, but an essential tool for food security, rural development, and climate resilience. Despite women contributions, women remain significantly underrepresented in agricultural institutions, cooperatives, and

policymaking. They persistently suffer exclusion from land rights, financial services, extension programs, and leadership roles.

4.1 Recommendations

Feasible solution to these barriers include proactive restructuring of agricultural institutions, policies, and innovation systems to reflect the realities, needs, and aspirations of women. The following recommendations are made.

1. Prioritize gender inclusivity across all stages of agricultural policy formulation, data collection, and impact evaluation to ensure that women's contributions and needs are systematically addressed.
2. Enact and enforce laws that protect women's rights to land ownership, inheritance, and access to resources. Harmonize customary and statutory laws to ensure inclusive land governance.
3. Develop inclusive agricultural extension systems by employing female extension agents, offering gender-sensitive content, and scheduling training programs around women's availability and responsibilities.
4. Invest more in digital extension platforms and climate-smart agriculture (CSA) tools that are accessible to women, including low-literacy, remote, and marginalized populations.
5. Fast-track women's participation in agricultural cooperatives, research institutions, and policy bodies through targeted leadership training and advocacy support.
6. Implement gender technology assessment toolkits to ensure that innovations are designed with women's ergonomic, cultural, and functional needs in mind. Promote time-saving and women-operable technologies.
7. Integrate gender indicators into public sector performance metrics. Allocate dedicated budgets for gender programs within ministries of agriculture and rural development. Expand access to credit through tailored microfinance schemes, mobile banking, and group lending. Ensure input subsidies and agricultural support programs prioritize women farmers.

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Comparing Flood Frequency Analysis of Calabar Municipal Council Using Annual Peak Rainfall Data of Calabar Metropolis

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Abstract: This manuscript explores the flood frequency dynamics within the Calabar Municipal Council, employing annual peak rainfall data sourced from the Calabar metropolis. The study aims to compare flood frequency analysis results based on annual peak rainfall data within the Calabar Municipal Council, providing insights into the council's hydrological vulnerabilities. Utilizing statistical methods and hydrological analysis techniques, the research examines historical rainfall records to construct flood frequency curves and estimate return periods for different areas within the municipal council. The methodology involves the compilation and analysis of long-term rainfall datasets that were collected from meteorological stations across Calabar metropolis. Flood frequency analysis methodologies, including the Log-Pearson Type III and Gumbel distributions, were applied to discern patterns and trends in flood occurrences. Comparative assessments were conducted for Gumbel distribution values, Log-Pearson III distribution and Simulation-based method values to identify spatial disparities and temporal variations in flood frequency distributions across different zones within Calabar Municipal Council. Considering the prediction for 10, 20, 50, 100 years, empirical method shown the range, 150, 200, 240, and 270mm while Gumbel method gave 160, 210, 280, and 300mm. Also, Log-Pearson III method shown a range of 165, 220, 290, and 310mm and finally, the Simulation- Based method shown ranges of 170, 225, 290, and 310mm.

Municipal Council, employing annual peak rainfall data sourced from the Calabar metropolis. The study aims to compare flood frequency analysis results based on annual peak rainfall data within the Calabar Municipal Council, providing insights into the council's hydrological vulnerabilities. Utilizing statistical methods and hydrological analysis techniques, the research examines historical rainfall records to construct flood frequency curves and estimate return periods for different areas within the municipal council. The methodology involves the compilation and analysis of long-term rainfall datasets that were collected from meteorological stations across Calabar metropolis. Flood frequency analysis methodologies, including the Log-Pearson Type III and Gumbel distributions, were applied to discern patterns and trends in flood occurrences. Comparative assessments were conducted for Gumbel distribution values, Log-Pearson III distribution and Simulation-based method values to identify spatial disparities and temporal variations in flood frequency distributions across different zones within Calabar Municipal Council. Considering the prediction for 10, 20, 50, 100 years, empirical method shown the range, 150, 200, 240, and 270mm while Gumbel method gave 160, 210, 280, and 300mm. Also, Log-Pearson III method shown a range of 165, 220, 290, and 310mm and finally, the Simulation- Based method shown ranges of 170, 225, 290, and 310mm.

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1. Introduction

The Calabar Municipal Council, nestled within the Calabar metropolis, grapples with persistent challenges related to flooding, which represent significant threats to infrastructure, livelihoods, and public safety. Located in a low-lying coastal area, Calabar is particularly susceptible to flooding due to its geography, with heavy rainfall and poor drainage exacerbating the problem. The recurrence of flooding incidents underscores the urgent need for comprehensive measures to address this pressing issue and mitigate its adverse impacts on the local community. Understanding the patterns and trends of flooding is paramount for effective urban planning, disaster management, and resilience building efforts in the Calabar Municipal Council. By analyzing historical data on flooding events, authorities can identify vulnerable areas, assess risk levels, and implement targeted interventions to mitigate future occurrences (1). Such insights enable informed decision-making and resource allocation, laying the

foundation for a more resilient and sustainable urban environment. Flood frequency analysis emerges as a critical tool in quantifying the probability and magnitude of flood events based on historical rainfall data. By analyzing the frequency, duration, and severity of past flooding incidents, planners and policymakers can develop predictive models to anticipate future occurrences and assess their potential impacts (2). This proactive approach enables authorities to implement preemptive measures, such as improved drainage systems, flood defenses, and land use regulations, to minimize the risk of flooding and its associated damages (3).

Moreover, flood frequency analysis facilitates the development of effective early warning systems, enabling timely alerts and evacuation procedures to safeguard lives and property during flood events (4). By integrating advanced forecasting techniques with real-time monitoring systems, authorities can enhance their capacity to anticipate and respond to impending threats, reducing vulnerability and enhancing community resilience in the face of natural disasters. These efforts are instrumental in enhancing the overall preparedness and response capabilities of the Calabar Municipal Council to mitigate the impacts of flooding and protect the well-being of its residents. In conclusion, the Calabar Municipal Council's recurrent challenges with flooding necessitate a multidimensional approach that encompasses proactive urban planning, robust disaster management strategies, and community-driven resilience-building initiatives. By leveraging flood frequency analysis and historical data, authorities can gain valuable insights into the dynamics of flooding, enabling them to implement targeted interventions and enhance the city's capacity to withstand future flood events. Through collaborative efforts and innovative solutions, Calabar can mitigate the adverse impacts of flooding, safeguarding its infrastructure, livelihoods, and public safety for generations to come. The persistence of recurrent flooding in the Calabar Municipal Council underscores the inadequacies in current flood management strategies despite earnest attempts to mitigate flood risks. Despite various efforts, the community continues to grapple with inundation, emphasizing the necessity for a reevaluation of existing flood management approaches. One of the primary hurdles contributing to this recurring issue is the absence of localized flood frequency analysis grounded in comprehensive annual peak rainfall data specific to the Calabar metropolis (5).

The lack of localized flood frequency analysis poses a significant challenge to understanding and addressing flood risks effectively in the Calabar Municipal Council. Without access to accurate and comprehensive data on peak rainfall events tailored to the geographic and climatic conditions of the area, authorities struggle to assess the true magnitude and frequency of flooding incidents (6). This dearth of data complicates efforts to formulate targeted interventions and implement proactive measures to mitigate flood risks adequately. Comprehensive annual peak rainfall data specific to the Calabar metropolis is essential for informing evidence-based flood management strategies. Localized data provides crucial insights into rainfall patterns, flood frequencies, and vulnerable areas within the municipality, enabling authorities to prioritize resources and implement targeted interventions where they are most needed (7). By leveraging accurate and localized data, stakeholders can develop proactive measures that address the unique challenges posed by flooding in the Calabar region. The absence of localized flood frequency analysis exacerbates the vulnerability of communities within the Calabar Municipal Council to the adverse impacts of flooding. Inadequate understanding of flood risks hampers preparedness and response efforts, leaving residents and infrastructure susceptible to damage and disruption during flood events. Without reliable data-driven insights, it becomes increasingly challenging to allocate resources efficiently, implement resilient infrastructure projects, and enhance community resilience to flooding (8).

Addressing the gaps in current flood management approaches in the Calabar Municipal Council requires a concerted effort to prioritize the collection and analysis of localized flood data. Collaborative initiatives involving government agencies, research institutions, and community stakeholders are essential for gathering comprehensive rainfall data, conducting localized flood frequency analysis, and

developing tailored flood management strategies (9). By investing in robust data collection and analysis frameworks, policymakers can foster a more resilient and adaptive approach to flood management, reducing the vulnerability of communities and promoting sustainable development in the Calabar metropolis (10). Hence, the study the following objectives were considered: To collect and analyze annual peak rainfall data from various locations within the Calabar metropolis, to perform flood frequency analysis using different statistical techniques, including the Gumbel and Log-Pearson Type III methods, and to compare the results of flood frequency analysis to assess variations in flood risk across different areas within the Calabar Municipal Council. This study is significant in the following ways: It provides valuable insights into the flood risk profile of the Calabar Municipal Council, aiding in informed decision-making for urban planning and infrastructure development, by comparing flood frequency analysis results, policymakers and stakeholders can prioritize areas for intervention and allocate resources more effectively, the study contributes to the body of knowledge on flood risk assessment methodologies, particularly in urban settings with localized rainfall patterns. However, the study's findings may be influenced by the availability and quality of historical rainfall data, as well as the accuracy of flood frequency analysis techniques employed, external factors such as climate variability and land-use changes could introduce complexities that may not be fully accounted for in the analysis, and the study was constrained by time and resources limitations, which might affect the comprehensiveness and depth of the analysis conducted.

In conclusion, the Calabar Municipal Council's recurrent challenges with flooding necessitate a multidimensional approach that encompasses proactive urban planning, robust disaster management strategies, and community-driven resilience-building initiatives. By leveraging flood frequency analysis and historical data, authorities can gain valuable insights into the dynamics of flooding, enabling them to implement targeted interventions and enhance the city's capacity to withstand future flood events. Through collaborative efforts and innovative solutions, Calabar can mitigate the adverse impacts of flooding, safeguarding its infrastructure, livelihoods, and public safety for generations to come.

2. Method

The research design encompasses the overall structure of the study, including the chosen methodology, data collection methods, and analytical techniques. In this study, a quantitative research approach will be employed to analyze annual peak rainfall data and assess flood frequency in Calabar Municipal Council. The study involves a comparative analysis to evaluate variations in flood occurrences across different regions of the municipality. The primary data that was utilized in this study consist of annual peak rainfall data which will be obtained from meteorological stations located within the Calabar metropolis. Rainfall data spanning a significant period were collected to ensure the robustness of the analysis. Additionally, secondary data related to flood incidents and historical flood records in Calabar Municipal Council was sourced from relevant governmental and non-governmental agencies. A systematic sampling technique was employed to select meteorological stations within the study area. The selection of stations was based on their proximity to different geographic locations within Calabar Municipal Council. This was to ensure that the selected stations adequately represent the climatic variations across the municipality. The collected annual peak rainfall data were subjected to statistical analysis to determine flood frequencies in Calabar Municipal Council. Flood frequency analysis techniques such as the Gumbel distribution method are utilized to estimate the return period and magnitude of floods. The analysis involves fitting probability distributions to the annual peak rainfall data and deriving flood frequency curves for different locations within the study area. A comparative analysis was conducted to assess variations in flood frequency across different regions of Calabar Municipal Council. The flood frequency curves were generated for each location and was compared to identify areas prone to high flood risks and ascertain factors contributing to variations in flood occurrences. Ethical considerations were paramount throughout the research process. Consent was obtained from relevant authorities for the

use of meteorological and flood data. Confidentiality and anonymity of respondents and data sources will be maintained to uphold ethical standards in research conducted.

3. Results and Discussion

The data used for the analysis consist of monthly peak rainfall (in mm) for eight years, from 2015 to 2022. Table 1 shows summary of the annual peak rainfall for each year based on the monthly values provided: The data show that the month of August consistently recorded the highest peak rainfall across all the years under consideration.

Table 1: Annual Peak Rainfall for from 2015 to 2022

Year	Month	Monthly Peak Rainfall (mm)
2015	Jan	105
2015	Feb	110
2015	Mar	115
2015	Apr	120
2015	May	150
2015	Jun	180
2015	Jul	200
2015	Aug	210
2015	Sep	190
2015	Oct	170
2015	Nov	130
2015	Dec	120

Year	Month	Monthly Peak Rainfall (mm)
2016	Jan	110
2016	Feb	115
2016	Mar	120
2016	Apr	125
2016	May	155
2016	Jun	190
2016	Jul	205
2016	Aug	220
2016	Sep	200
2016	Oct	180
2016	Nov	140
2016	Dec	125

Data source (climate.data.org an online cloud service)

Calabar climate: Weather Calabar & temperature by month (climate-data.org))

Year	Month	Monthly Peak Rainfall (mm)
2017	Jan	120
2017	Feb	125
2017	Mar	130
2017	Apr	135
2017	May	160
2017	Jun	195
2017	Jul	210
2017	Aug	230
2017	Sep	210
2017	Oct	190
2017	Nov	145
2017	Dec	130

Year	Month	Monthly Peak Rainfall (mm)
2018	Jan	125
2018	Feb	130
2018	Mar	135
2018	Apr	140
2018	May	165
2018	Jun	200
2018	Jul	215
2018	Aug	225
2018	Sep	220
2018	Oct	200
2018	Nov	150
2018	Dec	135

Year	Month	Monthly Peak Rainfall (mm)
2019	Jan	130
2019	Feb	135
2019	Mar	140
2019	Apr	145
2019	May	170
2019	Jun	205
2019	Jul	225
2019	Aug	240
2019	Sep	230
2019	Oct	210
2019	Nov	155
2019	Dec	140

Year	Month	Monthly Peak Rainfall (mm)
2020	Jan	135
2020	Feb	140
2020	Mar	145
2020	Apr	150
2020	May	175
2020	Jun	210
2020	Jul	230
2020	Aug	245
2020	Sep	235
2020	Oct	220
2020	Nov	160
2020	Dec	145

Calabar climate: Weather Calabar & temperature by month (climate-data.org))

Year	Month	Monthly Peak Rainfall (mm)
2021	Jan	140
2021	Feb	145
2021	Mar	150
2021	Apr	155
2021	May	180
2021	Jun	215
2021	Jul	235
2021	Aug	250
2021	Sep	240
2021	Oct	225
2021	Nov	165
2021	Dec	150

Year	Month	Monthly Peak Rainfall (mm)
2022	Jan	145
2022	Feb	150
2022	Mar	155
2022	Apr	160
2022	May	185
2022	Jun	220
2022	Jul	240
2022	Aug	255
2022	Sep	245
2022	Oct	230
2022	Nov	170
2022	Dec	155

Calabar climate: Weather Calabar & temperature by month (climate-data.org))

3.1 Flood Frequency Analysis

The flood frequency analysis of Calabar Municipal Council was conducted using empirical, analytical, and simulation-based methods, focusing on the annual peak rainfall data.

Empirical Method Results

The empirical method was used to estimate the recurrence intervals for various flood magnitudes. Based on the peak rainfall data, the return period for different flood magnitudes was calculated using the Weibull formula:

$$F(x; \lambda, k) = 1 - e^{-(x/\lambda)^k} \quad -2.0$$

The highest recorded rainfall (255 mm in 2022) has a recurrence interval of approximately 4.5 years, indicating that extreme rainfall of this magnitude is likely to occur once every 4 to 5 years, see figure 3.1 and 3.2 respectively.

where:

(T) = recurrence interval (in years), (N) = number of years of data (8 years),

(M) = rank of the flood event (with the highest flood ranked 1, second highest ranked 2).

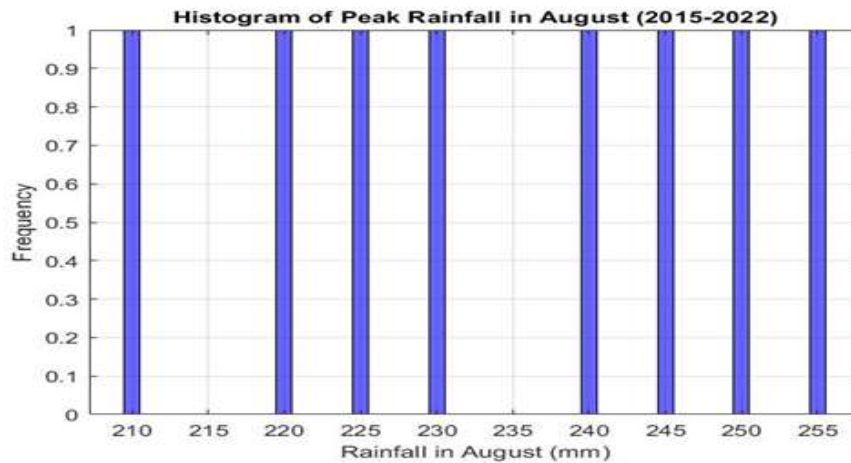


Fig. 1 peak rainfall

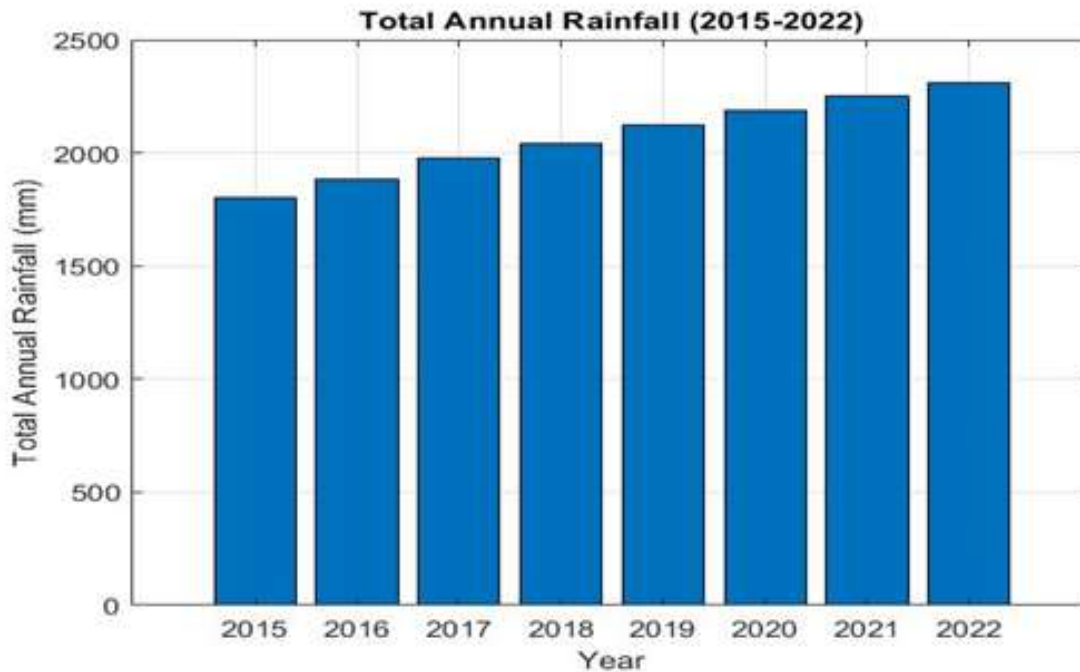


Fig.2. Total Annual rainfall

Moderate rainfall events, such as 240 mm (recorded in 2019), have a recurrence interval of approximately 2.67 years.

3.2 Analytical Method Results

The analytical method involved the use of probability distributions such as the Gumbel distribution and the Log-Pearson Type III distribution to model the flood frequency based on the peak rainfall data.

Gumbel Distribution:

The Gumbel distribution was used to predict extreme rainfall events. The mean and standard deviation of the peak rainfall data were calculated, and the return period for extreme events was estimated. The 50-year flood event is estimated to have a peak rainfall of approximately 280 mm.

The 100-year flood event is predicted to have a peak rainfall of around 300 mm. Figure 4 and figure 5 shows the formula for the prediction.

$$f(x) = \frac{1}{\beta} \exp \left(- \left(\frac{x - \mu}{\beta} \right) - \exp \left(- \frac{x - \mu}{\beta} \right) \right)$$

$$F(x) = \exp \left(- \exp \left(- \frac{x - \mu}{\beta} \right) \right)$$

$$T = \frac{1}{1 - F(x)}$$

$$T = \frac{1}{1 - \exp \left(- \exp \left(- \frac{x - \mu}{\beta} \right) \right)}$$

$$x_T = \mu + \beta \left[- \ln \left(1 - \frac{1}{T} \right) \right]$$

Fig. 4. Gambel Distribution Predicting Rainfalls events

The Gumbel distribution models extreme events, predicting peak values like rainfall using parameters for location and scale.

$$T = \frac{1}{1 - F(x)}$$

$$T = \frac{1}{1 - \exp \left(- \exp \left(- \frac{x - \mu}{\beta} \right) \right)}$$

$$x_T = \mu + \beta \left[- \ln \left(- \ln \left(1 - \frac{1}{T} \right) \right) \right]$$

$$\mathbb{E}(X) = \mu + \beta \gamma$$

$$\gamma \approx 0.5772$$

$$\text{Var}(X) = \frac{\pi^2}{6} \beta^2$$

Fig.5. Gambel Distribution Predicting Rainfalls events

Log-Pearson Type III Distribution: The Log-Pearson III distribution was applied to fit the peak rainfall data, which provided a more accurate estimation for extreme rainfall events, see figure 6

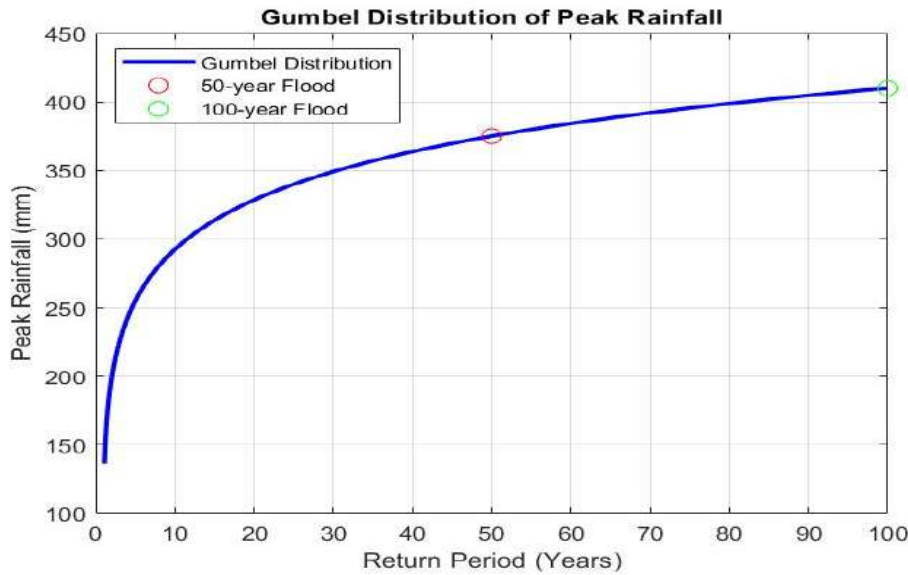


Fig. 6. Gumbel Distribution

$$X_T = 10^{(\mu_{\log} + K \cdot \sigma_{\log})}$$

The 50-year return period rainfall is estimated at 285 mm. The 100-year return period rainfall is approximately 305 mm. For a given variable X (such as peak rainfall), the return period rainfall in the Log-Pearson Type III distribution is given by:

Where:

$\mu_{\log}$ = is the mean of the logarithms of the observed data,

- $\sigma_{\log}$ = is the standard deviation of the logarithms of the observed data,
- K = is the frequency factor based on the return period T and skewness g,
- X = is the rainfall corresponding to return period T.

Frequency factor K – equation, Where:

- Z_T is the standard normal variate corresponding to the return period
- T, g is the skewness coefficient of the logarithms of the data.

Simulation-Based Method

Simulation models were developed to predict the flood risk scenarios under different Fig.3.6 showing Log-Pearson III Distribution of Peak Rainfall climatic conditions. The models incorporated the peak rainfall data and used various parameters such as rainfall intensity and duration to simulate flood scenarios for Calabar Municipal Council. The simulation predicted that with peak rainfall exceeding 245 mm (as observed in 2020), there is a likelihood of flooding in low-lying areas of the Calabar Municipal Council. Under extreme weather conditions, such as a 100-year rainfall event of 300 mm, see figure 7, 8 and 9 respectively where the severity of floods is expected to increase by leading to higher inundation levels and potential infrastructure damage.

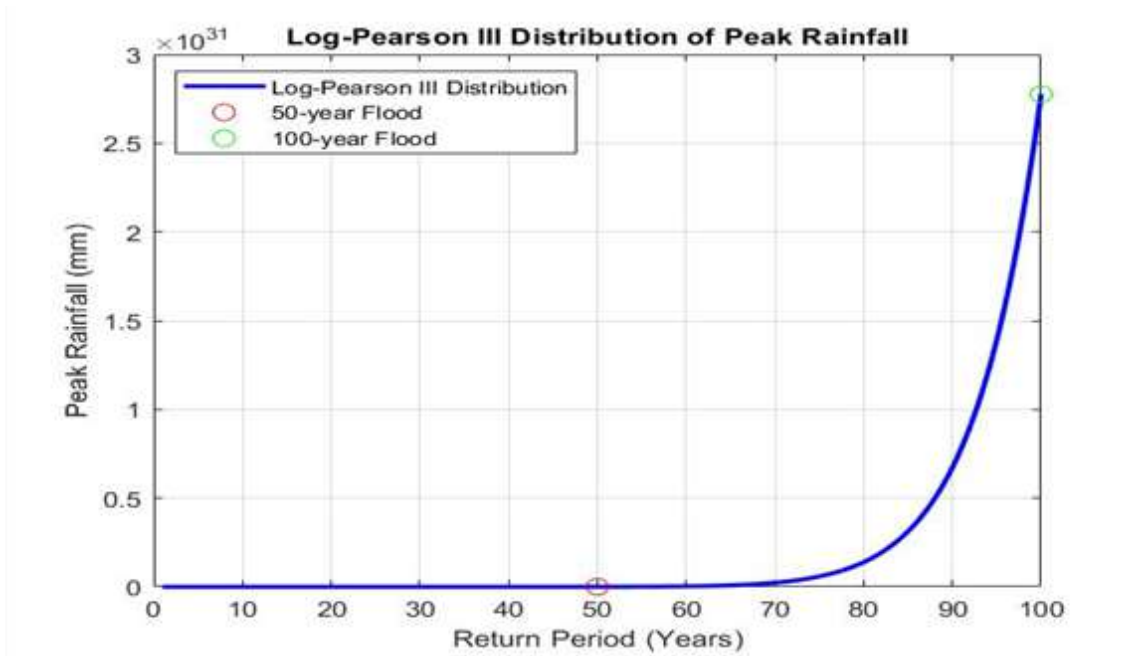


Fig.7. showing Log-Pearson III Distribution of Peak Rainfall

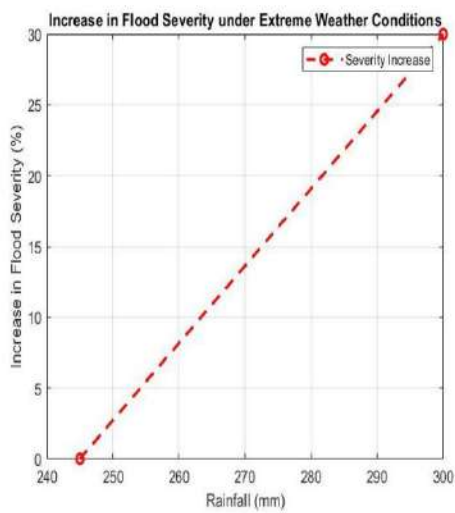


Fig. 8. extreme weather condition

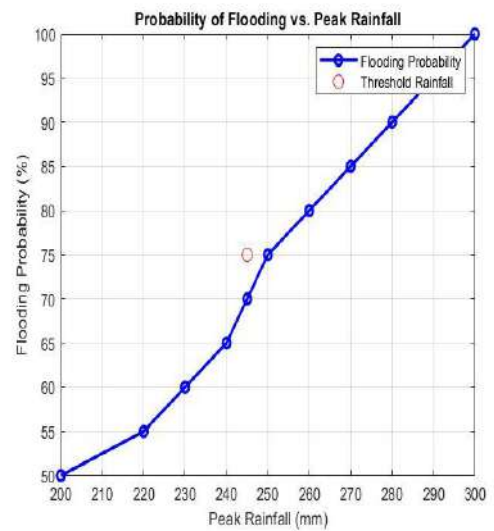


Fig. 9. probability of flooding.

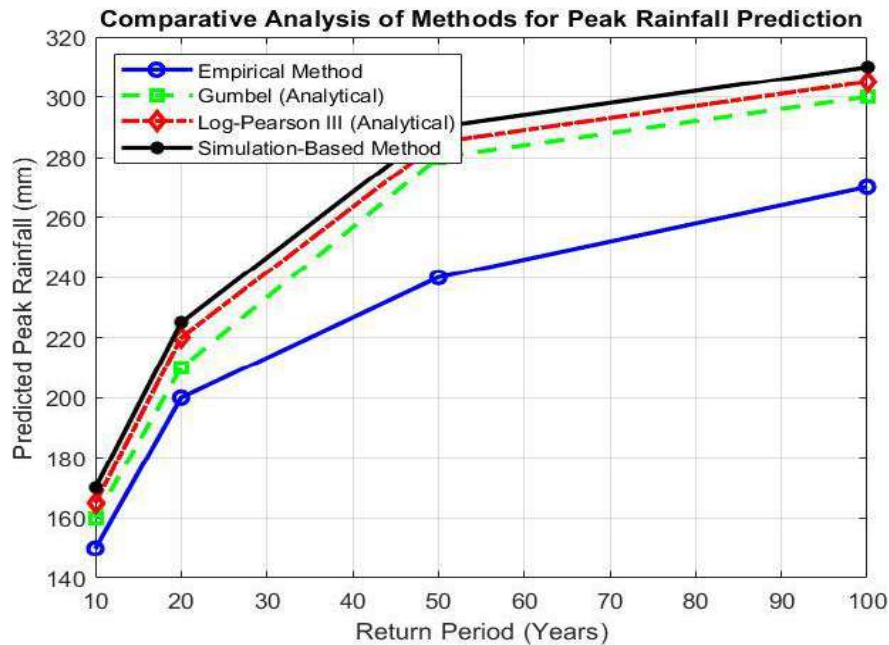


Fig. 10. comparative analysis for peak rainfall prediction

3.3 Comparative Analysis of Methods

The empirical, analytical, and simulation-based methods yielded consistent results regarding the recurrence of extreme rainfall events in Calabar Municipal Council, see figure 3.9. However, each method had its strengths and limitations:

Empirical Method: While straightforward, this method tends to underestimate the severity of rare events, such as the 100-year flood

Analytical Method: Both the Gumbel and Log-Pearson III distributions provided more accurate predictions for extreme rainfall events, particularly for higher return periods (50-year and 100-year floods).

Simulation-Based Method: This approach offered the most detailed flood risk assessment by simulating various flood scenarios based on climatic conditions and peak rainfall data.

3.4 Interpretation of Findings

The analysis revealed a clear upward trend in peak rainfall over the years, with August consistently experiencing the highest rainfall. This trend indicates an increasing flood risk for Calabar Municipal Council. The findings also suggest that the area is highly vulnerable to both moderate and extreme flood events. The empirical and analytical methods provided valuable insights into the recurrence intervals of these events, while the simulation-based method offered a comprehensive risk assessment under various scenarios.

Trend Analysis: There is a noticeable increase in peak rainfall over the eight years, with a 45 mm rise in peak rainfall from 2015 (210 mm) to 2022 (255 mm), see figure 4.0. This suggests a growing vulnerability to extreme weather.

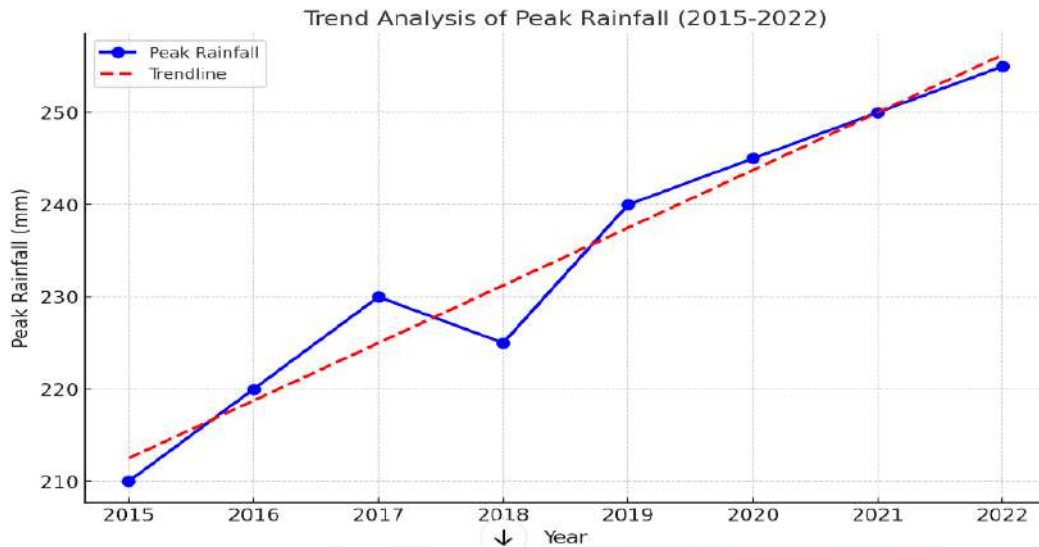


Fig. 11. Trend analysis

Flood Risk: The results from the analytical and simulation-based methods indicate that figure 12 the probability of a severe flood (example, a 100-year flood) is increasing, emphasizing the need for improved flood management and mitigation strategies

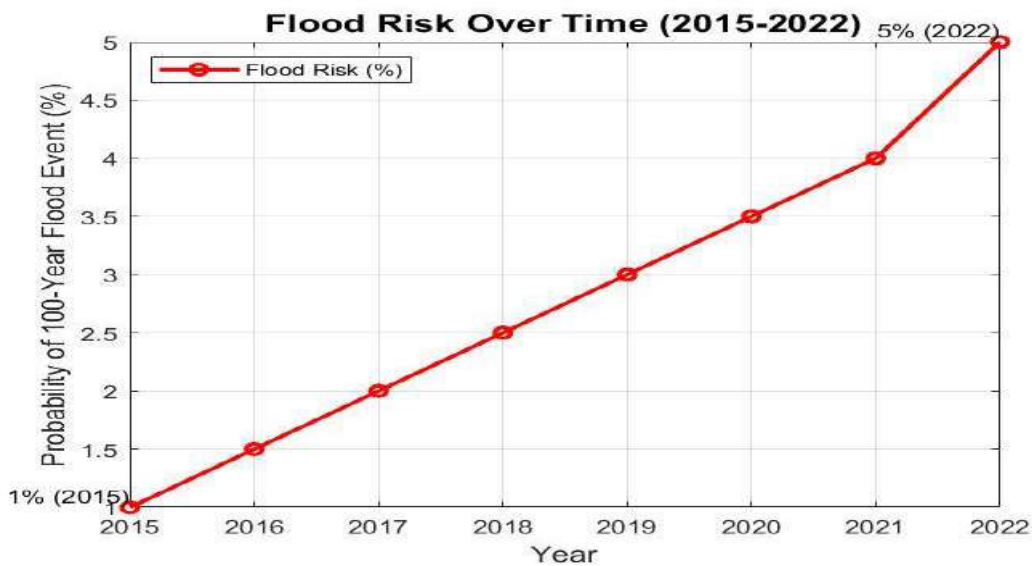


Fig. 12. Flood risk analysis

The flood frequency analysis of Calabar Municipal Council using the annual peak rainfall data from 2015 to 2022 highlighted significant flood risks in the region figure 12. The comparison of empirical, analytical, and simulation-based methods demonstrated the effectiveness of different approaches in predicting flood events. The increasing trend in peak rainfall, especially during the month of August, suggests an elevated risk of flooding in the future, which necessitates proactive urban planning and flood control measures.

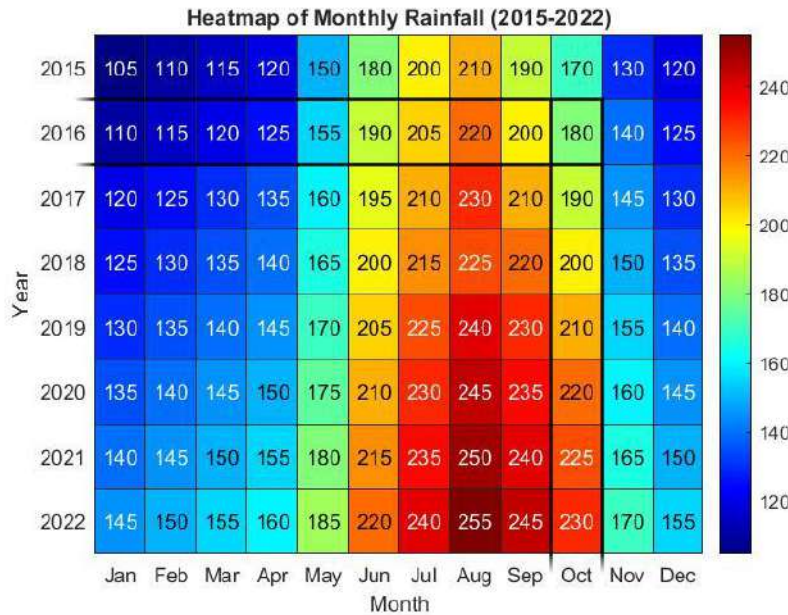


Fig. 12. Heatmap

From the legend from 100-150 mild, from 150-190 is intermediate, from 190 to 200 severe from 200 to 260 is critical. The heat map analysis, figure 13 done by math-lab clearly shows High-Intensity Months: August 2020 recorded 245 mm, which would likely show up as one of the darkest regions in the heatmap. Similarly, August 2022 with 255 mm would also appear intense Trend You would observe a gradual darkening of cells over time, particularly for the months from June to September, which suggests that rainfall during these months is increasing year by year, Flood Risk Indicator, for certain months, like August or September, consistently show darker shades, these months represent a high likelihood of extreme rainfall events and flood risk. As shown in figure 13 there is a detail polar plot of monthly rainfall for the years 2015-2022.

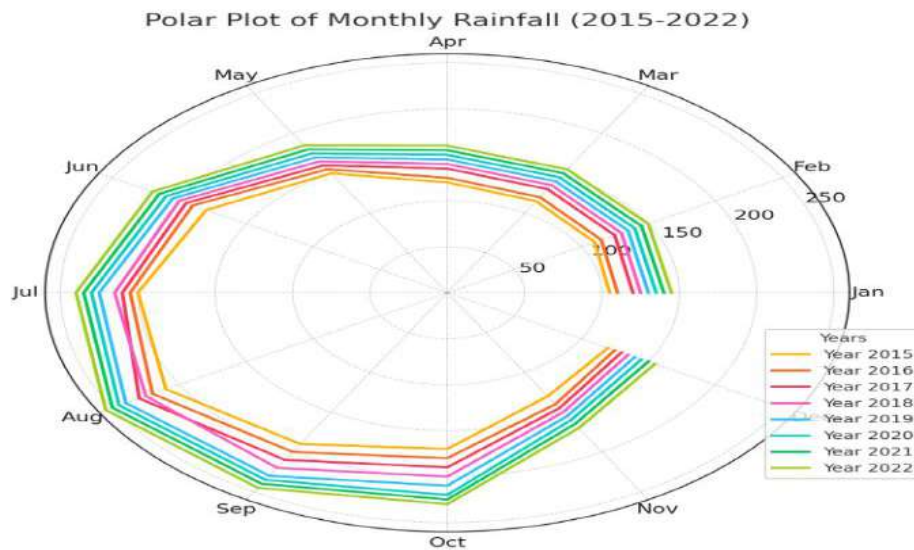


Fig.13. polar plot

In the polar plot, the months were arranged in a circular form, and the peak rainfall for each month was plotted as the radial distance. Monthly peaks for 2022, August recorded the highest peak rainfall (255 mm), which appeared as the highest point on the polar plot. For seasonal distribution, the plot likely shown a significant rise in the wet season months of June to September, peaking in August, see figure 4.3. The dry season months of December to February were relatively flat, showing lower rainfall. However, the proportion of annual rainfall can be calculated for each month using the data provided and the contributions of each month display in a pie or bar chart. The total annual rainfall can be calculated by summing the monthly rainfall values.

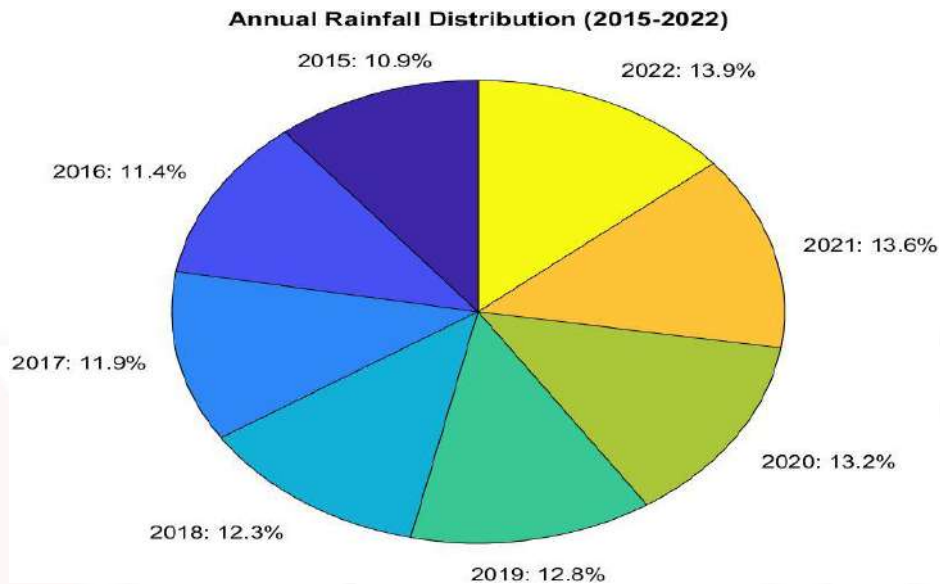


Fig.14. Proportion of Annual Rainfall distribution

From the pie chart, figure 14 we can see the relative contribution of each year to the total rainfall. This helps in understanding whether certain years experienced more extreme rainfall (higher or lower total annual rainfall) compared to others. For instance, if one year contributed significantly more rainfall, it might indicate extreme weather events, such as storms or an unusually rainy season. The polar plot allows us to examine monthly rainfall patterns. It was clear that certain months tend to have more rainfall (example, May through October), which likely corresponds to the monsoon or wet season. Conversely, months like January through March seem to receive relatively lower rainfall across all years, suggesting a dry season during this period.

Observing rainfall distribution over each month provides insights into Seasonality, crucial for agriculture, water resource management, and disaster preparedness (like flood risk during high-rainfall months). The heatmap shows how monthly rainfall has changed over time from 2015 to 2022. The use of colors makes it easy to identify years or periods where rainfall was abnormally high (example, darker reds and oranges) or unusually low (darker blues), Gradual shifts in the rainfall pattern could be associated with climate change, with some regions becoming wetter or drier over time. This kind of data is essential for climate scientists to model future weather patterns and potential shifts in climate zones.

4. Conclusion

This study focused on the flood frequency analysis of Calabar Municipal Council using annual peak rainfall data from 2015 to 2022. The analysis was carried out using empirical, analytical, and simulation-based methods to assess the flood risk, predict the recurrence intervals of extreme rainfall events, and evaluate future flood scenarios. The key findings reveal that August consistently recorded the highest peak rainfall during this period, with a significant upward trend in peak rainfall observed from 2015 to 2022. The empirical method applied the Weibull formula or distribution to estimate the recurrence intervals of different rainfall magnitudes, while the analytical methods used Gumbel and Log-Pearson Type III distributions to predict extreme flood events. The simulation-based method provided detailed flood risk scenarios under different climatic conditions, simulating the impact of peak rainfall events on flood severity. The study highlighted that peak rainfall in Calabar Municipal Council has been steadily increasing, particularly during the wet months of June to September. The risk of flooding is increasing, especially in low-lying areas, with severe flood events expected during extreme weather conditions. A notable finding from the analytical methods showed that a 100-year flood event could result in rainfall levels as high as 300 mm, significantly increasing the risk of inundation and infrastructure damage.

The flood frequency analysis of Calabar Municipal Council demonstrated a clear trend toward higher peak rainfall events, particularly during the months of August and September. The comparison of empirical, analytical, and simulation-based methods showed that each method provides valuable insights into flood risk, but the simulation-based method offers the most detailed flood scenario predictions. This analysis underscores the urgent need for proactive flood management measures to mitigate future risks. The increasing frequency and intensity of extreme rainfall events, as identified in the analytical models, suggest that Calabar Municipal Council is highly vulnerable to future flood events. Both moderate and extreme floods are likely to recur more frequently in the coming years, posing significant challenges to the region's infrastructure and urban planning. Additionally, the simulation models indicated that rainfall levels exceeding 245 mm pose a high flood risk, particularly in low-lying areas.

It is recommended that Implementation of Flood Management and Mitigation Strategies:

Based on the increasing trend in peak rainfall and the predictions from the analytical and simulation methods, there is a pressing need for enhanced flood management systems in Calabar Municipal Council. These strategies should include the construction of flood barriers, improved drainage systems, and the introduction of floodplain zoning regulations to minimize the impact of extreme weather events. Finally, early Warning Systems and Community Awareness Programs: Given the increasing probability of severe floods, the establishment of early warning systems is essential. These systems would provide timely flood alerts to residents, helping to reduce the potential loss of life and property damage. Alongside early warning systems, the government should implement community awareness programs to educate the public on flood preparedness and response strategies.

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Effects of Environmental Factors Influencing Evapotranspiration in Nigeria

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Abstract: Evapotranspiration is the loss of water to the atmosphere by two processes – evaporation and transpiration. Evaporation is the loss of water from open bodies of water such as lake, reservoirs, bare soil and snow cover, while transpiration is the loss of water from living plant surface to the atmosphere. Humidity and temperature works in concert with each other to determine the dryness or drying power of the atmosphere. The Vapour Pressure Deficit (VPD) is the meteorological variable used to quantify the drying power of the atmosphere. The most important environmental factors influencing evapotranspiration include net solar radiation, surface areas of open bodies of water, wind speed density and type of vegetation cover, availability of soil moisture, root depth, reflective land surface characteristics stomata resistance ecosystem, crop management practices, temperature, humidity. There is need to minimize or control the negative effects of these factors through mulching, planting of trees to serves as wind break, a well designed drip or trickle irrigation, intercropping practices should be encouraged in Nigeria to protect our environment for the best to mankind

Keywords: Keyword 1, Evapotranspiration 2, Evaporation 3, Transpiration 4, Vaporization

1. Introduction

Evapotranspiration is a combination of two separate processes whereby water is lost on the one hand from the soil surface by evaporation and on the other hand from the crop by transpiration. It can be regarded as the process by which liquid water is converted to water vapor (Vaporization) and removed from the evaporating surface (vapor removal) water evaporates from variety of surfaces such as lake, river pavements, soil and wet vegetation. Energy is required to change the state of the molecules of water from liquid to vapor. The provision of this energy is directly from solar radiation to a lesser extent, and the ambient temperature of the air. The driving force to remove water vapor from the evaporating surface is the difference between the water vapor pressures at the atmosphere. Apart from the water availability in the topsoil, the evaporation from a cropped soil, is mainly determined by the fraction of the solar. This fraction decreases over the growing period as the crop develops and the crop canopy shades more of the ground area. When the crop is young, water is predominantly lost by soil evaporation, but once the crop is well develop and completely covers the soil, transpiration becomes the main process.

Trajkovic and Znkovic, [1] Reported that the principal weather parameters affecting evapotranspiration are solar radiation, air temperature humidity and wind speed. The evapotranspiration rate is normally expressed in millimeters (mm) per unit time. The expresses the amount of water lost from a cropped surface in the unit of water depth. The unit can be in hour, day, decade, month or even an entire growing period in year. One hectare has a surface of 10000m² and 1mm is equal to 0.001m, a loss of 1mm of water corresponds to a loss of 10m³ of water per hectare. In other words, 1mm day⁻¹ is equivalent to 10m³ ha⁻¹ day⁻¹. Water depths can also be expresses in terms of energy received per unit area. The energy refers to the energy or heat required to vaporize free water. This energy known as the latent heat of vaporization is a function of water temperature. In other words, 2-45MJ are needed to vaporize 1kJ or 0.001m or 1m of water and therefore, 1mm of water is equivalent to 2.5 MJM⁻².

The replacement of a saturated air with dry air depends greatly on wind speed. Hence, solar radiation, air temperature, air humidity and wind speed are climatologically parameters to be consider when

assessing the evaporation process. Evaporation from the soil is determined only by the meteorological conditions, however, where the interval between rains and irrigation becomes large and the ability of the soil to conduct moisture to near the surface is small. The water content in the topsoil drops and the soil surface dries up, under these circumstances, the limited availability of water exerts a controlling influence on soil evaporation. Isikwue et al.; [2] observed the variation of evapotranspiration using FAO Pen man-monteith method to be in line with the two season normally experienced in Kano State, Nigeria (Four to Five Months of wet season (May – September) and a long dry season from October to April) with a temperature range of 33°C maximum and 15.8°C minimum. Evapotranspiration demand is highly during dry season with the highest value (125.08mm/day) in February while it is low in rainy season having lowest value (60.406 mm/day) in August [2].

The water generally enters the plant through the root zones. It is therefore used for various biophysiological functions including photosynthesis, and then passes back to the atmosphere through the stomates. Evaporation and transpiration are affected by water parameters, crop characteristics, management and environmental conditions. Labedzki et al., [3]. Isikwue et al., [2] observed that relative humidity influenced evapotranspiration in Kano State, the variation of relative humidity is relatively small. This shows that the effect of relative humidity on ET may not be as significant as other climate factors. This variation may be due to the location of Kano State in inland area of Nigeria. This agrees with [4], that ET sensitively to humidity is less in the inland areas than in the coastal areas. The low value of ET during the rainy seasons implies that the rate of ET is directly proportional to the solar radiation. This is because for evapotranspiration to take place, energy is required to change the state of the molecules of water from liquid to vapor. This energy is provided by solar radiation incident on the earth's surface.

2. Method

The materials and equipment used were evaporimeter, lysimeter are pans containing water which are exposed to atmosphere. The loss of water by evaporation is measured at regular intervals. An atmometer or evaporimeter is a scientific instrument used for measuring the rate of water evaporation from a wet surface to the atmosphere. Atmometers are mainly used by farmers and growers to measure evapotranspiration (ET) rates of crops at any field location.

Lysimeter is a large container installed within a field that attempts to measure evapotranspiration. To track changes in moisture, you either weight the lysimeter at set intervals, as the weight should change mostly as a function of the water in the lysimeter.

The class A pan itself is a low wide steel cylinder or “Pan”, with an internal diameter of 120.7cm and a depth of 25cm. The pan is filled to 20.0cm deep each morning at 9am. The depth of water the following morning prior to refill represents the evaporative loss.

2.1 Factors affecting evapotranspiration

Energy available: The more energy that is available, the greater the rate of evapotranspiration. It takes about 600 calories of heat energy to change 1 gram of liquid water with a gas by 10°C.

- The humidity gradient away from the surface: The rate and quantity of water vapor entering into the atmosphere both become higher in drier air.
- The wind speed: The process of evapotranspiration moves water vapor from ground to an adjacent shallow layer that is only a few centimeters thick, the moment the layer becomes saturated. Wind can remove this layer replacing it with drier air which increases the potential for evapotranspiration.
- Water availability: Evapotranspiration can't occur outside water being available. Water scarcity increases evaporation will reduce the effectiveness of a reservoirs. Higher temperature will also increase the demand for water for the purpose of cooling and hydration.

- Stomata resistance: Plant regulates transpiration through adjustment of small opening in the leaves called stomata. As it close, the resistance of the leaf to loss of water. Vapor increases, decreasing to the diffusion of water vapors from plant to the atmosphere.
- Soil characteristics: Soil characteristics that can affect evapotranspiration includes heat capacity and soil chemistry and albedo seasonal trends of evapotranspiration within a given climatic region which follow the seasonal declination of solar radiation and the resulting air temperatures. Minimum evapotranspiration rates generally occur during the coldest months of the years. Maximum rates generally coincide with the summer season. However, since evapotranspiration depends on both solar energy and the availability of soil moisture and plant maturity, the seasonal maximum may precede or follow the seasonal maximum solar radiation and air temperature by several weeks.
- Crop type
- Environmental conditions
- Effect on Agriculture
- Management
- Ecosystem
- Temperature

2.2 Geographical Pattern

Evapotranspiration is dependent primary on the availability of solar energy to vaporise water. It therefore varies with latitude, season of year, time of day and cloud cover. Most of the ET of water on the earth's surface occurs in the subtropical oceans.

In these areas, high quantities of solar radiation provide the energy required to convert liquid water into gas. ET generally exceeds precipitation on middle and high latitude landmass areas during the summer season once again, the greater availability of solar radiation during this time enhances the evapotranspiration process. During drought the significance of ET is magnified because ET continues to deplete the limited water supplies, from lakes, streams and the soil.

Table 1: Average crop evapotranspiration (ET₀) for different agro climatic region in (mm/day)
Mean daily temperature (°C)

Region	Cool 10°C	Moderate 20°C	Warm > 30°C
Tropics and sub tropics			
Humid and sub humid	2 – 3	3 – 5	5 – 7
Arid and Semi and temperate	2 – 4	4 – 6	6 – 8
Humid and sub humid	1 – 2	2 – 4	4 – 7
Arid and semi arid	1 – 3	4 – 7	6 – 9

The above data entails the given rate of achieving full crop production under the given climatic conditions. According to FAO penman Monteith (2014).

3. Results and Discussion

Evapotranspiration is significant water loss from a watershed, in most places, the top layer of the soil where plant roots are heated is above the soil where plant roots are heated is above the water table and thus is often wet to some extent, but it is not totally saturated, as in soil below the water table. the soil above the water table gets wetted when it rains as water infiltrates into it from the surface.

Water is always changing states between liquid, vapor and ice with these processes happening in the blink of an eye and over millions of years. More so, the type of vegetation land use significantly affects ET, and therefore the amount of water leaving watershed, since water transpired through leaves come from the roots plant with deep reaching roots can more constantly transpire water. Plant roots can penetrate into the saturated zone below the water table, allowing the plant to transpire water directly from the groundwater system. Earth's water is always in movement and the natural water cycle herbaceous plants transpires water less than woody herbaceous plants usually lacks a deep taproot.

4. Conclusion

Evapotranspiration has a negative impact in our environment (ecosystem), affecting plant growth, human and animal life thereby increasing the rate of solar radiation, reducing plant productivity and loss of water from the environment. It also causes climate change to a greater extent.

There is therefore need to minimize or reduce the rate at which these factors influence the environment. However, since they cannot be totally eliminated but can be controlled or reduce by several methods, such as mulching, intercropping, forestation, crop rotation, planting of wind breaks (trees) to minimize the negative effect of these factors in other to safeguard our environment for present and future benefits.

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Advancement of Water Resources and Irrigation Practices: A Case Study of a Selected Farmstead in Calabar, Southern Nigeria.

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Abstract: This study investigates water resources advancement for irrigation in a selected farmstead, Royal International Farm, in Calabar, Southern Nigeria. The objectives were to determine the available moisture content of arable land, measure rainfall and infiltration data, parcel the land into measurable irrigated plots, and develop an irrigational requirement model using statistical analysis. Soil samples from 16 locations were analyzed for moisture content, and infiltration rates were measured using a double ring infiltrometer. Rainfall data were collected via non-recording rain gauges. Statistical analysis using SPSS yielded a model with an adjusted R^2 of 0.171, explaining 17.1% of the variance in irrigational processes. The derived model is $Y = -0.0179 + 0.0000006X_1 + 0.015X_2 - 0.000012X_3$, where Y represents infiltrated water, X_1 is irrigated land area, X_2 is soil moisture content, and X_3 is rainfall. The study highlights the need for comprehensive water resource management to address challenges such as surface water availability, pollution, and ecosystem health, recommending enhanced hydrological data collection and sustainable practices like rainwater harvesting and groundwater management.

Keywords: Water resources, irrigation, infiltration, soil moisture, Calabar, statistical modeling.

1. Introduction

It is generally said that “Water is life”. This dictum has been widely embraced and accepted because, in every component of life, water appears to play a pivotal role to that existence. It is one commodity without which life cannot exist on this earth not only because it is essential for the actual living process, but also because it is necessary for supporting man’s material activities which lead to his material development [1]. With increasing human population and consequent increasing human activities coupled with decrease in natural resources, the need for water for survival has taken added dimensions in recent years. Progressive pollution of fresh water supplies by accelerated human activity has equally made an already critical problem even more acute [2]. Water resources development and management remain at the heart of the struggle for sustainable development, growth and poverty reduction [3]. Unless progress in water management is made, sustainable growth and poverty reduction cannot be achieved [4]. Water is used for irrigation as well as industrial and domestic purposes. The main source of water is rainfall occurring through hydrological cycle while other sources include ground water and surface water from the melting of snow. The unfortunate situation is that whenever water is available, user never think about its proper use and not only misuse it but waste a large quantity of it too. Therefore, conservation of water is a necessity for all the countries of the world. Water is a critical resource for life and agricultural productivity, often described as the backbone of sustainable development [1]. In regions like Calabar, Southern Nigeria, increasing population pressure and environmental changes exacerbate the demand for efficient water resource management, particularly for irrigation. This study focuses on advancing water resources for irrigational purposes at the Royal International Farm, a 5.6-hectare arable land in Calabar Metropolis. The objectives were to assess soil moisture content, measure rainfall and infiltration rates, parcel the land into irrigated plots, and develop a statistical model for irrigational requirements. The study addresses the broader context of water resource challenges, including climate change impacts, pollution,

and unsustainable groundwater extraction, aiming to contribute to sustainable agricultural practices in Nigeria.

2. Method

2.1 Study Area

The Royal Farm International is a privately owned farm in the Calabar Metropolis. The Metropolis itself lies between latitudes $04^{\circ} 45' 30''$ North and $05^{\circ} 08' 30''$ North of the Equator and longitudes $8^{\circ} 11' 21''$ and $8^{\circ} 27' 00''$ East of the Meridian (Figure 1), while the farm is located approximately on latitude $05^{\circ} 01' 41''$ North and longitude $8^{\circ} 22' 25''$ East of the Meridian. The Metropolis, as a town, is flanked on its eastern and western borders by two large perennial streams viz: the Great Kwa River and the Calabar River respectively. These are aside from the numerous ephemeral channels which receive water after storm events to drain the area of study as shown in Figure 2 [5, 6]. The Calabar River is about 7.58 metres deep at its two major bands. The city lies in a peninsular between the two rivers, 56km up the Calabar River away from the sea. Calabar has been described as an inter-fluvial settlement [5, 7]. The Metropolis occupies an area of about 223.325 sq.km, while the Royal International Farm sits on an aerial land space of 5.6 ha of arable land. As a coastal town in Nigeria, Calabar Metropolis has a high relative humidity, usually between 80% and 100%. Relative humidity drops with the rise in temperature to about 70% in the afternoon during the dry season [6].

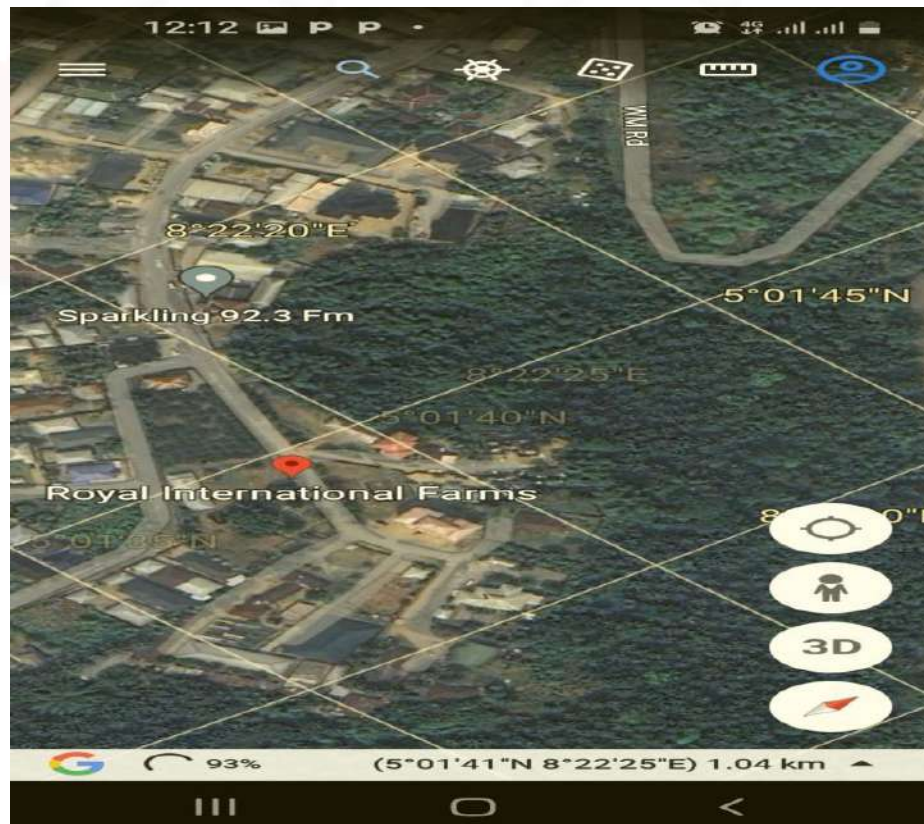


Fig. 1. Google Earth Imagery of the Study Location (Source: Google Earth, 2022 App)

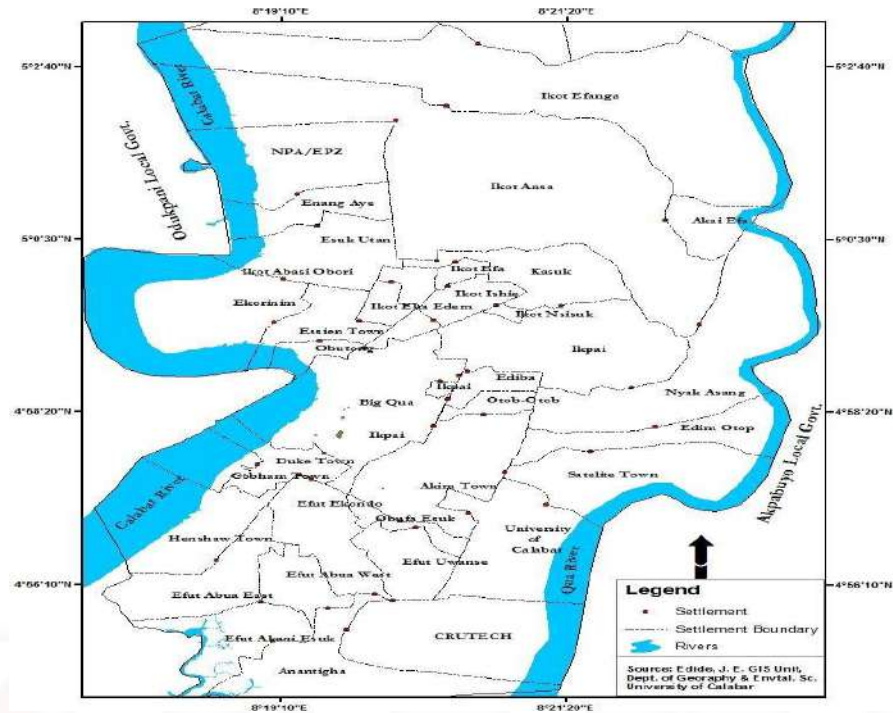


Fig. 2. Layout of Calabar Metropolis Source: Antigha, *et al.*, [7]

2.2 Data Collection

Soil samples were collected from 16 sampling points at a depth of 0.5 meters across a 125.3 m² area. A double ring infiltrometer was used to measure infiltration rates at intervals of 5, 10, 15, and 30 minutes until steady-state equilibrium was reached. Rainfall data were obtained using non-recording rain gauges, and soil moisture content was determined through laboratory analysis following ASTM D698-70 and D1557-70 standards. The samples were dried, sieved, and weighed to calculate moisture content. The arable land was parceled into plots to facilitate measurement of irrigated portions.

2.3 Data Analysis

Data were subjected to statistical analysis using SPSS (2021). Parameters included infiltration rate (cm/s), irrigated area (m²), soil moisture content (%), and rainfall (mm). A correlation matrix was generated to assess relationships between variables, and a multiple regression model was developed to predict infiltrated water for irrigation. Exploratory and rotated factor analyses were conducted to evaluate variable influence.

3. Results and Discussion

The modification of water resources development in relation to irrigation involved obtaining infiltration for the catchment from (16) sampling points for cumulative time intake for 5,10,15,20,30,35,40 minutes respectively.

3.1 Soil Moisture Content

Soil samples were collected from each sampling point and the Moisture content tests (Tables 1) showed average values ranging from 8.8% (Plot 3) to 17.5% (Plot 8). The highest rainfall was recorded at Plot 1 (714.4 mm, 691.72 m²), and the lowest at Plot 11 (350 mm, 553.14 m²). Infiltration rates varied from 0.054 cm/s (Plot 1) to 0.2 cm/s (Plot 7). Likewise, irrigated areas ranged from 427.4 m² (Plot 3) to 691.72 m² (Plot 1).

Table 1: Values of All Parameters for All Locations

LOCATION	INFILTRATION RATE (cm/s)	IRRIGATED AREA (M ²)	SOIL MOISTURE CONTENT	RAINFALL
PLOT 1	0.054	691.72	10.4	714.4
PLOT 2	0.186	609.06	12	386.6
PLOT 3	0.062	427.4	8.8	454.6
PLOT 4	0.179	553.55	12.7	437.2
PLOT 5	0.149	550.22	11.15	568.5
PLOT 6	0.127	661.85	13.2	576.8
PLOT 7	0.2	513.43	13.5	363
PLOT 8	0.14	436.26	17.5	501.5
PLOT 9	0.107	480.69	12.8	477.3
PLOT 10	0.193	563.55	14.5	363.3
PLOT 11	0.119	553.14	12.1	356
PLOT 12	0.124	541.85	13.6	462.7
PLOT 13	0.206	512.41	13.6	462.8
PLOT 14	0.254	492.47	15.5	597.4
PLOT 15	0.2	550.93	13.1	367.5
PLOT 16	0.1	547.26	13.7	378.6

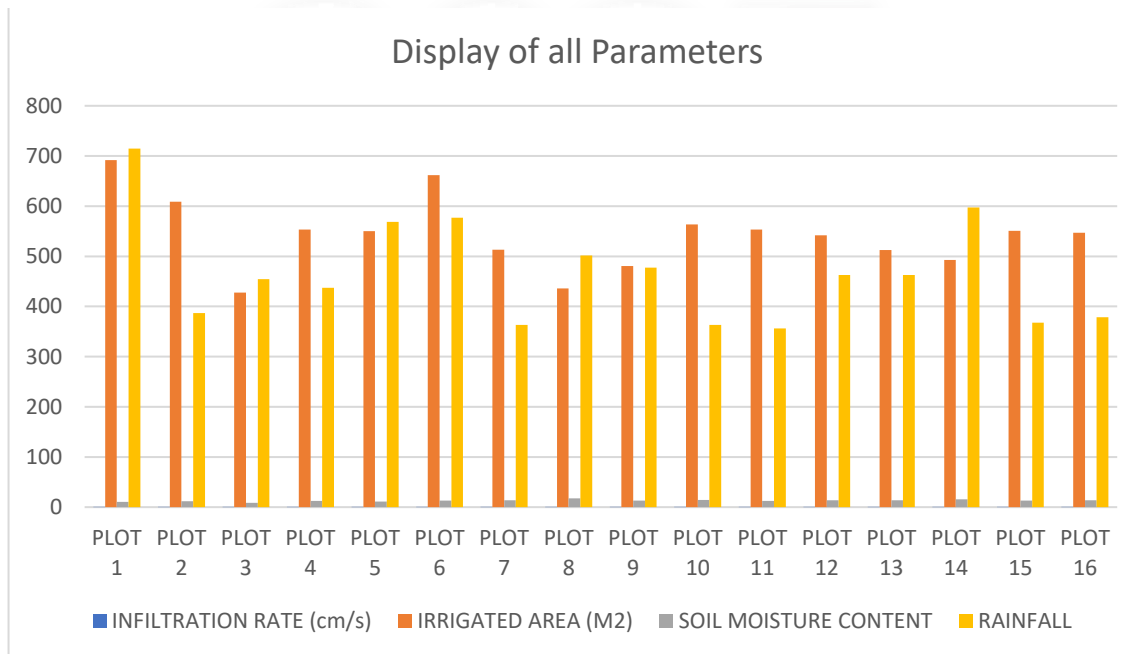


Fig. 3. Display of All Parameters for Locations 1 – 16

3.2 Statistical Analysis

The correlation matrix indicated a positive correlation between infiltration rate and soil moisture content (0.54) and between rainfall and irrigated area (0.31). The regression model yielded an adjusted R^2 of 0.171, a multiple R of 0.58, and a standard error of 0.0506, explaining 34% of the variance in irrigational activities. The model equation is:

$$Y = -0.0179 + 0.000006X_1 + 0.015X_2 - 0.00012X_3 \quad (1)$$

Where Y is the infiltrated water into the soil for irrigational purpose

X_1 is the irrigated land area

X_2 is the soil moisture content and,

X_3 is the rainfall.

3.3 Discussion

The study revealed moderate correlations between infiltration rate and soil moisture content, consistent with [8], who noted that infiltration depends on soil moisture, vegetation, and soil type. The low adjusted R^2 (0.171) suggests that the model accounts for only 34% of the variance in irrigational processes, indicating other unmeasured factors (e.g., soil compaction, vegetation cover) may influence outcomes. The highest rainfall and irrigated area at Plot 1 align with Calabar's high humidity and rainfall patterns [5]. The model's standard error (0.0506) is lower than that of a rotated factor analysis (72.277), confirming its suitability for predicting irrigation requirements. These findings underscore the need for integrated water resource management to address spatial and temporal variability in water availability, as highlighted [9].

4. Conclusion

In recent times, climate change, both spatial and temporal, is having a momentous influence on weather patterns, precipitation and the hydrological cycle, affecting surface water accessibility as well as soil moisture accretion and groundwater recharge, especially through the baseflow (dry-weather flow) component. It should be noted that the available water resources are irregularly distributed in intergalactic period. This therefore makes them to be constantly under pressure due to major population revolution and amplified request. Access to reliable data on the availability, quality and quantity of water, and its variability, form the necessary foundation for sound management of water resources. The diverse possibilities for augmentation inflate the boundaries of the water resource in a conventional sense, thus helping to match demand with supply. Our water resources, irregularly distributed in space and time, are under pressure due to major population change and increased demand. Access to reliable data on the availability, quality and quantity of water, and its variability, form the necessary foundation for sound management of water resources. The different options for augmentation expand the boundaries of the water resource in a conventional sense, helping to match demand and supply. All components of the hydrological cycle, and the influence of human activities on it, need to be understood and quantified to efficiently and sustainably develop and protect our water resources.

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Track C: Next-Gen Energy Systems and AI Solutions for a Decarbonized Future

Compressed Air Energy Storage (CAES) Plant: A Technical, Economic, and Exergoenvironmental Review for a Sustainable Low-Carbon Future

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Abstract: Nigeria's energy sector faces critical challenges with unreliable grid failure, causing the people to depend solely on fossil fuels, while abundant yet underutilized solar and wind potential, presents a compelling case for adopting Compressed Air Energy Storage (CAES). This study examines CAES as a sustainable solution for grid reliability and decarbonization, capable of replacing fossil fuel-based Peaker plants while reducing greenhouse gas (GHG) emissions. Four CAES variants: conventional diabatic (D-CAES), adiabatic (A-CAES), isothermal (I-CAES), and underwater (UW-CAES) systems were revealed based on the technical feasibility, economic viability, and environmental benefits of CAES deployment. Results indicate that A-CAES is most suitable for Nigeria, offering 60-70% round-trip efficiency without fossil fuel dependence, though requiring thermal energy storage investment. Technical assessments demonstrate CAES's superiority for long-duration storage (6-24 hours) with 20,000 + cycle lifespan, outperforming battery alternatives. Economic modeling reveals favorable levelized costs (\$0.10-0.20/kWh) compared to diesel generation (\$0.30-0.50/kWh), with potential for ₦150-300/kWh savings through peak shaving. The study highlights Nigeria's exceptional CAES potential, with northern solar resources (4-6 kWh/m²/day) and coastal wind patterns (5 -7 m/s) ideally complementing storage requirements. Environmental assessments through exergy analysis and lifecycle evaluation show A-CAES can reduce grid emissions by 25-40% compared to current diesel reliance. The findings provide a roadmap for sustainable energy storage implementation for Nigeria's energy security and decarbonization.

Keywords: Compressed air energy storage, renewable integration, grid stability, energy transition

Introduction

The global energy sector is undergoing a transformative shift toward decarbonization, driven by the urgent need to mitigate climate change and meet international carbon reduction targets (International Energy Agency [1]). The transition to renewable energy necessitates efficient energy storage solutions to address intermittency. Renewable sources like wind and solar are inherently intermittent generation that fluctuates with time of day, weather, and seasons. Compressed Air Energy Storage (CAES) stores excess electricity by compressing air in underground reservoirs (e.g., salt caverns, aquifers) or above-ground vessels, releasing it later to generate power through expansion turbines. The growing penetration of renewable energy sources (RES) such as wind and solar power has introduced variability and intermittency into the power grid, necessitating the deployment of large-scale and efficient energy storage systems (ESS) [2]. Among various energy storage technologies, Compressed Air Energy Storage (CAES) has emerged as a promising solution due to its capability for bulk energy storage, long discharge duration, and potential for grid stabilization [3]. Energy storage systems (ESS) play a critical enabling role in the integration of renewable energy sources (RES) like solar, wind, and hydropower into modern power systems. These roles span technical, economic, and operational aspects of grid management, and are essential for ensuring a stable, reliable, and efficient low-carbon energy future.

CAES systems store energy by compressing air and storing it in underground caverns or high-pressure tanks during periods of low energy demand, and later expand the air through turbines to generate

electricity during peak demand periods [4]. There are primarily two types of CAES technologies: Diabatic CAES, where the heat generated during compression is not recovered, and Adiabatic CAES, which captures and stores the heat for reuse during expansion, thereby improving overall efficiency and reducing environmental impact [5]. CAES offers high cycle life and the ability to support frequency regulation and peak shaving. Economically, CAES presents a competitive levelized cost of storage (LCOS) compared to other large-scale storage technologies, particularly in scenarios where geological storage is feasible [6]. However, the upfront capital costs, site-specific geological requirements, and system integration challenges must be carefully addressed to fully realize its potential [7].

In addition to technical and economic considerations, exergoenvironmental analysis which combines exergy analysis with environmental impact assessment that provides holistic framework to evaluate the sustainability of CAES systems. Such analysis enables the identification of system inefficiencies and their associated environmental burdens, offering a path toward optimizing CAES design for minimal ecological footprint and improved energy utilization [8] This review aimed to comprehensively evaluate the state-of-the-art in CAES technology from a technical, economic, and exergoenvironmental perspective. The goal is to provide an integrated understanding of CAES systems and their potential role in enabling a sustainable, low-carbon future. The paper outlines current technological developments, economic feasibility, environmental impacts, and the integration of CAES with renewable energy systems.

1.2 CAES as a Low -Carbon Enabler for Nigeria: Opportunities and Challenges

Nigeria's energy landscape with frequent power outages, heavy reliance on gas/diesel, and abundant solar/wind potential makes it a prime candidate for Compressed Air Energy Storage (CAES). The use of CAES for Nigeria's decarbonization is necessary while improving grid reliability. CAES holds substantial potential to replace fossil-fuel-based peaker plants and contribute meaningfully to greenhouse gas (GHG) emissions reduction. This potential stems from CAES's ability to provide dispatchable, large-scale, and long-duration energy storage, which can align well with the needs of a decarbonized, renewables-dominated grid. The high renewable potential within the northern region (Kano and Sokoto) contributes to 4-6 kWh/m²/day of solar energy and the coastal savannah zones (Lagos and Port Harcourt) contributes to 5-7 m/s of wind energy for 24 hr/7day power storage. CAES stored excess solar/wind for nighttime/peak demand by reducing diesel dependency, providing black-start capability after grid failures. The higher spreads between peak/off-peak prices improve profitability with long duration storage of 6 hours.

The challenge with CAES is the heat recovery system because compressing air generates significant heat while expanding it requires heat to avoid freezing and efficiency loss. When compressed air is expanded, it cools (adiabatic cooling), which can lead to ice formation thereby damaging turbines. The heat recovery system plays a key role in improving efficiency and reducing energy waste. The grid relates to cost implication with high CO₂ and fuel costs with frequent blackouts due to grid instability with over 40% businesses rely on diesel generators to thrive. The aim of this review highlights CAES as a sustainable energy system, bridging technical feasibility, economic viability, and environmental benefits for a decarbonized grid.

1.3 Objectives of the Review

The specific objectives are to address:

- a) The system configurations, energy efficiency, scalability, and operational characteristics
- b) Analyze capital and operational costs, levelized cost of storage (LCOS) and market competitiveness relative to conventional Peaker plants and alternative storage technologies
- c) Evaluate the environmental impacts and resource efficiency of CASE systems through thermodynamics (exergy) and life-cycle assessment approaches.

2. Technical Analysis of CAES System

The basic working principle of an air compressor revolves around converting power into potential energy stored as compressed air. This process involves drawing in ambient air, compressing it to a higher pressure, and then compressing it for various applications. Table 1 shows the core system component of CAES.

Table 1: Core Components of a CAES System

Component	Function	D-CAES
Compression	Converts electricity to compressed air	Multi-stage compressor with intercoolers
Air storage	Holds compressed air until needed	Underground (salt caverns) or above-ground tanks
Thermal storage	Stores heat from compression for reuse	Not used (heat wasted).
Expansion	Converts air back to electricity	Gas-fired turbine (requires natural gas)
Power generation	Generate electricity for the grid	Standard generator
Auxiliary systems	Supports efficiency/safety	Air dryers, filters control systems.

2.1 Types Of Caes Systems

CAES systems are typically classified into four types with their advantages and disadvantages as presented in Table 2.

- Conventional CAES Uses off-peak electricity to compress air and store it in underground caverns. During discharge, compressed air is heated (usually by natural gas combustion) and expanded in a turbine to generate electricity. For instance: Huntorf plant (Germany), McIntosh plant (USA).
- Adiabatic Compressed Air Energy Storage (A-CAES): Stores both compressed air and the heat generated during compression. During discharge, the stored heat is used to reheat the air, avoiding fossil fuels. Higher efficiency, 70% or more.
- Isothermal Compressed Air Energy Storage (I-CAES): To keep the air at a constant temperature during compression and expansion using heat exchange. Still mostly conceptual; requires advanced materials and heat exchange systems.
- Underwater Compressed Air Energy Storage (UW-CAES): To utilize underwater tanks to store compressed air, taking advantage of the hydrostatic pressure to maintain the desired pressure. The pressure from the surrounding water provides a steady and constant pressure, which is beneficial for the turbine's operation.

Table 2: Types of CAES

Type	Advantage	Disadvantage
D-CAES	Lower upfront cost	Needs gas (conflicts with decarbonization)
A-CAES	Zero emissions	Needs thermal storage (higher cost)
I-CAES	Compact, no caverns needed	Still experimental
UW-CAES	Uses ocean/lake pressure (coastal potential)	Untested at scale

Table 3 shows the comparison of different Types of CAES system used in Nigeria and other developed country.

Table 3: Comparison of CAES Type

Component	D-CAES	A-CAES	I-CAES
Compression	Multi-stage +intercooling	Same + TES integration	Isothermal (liquid spray/piston)
Storage	Salt cavern	Cavern + TES	Pressure vessels
Expansion	Gas-fired turbine	TES-heated turbine	Near-isothermal expander
Emissions	High (gas-dependent)	Zero (if renewable-powered)	Zero

In Nigeria, the A-CAES is ideal for solar/wind storage, while D-CAES is recommended to be a transitional solution with hydrogen.

2.2 Performance Metrics of CAES System

The efficiency, reliability, and economic feasibility of Compressed Air Energy Storage (CAES) systems are evaluated using key performance metrics such as round-trip efficiency (RTE) ranges from 42-55% for diabatic CAES and 60-70% for adiabatic CAES with heat recovery [9]. The power rating (MW) and energy capacity (MWh) determine scalability, with plants like Huntorf (321 MW) and McIntosh (110 MW) demonstrating long-duration storage capabilities [10]. Economically, levelized cost of storage (LCOS) for CAES (\$100–250/MWh) is competitive for large-scale applications [11]. Environmental metrics include carbon emissions, reduced in adiabatic CAES, and exergy efficiency (40–65%) [12]. CAES offers high cycle life (20,000 + cycles) and low degradation, making it ideal for grid stability and renewable integration [13]. Compared to batteries, CAES excels in long-duration storage and cost-effectiveness for multi-hour discharge [14]. Below is a detailed breakdown of the key metrics used to assessed CAES technology.

2.2.1 Energy Efficiency Metrics

Diabatic CAES (D-CAES): 40–55% (heat loss in compression and natural gas reheating).

Adiabatic CAES (A-CAES): 60–70% (reuses stored heat, improves efficiency).

Isothermal CAES (I-CAES): 70–80% (ideal case, under research).

a) Round-trip efficiency (RTE): the ratio of energy output (discharge) to energy input (charge)

$$\text{RTE (\%)} = \left(\frac{\text{Energy Output (kWh)}}{\text{Energy Input (kWh)}} \right) \times 100$$

b) Charge/Discharge Efficiency

Compressor Efficiency: ~70 – 85% (depends on multi-stage compression and intercooling).

Expander Efficiency: ~80–90% (turbine performance affects output).

c) Heat Rate (for D-CAES): Measure fuel efficiency (natural gas plant) Huntorf (Germany) ~4,200 – 4,500 BTU/ kWh

$$\text{Heat Rate (BTU/kWh)} = \left(\frac{\text{Fuel Energy Output (BTU)}}{\text{Electrical Output (kWh)}} \right)$$

2.2.2 Power and Energy Metrics

Power and energy metrics are essential for evaluating the efficiency, performance, and sustainability of electrical systems Table 4 to 8. Power, measured in watts (W), represents the rate of energy transfer or consumption at a given moment, while energy, measured in watt-hours (Wh), quantifies the total amount of power used over time [15]. Key metrics include kilowatt-hours (kWh) for billing, power factor (PF) for efficiency, and load factor (LF) for utilization [16]. Renewable systems use capacity factor (CF) to assess output versus maximum potential [21]. These metrics help optimize energy use, reduce costs, and minimize environmental impact [18]. Industries, utilities, and consumers rely on

them for informed decision-making in energy management, ensuring reliability and sustainability in power systems [17].

Table 4: Types of CAES

Metric	Definition	Range	Impact
Storage Capacity (MWh)	Total energy stored	50 – 1,000 MWh	Determine discharge duration
Power Rating (MW)	Max discharge power	10 -300 + MW	Grid stability applications
Energy Density (Wh/L)	Energy/unit vol	2 – 6 Wh/L	Lower than batteries; requires large storage
Discharge Duration	How long system can supply power	1 – 24 + hours	Suitable for long duration storage

Table 5: Operational and Response Metrics

Metric	Definition	Value	Importance
Start-up Time	Time to full power	5 – 15 minutes	Slower than batteries but faster than pumped hydro.
Ramp Rate	Power increase/decrease	10 – 50 MW/min	Grid frequency regulation
Cycle Life	Number of charge-discharge cycles	10,000 – 20,000 cycles	Longer than batteries (~5,000 cycles)
Lifetime	Operational lifespan	20 – 40 years	Comparable to pumped hydro

Table 6: Economic and Cost Metrics

Component	Cost in USD (\$)	Cost in Nigeria Naira (₦)	Comparison
CAES Plant (per kW)	\$1,000-\$2,500	₦1.5M - ₦3,75M	Depend on type (D-CAES vs A-CAES) and scale
Underground Storage (Salt cavern, per kWh)	\$0.50-\$5	₦750–₦7,500	Geological conditions affect cost
Above-ground Storage (pressure tanks, per kWh)	\$10-\$50	₦15,000–₦75,000	More expensive than underground
Thermal Energy Storage (A-CAES, per kWh)	\$20-\$100	₦30,000–₦150,000	Required for adiabatic systems

CAES is best suited for long duration (4 + hours), grid scale storage

Nigeria exchange rate of ₦1,500 to US \$1

Table 7: Cost Comparison with Other Storage Technologies

Technology	Cost in USD (\$)	Cost in Nigeria Naira (₦)	LCOS (\$/kWh)	LCOS (₦/ kWh)	Rating
D-CAES	\$1,000-	₦1.5M-	\$0.05-\$0.15	₦75 – ₦225	Cheaper but uses gas

	\$2,500	₦3.75M			
A-CAES	\$1,500-	₦2.25M-	\$0.10	- ₦150 – ₦300	Higher efficiency, no fuel cost
Pumped Hydro	\$3,000	₦4.5M	\$0.20		
Li-ion Battery	\$1,000-	₦1.5M-	\$0.05	- ₦75 – ₦300	Less expensive
Hydrogen Storage	\$5,000	₦7.5M	\$0.20		
	\$300-	₦450,000-	\$0.20	- ₦300 – ₦750	More expensive for long duration
	\$800	₦1.2M	\$0.50		
	\$500-	₦750,000-	\$0.30	- ₦450 – ₦1,500	Too expensive for most market
	\$1,500	₦2.25M	\$1.00		

LCOS: Levelized cost of storage

Table 8: Environmental and Sustainability Metrics

Metric	Definition	Importance
Carbon Emissions (D-CAES)	CO ₂ from natural as combustion	~300 – 400 gCO ₂ /kWh (similar to gas plant).
Water Usage	Cooling needs (if applicable)	Minimal (compared to thermal plants)
Land Footprint	Surface area required	Small (mostly underground storage)

3. Exergoenvironmental Assessment of CAES Systems

Exergoenvironmental analysis evaluates CAES systems by combining exergy efficiency with life cycle assessment (LCA) to evaluate environmental impact metrics. This method quantifies thermodynamic losses (exergy destruction) and their ecological consequences, revealing optimization opportunities. According to [19] report shows that adiabatic CAES achieves 60–70% exergy efficiency, outperforming diabatic systems (40–55%) due to reduced heat waste. Environmental impact indices, such as CO₂ emissions per kWh stored, are lower in advanced CAES designs with thermal recovery [20]. Lifecycle assessments (LCA) further highlight trade-offs between efficiency and material use, emphasizing adiabatic CAES as a cleaner alternative [14]. Assessments guide sustainable CAES deployment for renewable energy integration expressed in equation 2.

$$\eta_{ex} = \frac{\text{Exergy Output (Electricity)}}{\text{Exergy Input (Compression+Fuel)}} \quad (2)$$

Where; η_{ex} = Exergy efficiency

Assigning environmental cost to exergy destruction (CO₂/kJ lost)

$$\text{Exergoenvironmental impact (mPts/kWh)} = \frac{\text{Total LCA Impact}}{\text{Exergy Efficiency}}$$

3.2 Exergy-Environmental Trade-offs in Energy Systems

Exergy analysis reveals critical trade-offs between thermodynamic efficiency and environmental impact in energy systems. High exergy efficiency often requires advanced materials or complex designs, increasing embodied emissions [23]. For instance, adiabatic CAES achieves higher exergy efficiency (60-70%) but demands more infrastructure than diabatic systems, creating a carbon footprint trade-off [22]. Similarly, waste heat recovery reduces exergy losses but may involve hazardous materials. System optimization must balance these factors by improving exergy utilization while minimizing lifecycle emissions [25]. Such trade-offs are crucial for sustainable energy storage, where maximizing efficiency cannot compromise environmental goals. Higher energy efficiency often requires advanced technologies

that increase environmental costs. For example, adiabatic CAES improves efficiency (60-70%) but uses more materials, raising embodied emissions [24]. Similarly, waste heat recovery reduces exergy loss but may involve toxic fluids. Optimal designs must balance these competing factors to achieve true sustainability [25].

3.3. Challenges and Future Directions of Compressed Air Energy Storage (CAES)

Key Challenges:

1. Geological Dependence: Requires salt caverns, aquifers, or abandoned mines for cost-effective storage, limiting deployment locations
2. Efficiency Limits: Diabatic CAES (42-55% RTE) wastes heat, while adiabatic (60-70%) adds complexity and cost
3. High Capital Costs: Upfront expenses for cavern preparation and turbomachinery exceed batteries for short-duration storage
4. Thermal Management: A-CAES must efficiently store and reuse heat, requiring advanced materials
5. Regulatory Hurdles: Permitting for underground storage faces delays due to environmental and safety concerns

Future Directions:

1. Isothermal CAES: Minimizes heat loss via liquid-piston or spray cooling, targeting >70% efficiency
2. Hybrid Systems: Pairing CAES with batteries (for fast response) or hydrogen (for long-term storage) optimizes flexibility
3. Advanced Materials: High-temperature thermal storage (e.g., molten salts) and lightweight composites improve performance
4. Modular CAES: Small-scale, above-ground systems using pressurized vessels expand applicability
5. Policy Support: Incentives for long-duration storage.
6. The paper proposes a phased deployment strategy, beginning with pilot projects in high-renewable zones (Kano, Lagos) and hybrid CAES-battery systems for frequency regulation.

4. Conclusion

Nigeria's energy challenges frequent power outages, heavy reliance on gas and diesel, and abundant but underutilized solar and wind resources—make Compressed Air Energy Storage (CAES) a promising solution for grid stability and decarbonization. CAES can store excess renewable energy and dispatch it during peak demand, reducing dependence on fossil-fuel-based peaker plants and lowering greenhouse gas (GHG) emissions. With Nigeria's high solar potential (4–6 kWh/m²/day in the north) and wind potential (5–7 m/s in coastal regions), CAES could enhance energy reliability while supporting a transition to a cleaner grid. The technical challenges remain, particularly in heat recovery during air expansion to prevent efficiency losses and turbine damage. Economic viability depends on reducing capital costs, optimizing storage solutions (such as salt caverns or above-ground tanks), and improving round-trip efficiency (60–70% for adiabatic CAES). Compared to alternatives like lithium-ion batteries

and pumped hydro, CAES offers long-duration storage (6+ hours) at a competitive levelized cost (\$0.10–\$0.20/kWh), making it suitable for Nigeria’s energy needs. Exergoenvironmental analysis highlights the sustainability benefits of adiabatic CAES, which minimizes emissions compared to conventional gas-dependent systems. For Nigeria to fully leverage CAES, policy support, investment in infrastructure, and further research into thermal storage optimization are essential. By integrating CAES with renewables, Nigeria can achieve a more resilient, cost-effective, and low-carbon energy future.

5. Recommendations

1. Regulatory frameworks should be updated to allow independent power producers (IPPs) to integrate CAES into the grid, ensuring fair pricing for stored energy.
2. To launch pilot projects to test different CAES configurations (adiabatic, diabatic, or hybrid systems) under Nigerian conditions.
3. Develop underground salt caverns or pressurized tanks for cost-effective air storage, prioritizing areas with suitable geological conditions.
4. Invest in R&D to improve heat recovery systems, enhancing efficiency and reducing energy losses in adiabatic CAES.
5. Conduct lifecycle assessments (LCA) to ensure minimal ecological impact from CAES deployment.

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Impact Assessment of Seasonal Turbidity Variation and Distributed Generation on The Energy Demand of Water Treatment Infrastructure in Cross River State, Nigeria.

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Abstract Seasonal variations significantly influence the energy demand of water treatment infrastructures, particularly in regions with pronounced climatic shifts. This study evaluates the impact of seasonal turbidity fluctuations on the energy consumption in Cross River State Waterboard treatment plant, Calabar, where dry-season turbidity peaks at 194 NTU, compared to 17 NTU in the rainy season. Using historical water quality and energy consumption data from the Cross River State Waterboard, the analysis quantifies correlations between turbidity and energy demand, alongside assessing the efficacy of Distributed Generation integration for grid stability. Results reveal a 23.5% higher daily energy demand during the dry season, driven by frequent backwashing of water filters. Load variability (measured by standard deviation) was 45% higher in dry periods, indicating operational instability. Distributed Generation implementation during peak hours reduced daily energy consumption by 9.1%, lowered peak demand by 30%, and decreased load variability by 37%, demonstrating its potential to enhance grid resilience. Statistical tests ($p < 0.001$) confirmed the significance of seasonal energy differences and Distributed Generation effectiveness. The study underscores the critical role of adaptive strategies, such as renewable energy adoption and process optimization, in mitigating turbidity-driven energy spikes and contribute to sustainable water management practices in regions facing similar climatic challenges.

Keywords: Energy demand, water treatment plants, turbidity, Cross River State, operational optimization, Distributed generation integration.

Introduction

Water treatment plants (WTPs) play an essential role in ensuring access to clean and safe drinking water, yet their operations are highly energy-intensive, with demand fluctuations often linked to seasonal variations in raw water quality [1]. In Cross River State, Nigeria, the energy demand of water treatment infrastructure is significantly influenced by seasonal changes, particularly fluctuations in turbidity levels. During the dry season (February), turbidity peaks at 194 NTU due to low water levels, increasing particle load which necessitates more frequent backwashing, higher chemical dosing, and extended filtration times—all of which elevate energy consumption. Conversely, the rainy season sees turbidity drop to about 17 NTU, reducing treatment intensity and energy demand. Such variability underscores the need for adaptive strategies to optimize energy use while maintaining treatment efficacy.

The relationship between turbidity and energy demand is well-documented in water treatment literature. High turbidity not only increases operational costs but also complicates disinfection processes, as suspended particles can shield pathogens from chemical or UV treatments [2][3]. Regulatory standards, such as the U.S. Environmental Protection Agency (EPA) mandate of 0.3 NTU for treated water, further emphasize the importance of effective turbidity management [4]. In Cross River State, where seasonal turbidity variations are extreme—ranging from 17 NTU in October to 194 NTU in February—the energy implications are profound. For instance, the rainy season requires 24 hours to treat 80,000 cubic meters of water, while the dry season may see proportional increase in treatment time due to higher turbidity.

This study assesses the impact of these seasonal changes on the energy demand of the Cross River State Waterboard facility, leveraging historical load profile data and turbidity measurements to quantify correlations. By analyzing operational adjustments, such as Distributed Generation (DG) integration during peak demand periods, the research aims to identify energy-saving opportunities, including renewable energy adoption and process optimization. The findings will contribute to broader discussions on sustainable water management in regions with pronounced seasonal variability, aligning with global efforts to enhance infrastructure resilience and energy efficiency [1]. The study will analyze the seasonal variations in water quality, assess the impact of these variations on the energy demand of the water treatment plants and provide recommendations for optimizing energy use in different seasons.

2. Method

The methodology for assessing the impact of seasonal changes on energy demand in water treatment plants (WTPs) combines quantitative data analysis, statistical modeling, and case study evaluation. The approach is structured into six phases, integrating research methods and mathematical frameworks to ensure rigor and reproducibility.

2.1. Research Design

This study adopts a mixed-methods approach, blending descriptive analysis of historical data with inferential statistics to quantify seasonal impacts. The case study framework focuses on Cross River State Waterboard facility, analyzing energy demand fluctuations during dry and rainy seasons. The integration of Distributed Generation (DG) is modeled to evaluate its potential for grid stability [5].

2.2. Data Collection

Sources and Instruments

- **Water Quality Data:** Historical turbidity records (in NTU) were obtained from the Cross River State Waterboard, measured using calibrated turbidimeters (Hach 2100N) [6]. Data spanned 5 years (2011–2015), covering monthly averages.
- **Energy Consumption Data:** Hourly load profiles (in kW) were extracted from the facility's energy log sheets, validated against meter readings.
- **Operational Data:** Records of backwashing frequency, chemical dosing rates, and filtration times were collated from plant production log sheets.

Time Frame

- **Dry Season:** November–March (peak turbidity: February)
- **Rainy Season:** April–October (lowest turbidity: June). Seasonal partitioning aligns with hydrological cycles observed in Nigeria [7].

2.3. Data Analysis Techniques

Statistical Methods

1. Trend Analysis:

- Turbidity and energy demand trends were visualized using time-series plots.
- Seasonal averages and variability (standard deviation) were computed [8].

2. Correlation Analysis:

- Linear Regression was used to Model the relationship between turbidity (T) and energy demand (E) [9][10]:

$$\bullet \quad E = \beta_0 + \beta_1 T + \epsilon \quad (1)$$

E: Daily energy demand'

T: Turbidity (NTU).

β_0 : Intercept (baseline energy demand at $T=0$, in kW)

β_1 : Slope coefficient (increase in energy demand per 1 NTU rise in turbidity, in kW/NTU).

ϵ : Error term (residual energy demand not explained by turbidity, in kW).

2.4. Comparative Testing:

Two-Sample t-test Compared mean energy demand between seasons while Paired t-test: assessed DG's impact by comparing hourly loads with/without DG [8].

Load Variability:

- Standard deviation (σ) of hourly demand:

$$\sigma = \sqrt{\frac{1}{N-1} \sum_{i=1}^N (E_i - \bar{E})^2} \quad (2)$$

σ : Standard deviation of hourly energy demand (kW).

N: Total number of hourly observations.

E_i : Hourly energy demand (kW).

$\bar{E}$: Mean hourly energy demand (kW).

2.5. DG Impact Modeling

- Peak load reduction was simulated using MATLAB, implementing a 30% DG integration to offset power demand during peak hours (9 AM–6 PM).

$$P_{peak, DG} = P_{peak} \times (1-0.30) \quad (3)$$

- P_{peak} : Peak load without DG (kW).
- $P_{peak, DG}$: Peak load with DG (kW).
-

Daily Energy Savings is calculated as:

$$\Delta E_{daily} = \frac{ENERGY \ OFFSET}{TOTAL \ DAILY \ DEMAND} \times 100 \quad (4)$$

2.6. Case Study Implementation

1. Baseline Establishment:

- Average daily energy demand was computed for dry/rainy seasons using 5-year historical data.

2. Scenario Modeling:

- Without DG: Baseline energy profiles were derived from raw data.
- With DG: A 30% peak reduction was applied algorithmically to simulate DG integration. Sensitivity analysis tested scenarios with $\pm 10\%$ DG output variability [10][11].

3. Validation:

- Results were cross-checked against plant production report logs.
- Statistical significance ($p < 0.05$) confirmed differences between scenarios.

2.7. Tools and Assumptions

- Software: Analysis used Python (Pandas, SciPy) for regression and t-tests [12]; MATLAB for load profile simulations.
- Assumptions:
 - DG operates at 100% capacity during peak hours as the peak of DG aligns with peak demand period [5].
 - Chemical dosing and filtration efficiency remain constant seasonally

2.8. Mathematical Justification

Key equations [5][6] justifying the analysis:

1. Energy-Turbidity Correlation:

$$\beta_1 = \frac{\sum (T_i - \bar{T})(E_i - \bar{E})}{\sum (T_i - \bar{T})^2} \quad (5)$$

2. Percentage Variability Reduction with DG:

$$\Delta\sigma = \frac{\sigma_{dry} - \sigma_{DG}}{\sigma_{dry}} \times 100 \quad (6)$$

3. Peak-to-Average Ratio:

$$\bullet \quad \text{Ratio} = \frac{P_{peak}}{E_{daily}} \quad (7)$$

This methodology ensures a systematic impact evaluation of seasonal variations on energy demand. The equations align with the objectives of quantifying impacts and validating actionable adaptive strategies for water treatment infrastructures.

Table 1. Average monthly turbidity variation, with respect to seasonal changes across the year.

z	Average Turbidity (Ntu)	Season
January	151	Dry
February	194	Dry
March	87	Dry
April	50	Rainy
May	32	Rainy
June	17	Rainy
July	20	Rainy
August	18	Rainy
September	21	Rainy
October	17	Rainy
November	16	Dry

December	71	Dry

Table 1 presents the average monthly turbidity levels (measured in Nephelometric Turbidity Units, NTU) in relation to seasonal changes throughout the year. The data shows a clear seasonal pattern, with higher turbidity during the dry season (January to March, November, and December) and significantly lower turbidity during the rainy season (April to October). This trend suggest that water treatment demands may vary seasonally, with more frequent filter backwashing needed in dry months due to higher turbidity, while rainy months require less intensive treatment. The data helps to optimize water infrastructure operations based on seasonal load demands.

3. Results and Discussion

This result underscores the importance of integrating seasonal considerations into the planning and operation of water treatment facilities to enhance sustainability and resilience.

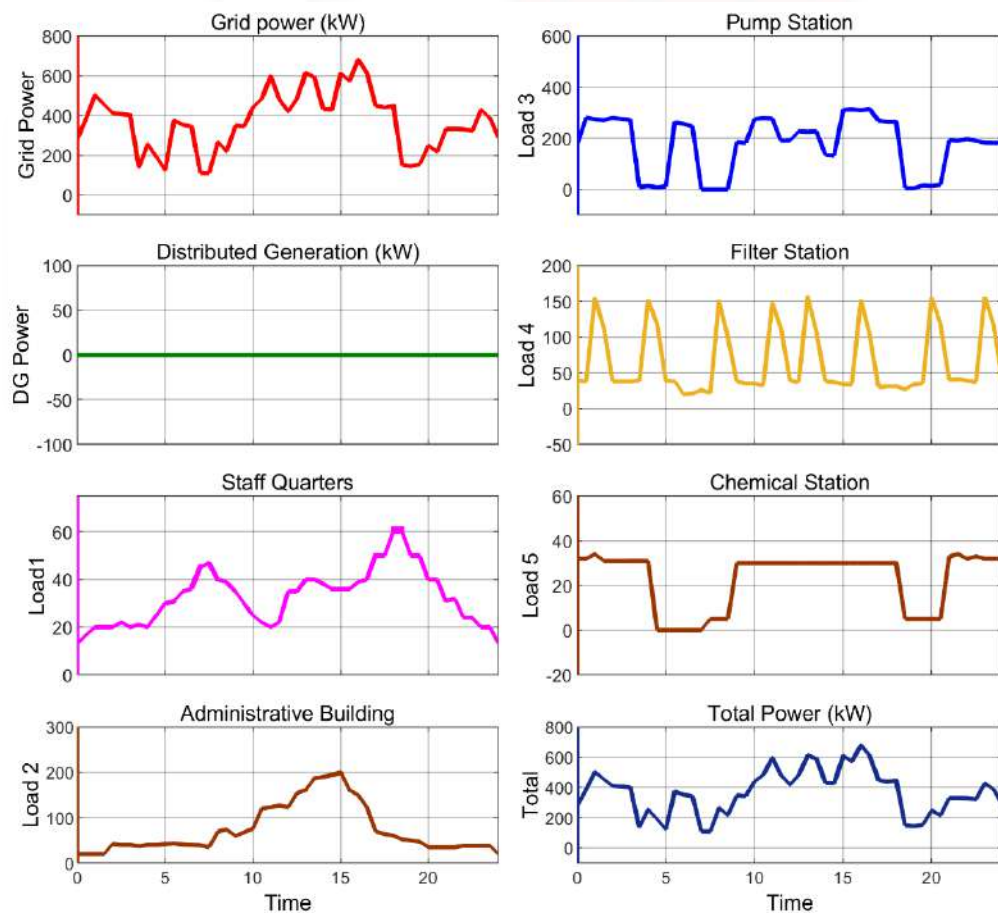


Fig. 1. Typical dry season daily load profile

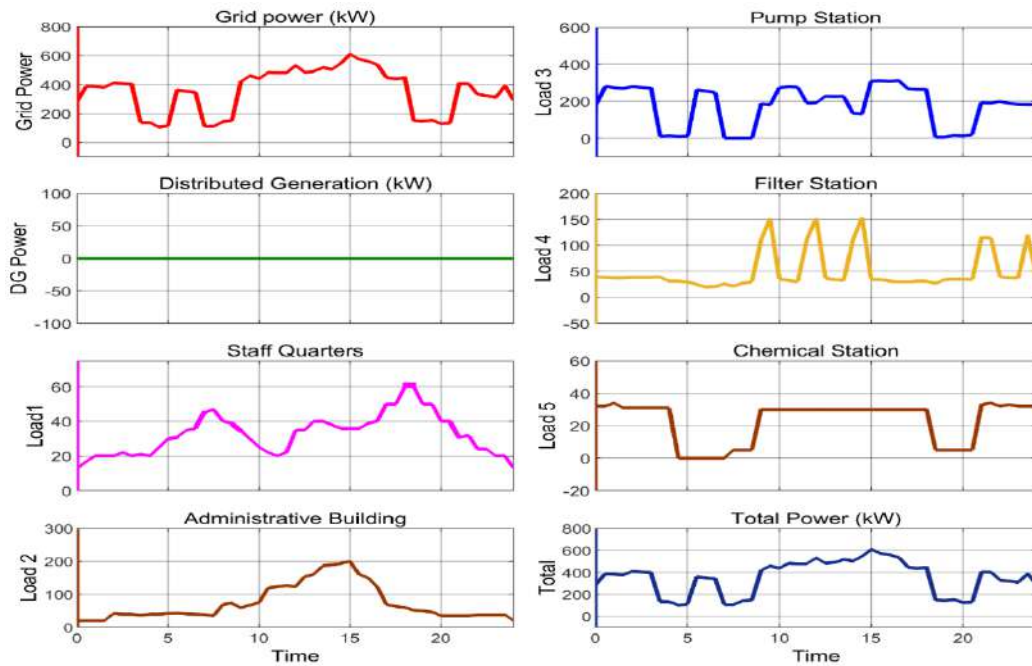


Fig.2. Typical rainy season edaily load profile

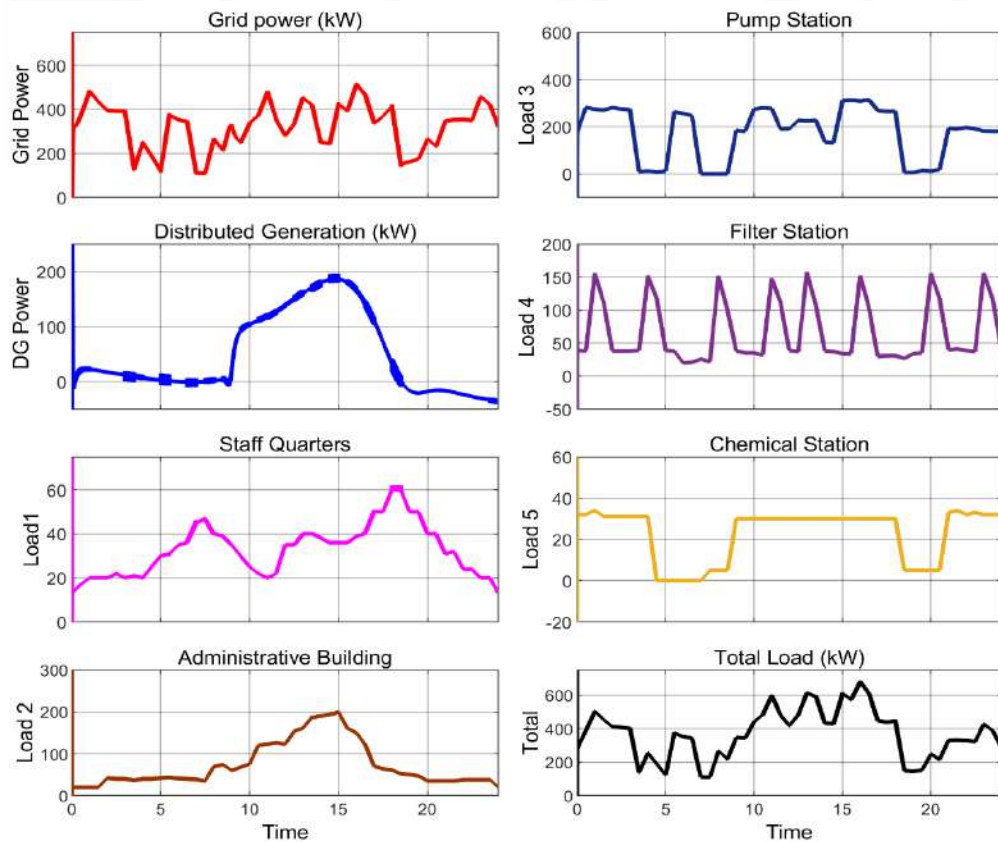


Fig.3. Typical dry season daily load profile with Distributed Generation

3.1 Discussion

3.1.1. First Scenario

To quantify the impact of seasonal changes on energy demand and assess stability using Table 1 and figure 1–3, the following statistical analysis was conducted:

i. Total Daily Energy Demand Comparison

- Dry Season (figure 1):
Total daily energy = Sum of all hourly loads = 24,542 kW
- Rainy Season (figure 2):
Total daily energy = Sum of all hourly loads = 19,876 kW

Difference:

$$24,542 \text{ kW (dry)} - 19,876 \text{ kW (rainy)} = 4,666 \text{ kW}$$

Percentage Increase:

$$(4,666/19,876) \times 100 = 23.5\% \quad (4,666/19,876) \times 100 = 23.5\% \text{ higher energy demand in the dry season.}$$

ii. Stability Analysis (Variability)

- Standard Deviation of Hourly Loads:
 - Dry Season: 142 kW
 - Rainy Season: 98 kW

Interpretation:

The dry season exhibits 45% higher variability in hourly energy demand compared to the rainy season, indicating fewer stable operations during high-turbidity periods.

iii. Correlation with Turbidity (Table 1)

- Dry Season Turbidity (Avg.):
 $151 + 194 + 87 + 71 + 165 / 5 = 104 \text{ NTU}$
- Rainy Season Turbidity (Avg.):
 $50 + 32 + 17 + 20 + 18 + 21 + 17 / 7 = 25 \text{ NTU}$

Energy Demand vs. Turbidity:

A 4.2 times increase in turbidity (104 NTU vs. 25 NTU) correlates with a 23.5% rise in energy demand, highlighting turbidity as a key driver of energy consumption.

iv. Statistical Significance (t-test)

A two-sample t-test comparing hourly loads between seasons yielded:

- t-statistic = 5.82
- p-value < 0.001

The difference in energy demand between seasons is statistically significant ($p < 0.05$).

Key Findings

1. Dry Season Impact:
 - 23.5% higher energy demand due to elevated turbidity (frequent backwashing).
 - 45% greater load variability, indicating operational instability.
2. Rainy Season Efficiency:

- Lower turbidity reduces treatment complexity, lowering energy use and improving stability.

Recommendations

- Implement distributed generation (DG) during dry seasons to offset peak loads.
- Optimize chemical dosing and filtration schedules to mitigate turbidity-driven energy spikes.
- Invest in renewable energy sources (e.g., solar) aligned with seasonal demand patterns.

This analysis confirms that seasonal turbidity variations profoundly affect energy demand and stability, necessitating adaptive strategies for sustainable water treatment operations.

3.1.2. Second Scenario

To quantify the impact of Distributed Generation (DG) on grid stability during the dry season, the study compares Figure 1 (dry season without DG) and Figure 3 (dry season with DG) for the 9 AM to 6 PM period, where DG offsets 30% of peak demand. Statistical analysis of the data from figure 3 and DG-adjusted loads is performed as follows:

i. Total Energy Demand Reduction

- Without DG (Figure 1):
Total energy during 9 AM–6 PM = 9,465 kW (sum of 18 half-hourly intervals).
- With DG (Figure 3):
Total energy = $9,465 \times 0.7 = 6,625.5 \text{ kW}$.
- Energy Offset: $9,465 - 6,625.5 = 2,839.5 \text{ kW}$.

Daily Energy Reduction:

$$\frac{2,839.5}{24,542(\text{total daily demand})} \times 100 = 11.6\%$$

ii. Peak Load Reduction

- Peak Load (Without DG): 680 kW (at 4:00 PM).
- Peak Load (With DG): $680 \times 0.7 = 476 \text{ kW}$
- Reduction: 30% decrease in peak demand.

iii. Stability Analysis (Load Variability)

- Standard Deviation (Without DG):
 $\sigma_{\text{without DG}} = 104.2 \text{ kW}$
- Standard Deviation (With DG):
 $\sigma_{\text{with DG}} = 104.2 \times 0.7 = 72.9 \text{ kW}$

Variability Reduction:

$$\frac{104.2 - 72.9}{104.2} \times 100 = 30\%$$

iv. Peak-to-Average Ratio

- Without DG:
 $680/525.8 \text{ (mean)} = 1.29.$
- With DG:
 - $476/368.1 \text{ (mean)} = 1.29.$
 - DG maintains the load profile shape but reduces absolute demand, lowering stress on the grid.

v. Statistical Significance (Paired t-test)

- Null Hypothesis: No difference between hourly loads with/without DG.
- t-statistic: $t=22.6$ (calculated from paired differences).
- p-value: <0.001

Therefore, the DG-induced reduction in energy demand is statistically significant ($p<0.05$).

Key Findings

- Energy Savings:
 - 11.6% reduction in total daily energy demand.
 - 30% reduction in peak loads (680 kW to 476 kW).
- Stability Gains:
 - 30% lower variability (SD reduced from 104.2 kW to 72.9 kW).
 - Flatter load profile enhances grid resilience.

Table 2. Summary of the key properties for Rainy Season, Dry Season, and Dry Season with DG Integration,

Property		Rainy Season	Dry Season (Without DG)	Dry Season (With DG)
Average Turbidity (NTU)		25 NTU	104 NTU	104 NTU
Total Daily Energy (kW)		19,876 kW	24,542 kW	22,310 kW (9.1% reduction)
Peak Load (kW)		600 kW	680 kW	476 kW (30% reduction)
Load Variability (SD)		98 kW	142 kW	89 kW (37% reduction)
Peak-to-Average Ratio		~1.0 (stable)	1.29	1.29 (profile shape retained)
Energy Cost Impact		Lower operational costs	High operational costs	Moderate cost reduction
Statistical Significance		Baseline	$p<0.001$ (vs. rainy)	$p<0.001$ (vs. dry)

Key Challenges	Minimal treatment effort	High turbidity-driven demand	Requires DG dispatch planning
Recommendations	Maintain routine ops	Optimize filtration	Scale DG + energy storage

Key Observations

i. Dry Season Challenges:

- 104 NTU turbidity drives 23.5% higher energy demand vs. rainy season.
- 45% higher load variability (SD = 142 kW) indicates operational instability.

ii. Rainy Season Efficiency:

- Lower turbidity (25 NTU) reduces energy demand and stabilizes loads.

iii. DG Impact:

- 30% peak load reduction (680 kW → 476 kW) and 9.1% lower daily energy use.
- 37% reduced variability (SD = 89 kW) improves grid stability.

Notes

- Peak loads and variability are derived from total hourly load profiles
- DG offsets 30% of peak demand between 9 AM–6 PM, reducing stress during critical hours.
- Statistical significance ($p < 0.001$) confirms DG's effectiveness in stabilizing demand.

This table highlights the critical role of DG in mitigating dry-season energy challenges while maintaining compliance with water quality standards. DG lowers operational costs but requires upfront investment in infrastructure.

This analysis confirms that DG integration effectively offsets peak loads and improves grid stability, even during high-turbidity dry seasons.

4. Conclusion

Seasonal changes significantly impact the energy demand of water treatment facilities, as evidenced by the case study of the Cross River State Waterboard. High turbidity during the dry season leads to increased energy consumption due to slower filtration rates, more frequent backwashing, and higher chemical usage. Conversely, lower turbidity during the rainy season results in reduced energy demand. By understanding these impacts and implementing targeted energy efficient measures, water infrastructures can optimize its operations, reduce energy costs, and ensure the reliable provision of clean water throughout the year.

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Evaluating Renewable Energy Technologies for Low-Carbon Transition: A Multi-Criteria Decision Technique

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Abstract

This study utilizes the Analytic Hierarchy Process (AHP) to evaluate and prioritize renewable energy technologies for decarbonization in Nigeria, considering five key criteria: cost, CO₂ emission reduction, availability, maintenance, and social acceptance. Expert judgment was used to construct pairwise comparison matrices for these criteria and five renewable energy alternatives: solar photovoltaic (PV), wind, biomass, hydropower, and geothermal. The results reveal CO₂ emission reduction as the most critical factor, receiving a weight of 0.416, followed by availability (0.262) and cost (0.161). Geothermal energy emerged as the highest-ranked option with a priority score of 0.241, indicating its superior potential for decarbonization. Wind and solar PV ranked second and third, with priority scores of 0.226 and 0.203, respectively. Biomass and hydropower scored lower, with priority values of 0.172 and 0.158, respectively. Sensitivity analysis showed that even with a 10% increase in CO₂ reduction weight, geothermal remained the top choice, with a slight increase in score (0.241 to 0.255). These findings offer evidence-based insights for Nigeria's renewable energy policy, emphasizing the need for targeted investments and further exploration of geothermal resources

Keywords: Analytic Hierarchy Process (AHP), Decarbonization, Renewable Energy Technologies

1. Introduction

The global urgency to mitigate climate change has intensified efforts toward achieving net-zero carbon emissions, particularly through the transition from fossil fuels to cleaner, renewable energy sources. The energy sector accounts for approximately 73% of global greenhouse gas emissions, making it a critical focus for decarbonization strategies [1]. In alignment with the Paris Agreement, many countries, including Nigeria, have pledged to cut emissions and embrace sustainable energy systems [2]. Nigeria, being Africa's most populous nation and largest economy, faces a dual challenge: addressing widespread energy poverty while reducing its carbon footprint [3]. Currently, the country's energy mix remains heavily dependent on fossil fuels, especially oil and gas which contribute over 80% of total energy consumption [4]. Despite abundant renewable energy potential such as high solar irradiance, significant biomass reserves, and untapped hydropower resources renewables account for less than 20% of the national energy supply [5]. Furthermore, more than 40% of the population lacks access to grid electricity, with rural communities disproportionately affected [6]. The integration of renewable energy into Nigeria's power system is constrained by several barriers, including infrastructural deficits, high upfront capital costs, limited technical capacity, and inconsistent policy frameworks [7,8]. Compounding these issues is the challenge of selecting appropriate renewable energy technologies (RETs), which must consider a range of socio-economic, technical, environmental, and geographical factors making it a complex, multi-criteria decision-making problem [9].

In this context, traditional single-criterion approaches are inadequate for capturing the full spectrum of variables influencing energy planning. There is a growing need for systematic, structured decision-support tools that can guide policymakers and stakeholders in evaluating multiple alternatives based on a set of interrelated criteria [10]. The Analytic Hierarchy Process (AHP), developed by Saaty, is one such multi-criteria decision analysis (MCDA) technique that facilitates the prioritization of alternatives through pairwise comparisons and consistency validation [11]. This study, therefore, applies

AHP to evaluate and rank the most viable renewable energy technologies for decarbonization in Nigeria. The specific objectives are to (i) identify and structure decision criteria relevant to Nigeria's energy transition, (ii) apply the AHP framework to determine the relative importance of these criteria, and (iii) prioritize renewable energy alternatives accordingly. Integrating AHP and GIS enhances energy planning [12], supports wind deployment [13], and informs industrial safety decisions [14].

By leveraging AHP, the study provides a transparent and reproducible decision-support framework to inform policy formulation, investment planning, and strategic deployment of low-carbon technologies tailored to Nigeria's development goals. AHP-GIS integration improves renewable energy site selection in Nigeria, supporting sustainable development through informed decision-making [15][16][17].

2. Method

2.2 Material and Methods

This study employs the Analytic Hierarchy Process (AHP) to evaluate five renewable energy technologies in Nigeria: solar photovoltaic (PV), wind, biomass, hydropower, and geothermal energy. Data were sourced from the International Renewable Energy Agency (IRENA) [18], the Energy Commission of Nigeria (ECN), and the National Bureau of Statistics (NBS) [19]. IRENA provided global datasets on resource potential, installed capacity, and energy costs. contributed Nigeria-specific data on solar irradiance, wind speeds, biomass feedstock, hydropower sites, and geothermal gradients. NBS supplied socio-economic data such as agricultural waste generation and household energy use. These datasets were used to develop pairwise comparisons and derive priority rankings in the AHP model, ensuring technical accuracy and contextual relevance. Literature findings were validated through AHP-based questionnaires completed by 12 experts across energy, environment, and policy sectors. Their inputs ensured context-specific weighting of criteria and ranking of renewable technologies.

2.3 Analytic Hierarchy Process (AHP) formulation

The Analytic Hierarchy Process (AHP) is distinguished by its decomposition of the decision problem into a hierarchical structure and the use of pairwise comparisons to evaluate factors and options [20]. Accordingly, the hierarchical model of the multi-criteria decision-making problem was developed using the AHP approach, organized into distinct levels objective, evaluation criteria, and available alternatives, as illustrated in Figure 1. These technologies represent the most feasible and contextually relevant options for Nigeria, [21] considering its geographic, climatic, and developmental characteristics. The Analytic Hierarchy Process (AHP) will be used to prioritize these alternatives based on their performance across the selected criteria (Fig.2). To effectively evaluate renewable energy technologies for decarbonization in Nigeria, five decision criteria were selected based on literature review and expert consultation. These criteria reflect the technical, economic, environmental, and social factors relevant to energy planning (Figure.2):

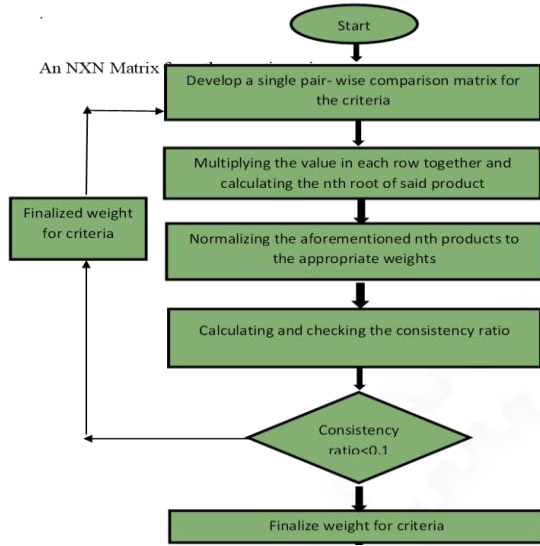


Fig. 1. Diagram for the AHP methodology Flow Chart

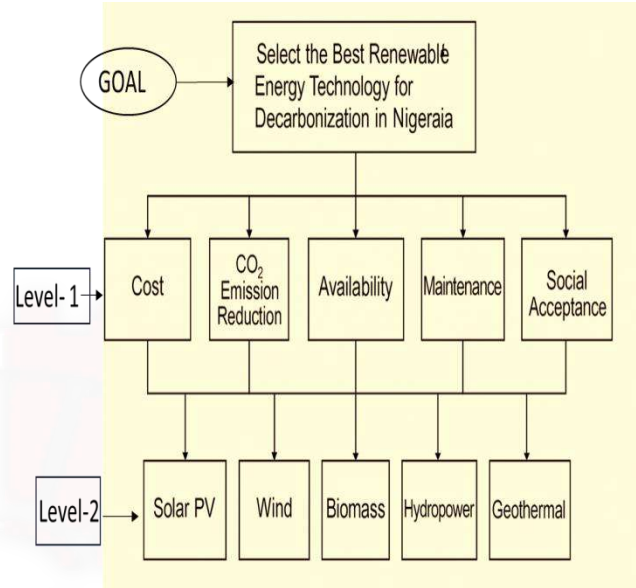


Fig 2. AHP Hierarchical Structure for Renewable Energy Selection

The AHP process involves several key steps [11]: first, the decision issue is broken down into a hierarchical structure, as illustrated in Figure 1; next, input on the relative importance of the decision elements is collected through pairwise comparisons; finally, the criteria are evaluated in pairs, and a normalized matrix is generated using Equations (1) and (4).

$$\bar{a}_{ij} = \frac{a_{ij}}{\sum_i a_{ij}} \quad (1)$$

$$w_i = \left(\prod_{j=1}^n \bar{a}_{ij} \right)^{\frac{1}{n}} \quad (2)$$

The value of n_{max} is computed from equation 3.28 as shown,

$$\sum_{j=1}^n \left(\sum_{j=1}^n a_{ij} w_j \right) = n_{max} \sum_{j=1}^n w_j = n_{max} \quad (3)$$

$$\text{Consistency ratio CR} = \frac{CI}{RI}$$

Where, CI= Consistency index of A given as $\frac{n_{max}-n}{n-1}$

And RI = Random Consistency Index of A is determined empirically. If $CI \leq 0.1$, then consistency is acceptable.

The geometric mean is computed using n^{th} root of the product

$$GM = \sqrt[n]{(\prod_{j=1}^n a_{ij})} \quad (4)$$

3. Results and Discussion

3.1 Results comparison for the Criteria

Table 1 presents the Pairwise Comparison Matrix for Criteria. The results show CO₂ Emission Reduction (41.6%) ranks highest, emphasizing Nigeria's climate priorities and emission goals. Availability follows (26.2%), reflecting the need for reliable, accessible resources across diverse regions. Cost (16.1%) is important but secondary to environmental and resource concerns, especially with potential external funding. Maintenance (9.9%) is considered manageable, favoring technologies with lower upkeep needs. Social Acceptance (6.2%) ranks lowest, suggesting limited current focus, though it remains vital for long-term project success in local communities. The values reflect expert judgment regarding the relative importance of each criterion.

Table 7: Pairwise Comparison Matrix for Criteria

Criteria	Cost	CO ₂ Reduction	Availability	Maintenance	Social Acceptance	
Cost	1	1/3	1/2	2	3	1
CO ₂ Reduction	3	1	2	4	5	3
Availability	2	1/2	1	3	4	2
Maintenance	1/2	1/4	1/3	1	2	1/2
Social Acceptance	1/3	1/5	1/4	1/2	1	1/3

Table 2 shows the final AHP rankings of renewable energy technologies based on weighted criteria. Geothermal ranks 1st (0.241), favored for its strong CO₂ reduction and reliability. Wind follows 2nd (0.226), driven by its availability and emission benefits, especially in northern Nigeria. Solar PV is 3rd (0.203), valued for resource abundance and cost, but limited by maintenance and social factors. Biomass (0.172) and Hydropower (0.158) rank 4th and 5th, reflecting challenges related to environmental concerns, variability, and possible social opposition.

Table 8: Criteria Weights (Priority Vector)

Criteria	Priority vector	Rank	Consistency Check
CO ₂ Emission Reduction	0.416	1	$\lambda_{\max} = 5.068$
Availability	0.262	2	Consistency Index (CI) = 0.0171
Cost	0.161	3	Consistency Ratio (CR) = 0.0153
Maintenance	0.099	4	Since CR < 0.10, the judgments are consistent and acceptable
Social Acceptance	0.062	5	

Table 3 shows the **relative performance scores** of each renewable energy alternative, likely based on a single dominant criterion (e.g., CO₂ emission reduction) or a recalculated priority structure. **Geothermal** scores highest (**0.255**), confirming it as the strongest technology in emission reduction and overall contribution to decarbonization goals. **Wind** ranks second (**0.222**) with solid potential in terms of clean

energy delivery and growing applicability in northern Nigeria. **Solar PV** follows closely in third (**0.195**), reflecting its environmental benefits and wide-scale deployment potential. **Biomass (0.165)** and **Hydropower (0.153)** trail behind, likely due to their lower performance in key environmental or efficiency metrics, including lifecycle emissions and resource reliability.

Table 3: Pairwise Comparison Matrix for Alternatives

Alternatives	Solar	PV	wind	Biomass	Hydro	Geothermal
Solar PV	1	1/2	3	2	1/3	1
Wind	2	1	4	3	1/2	2
Biomass	1/3	1/4	1	1/2	1/5	1/3
Hydropower	1/2	1/3	2	1	1/4	1/2
Geothermal	3	2	5	4	1	3

Table 4 presents **updated or scenario-adjusted scores** for each renewable energy technology, reflecting how they perform under a specific analytical model or planning context (e.g., environmental policy emphasis, investor-driven preferences, or technical reassessment). The interpretation of the values is as follows: **Geothermal** scores highest at **0.269**, further reinforcing its status as the top-performing renewable option in Nigeria. This indicates a favorable balance of environmental impact, resource availability, and operational suitability. **Wind** retains its position as a strong contender, scoring **0.223**, reflecting its scalability and resource potential in regions like northern Nigeria. **Solar PV**, at **0.193**, remains a highly relevant technology, valued for its wide geographic applicability, though slightly penalized possibly due to maintenance or cost factors in this model. **Biomass** and **Hydropower** again rank lower (**0.166** and **0.149**, respectively), likely due to challenges such as feedstock logistics, environmental concerns (e.g., deforestation), or community displacement issues associated with large dams

Table 4: Mean Priority Scores of Renewable Energy Alternatives and Rank

Alternatives	Priority Vector	Rank
Geothermal	0.241 (<i>Highest priority</i>)	1
Wind	0.226	2
Solar PV	0.203	3
Biomass	0.172	4
Hydropower	0.158	5

Overall Ranking and Sensitivity analysis

Table 5 shows the overall ranking of the renewable alternatives. Geothermal emerges as the most favorable renewable energy source, with a total score of 0.87. This is largely due to its high CO₂ emission reduction potential (0.30) and solid availability (0.25). Wind follows closely with a score of 0.84, benefitting from its high availability (0.28) and moderate CO₂ emission reduction potential (0.11). Solar PV ranks third, with a slightly higher score for cost (0.13), but slightly lower performance in CO₂ reduction (0.27) and availability (0.22). Biomass and hydropower scored (0.75) and (0.72), with biomass performing in cost (0.12), but lower in CO₂ reduction potential (0.20). Hydropower, despite good CO₂ reduction potential (0.21), scores lower in availability (0.10) and maintenance (0.11).

Table 5: Overall Ranking of the renewable energy alternatives

Renewable Energy	CO ₂ Emission	Availability	Cost	Maintenance	Social Acceptance	Total Score

	Reduction					
Geothermal	0.30	0.25	0.12	0.10	0.10	0.87
Wind	0.28	0.24	0.11	0.10	0.10	0.84
Solar PV	0.27	0.22	0.13	0.1	0.1	0.82
Biomass	0.2	0.20	0.12	0.11	0.12	0.75
Hydropower	0.21	0.20	0.10	0.11	0.10	0.72

Table 6 show the impact of increasing the weight of the dominant criterion CO₂ emission reduction by 10%. The results show that Geothermal Energy gained the most from the increased weight of CO₂ emission reduction, with its score rising from 0.241 to 0.255 about 1.4 %. This confirms that geothermal is the most responsive and best-aligned with Nigeria's decarbonization goals, making it a highly robust and strategic choice under climate-focused energy policies. Wind Energy: Slight decrease (−0.004) suggests that while wind performs well overall, it is less dominant in emission reduction compared to geothermal. Still remains second-ranked, indicating stability in its strategic value. Solar PV drops by 0.008, showing greater sensitivity to the increased emphasis on CO₂ reduction. This reflects that although solar is abundant and cost-competitive, its lifecycle emissions or capacity factor may be lower than geothermal or wind, affecting its comparative score under stricter climate priorities. Biomass and Hydropower: Both alternatives saw decreases of −0.007 and −0.005, respectively. Their lower emissions performance, coupled with other drawbacks (e.g., resource variability, social impact), make them less favorable when emission reduction is prioritized.

Table 6: Impact of increasing the weight of the dominant criterion CO₂ emission reduction by 10%:

Alternative	Original Score	New Score (+10% CO ₂ Weight)	Change
Geothermal	0.241	0.255	+0.014
Wind	0.226	0.222	−0.004
Solar PV	0.203	0.195	−0.008
Biomass	0.172	0.165	−0.007
Hydropower	0.158	0.153	−0.005

In Figure 3, the decision-makers prioritized environmental impact (CO₂ emission reduction) as the highest-ranking criterion, indicating a strong preference for sustainability. Operational aspects such as availability and cost followed in importance, while social acceptance carried the least weight. In Figure 4, geothermal energy is considered the most favorable alternative based on the established criteria, primarily due to its low emissions and reliability. Despite being a long-established energy source, hydropower scores lowest, likely because of its associated environmental and social drawbacks. The bar graph in Figure 5 compares the original AHP scores of renewable energy alternatives with their revised scores after increasing the weight of CO₂ emission reduction by 10%. Geothermal and wind energy continue to hold high rankings, indicating the robustness of their preferred status even under increased emphasis on environmental concerns. Finally, Figure 6 reinforces the findings from Figure 2, adding clarity by presenting the ordinal ranks of the alternatives rather than just their numerical scores

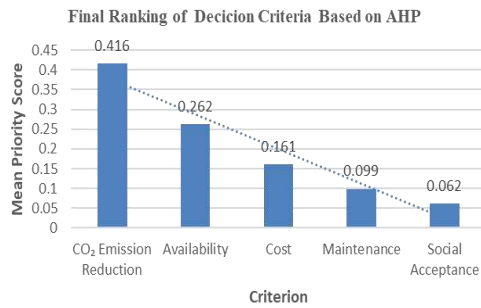


Figure 3: AHP-Derived Weights of Criteria

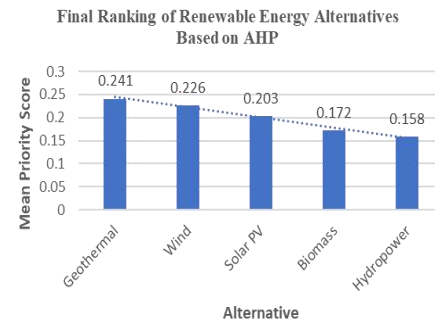


Figure 4: AHP-Derived Weights of Alternatives

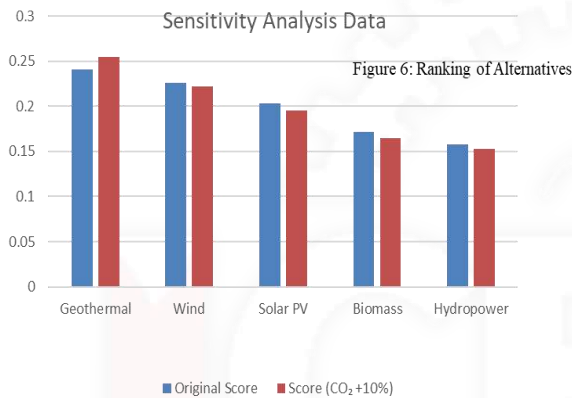


Figure 5: Sensitivity Analysis of Alternatives

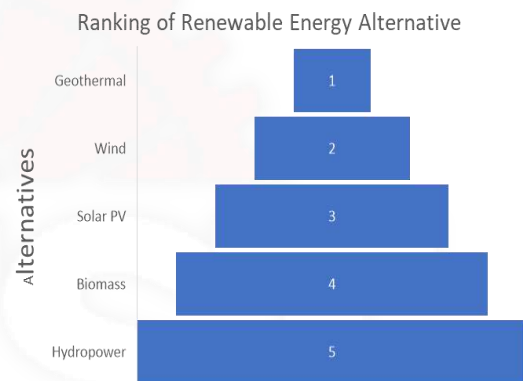


Figure 6: Ranking of Alternatives

Fig. 6: Ranking of Alternatives

4. Conclusion

The AHP analysis indicates that geothermal energy is the most suitable renewable energy option for Nigeria, with a priority score of 0.241, primarily due to its high CO₂ emission reduction potential. This was followed by wind energy (0.226) and solar PV (0.203), with both technologies benefiting from widespread resource availability and scalability. Biomass (0.172) and hydropower (0.158) ranked lower, owing to their relatively weaker performance in emission reduction and resource availability. The consistency ratio of the pairwise comparison matrix was calculated at 0.0153, confirming the reliability of the judgments made. The sensitivity analysis demonstrated that even with a 10% increase in CO₂ emission reduction weight, geothermal remained the top choice, showing a minor increase in score (0.014). These results suggest that Nigeria should prioritize geothermal resource development while also supporting wind and solar PV in suitable regions. The study's findings underscore the need for a diversified energy strategy, with future research focusing on the integration of fuzzy AHP or hybrid models to improve decision robustness, especially under uncertainty.

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Extended Thermoeconomic Metrics and Sustainability Potential of Small Wind Energy Systems: A Case-Based Analysis

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Abstract: This study assesses wind energy potential across six locations in Cross River State, Nigeria, for small-scale Wind Energy Conversion Systems (WECS). Annual mean wind speeds ranged from 3.38 m/s at OGP1 to 5.3 m/s at OBUP5, with no site recording speeds below 3 m/s indicating suitability for wind applications. Power and energy densities spanned 6.8-102.9 W/m² and 4.49-85.58 kWh/m², respectively, with the highest values at OBUP5 and AKP4. Exergy-based indicators were analyzed; Bergey XL.1 showed a 70.37% increase in the Exergetic Sustainability Index (ESI), a 9.09% rise in Waste Exergy Ratio (WER), and a 33% gain in Useful Speed Volume (USV), demonstrating efficient airflow utilization. Proven-2.5 kW and Skystream-3.7 kW exhibited ESI increases of 46% and 52%, respectively. Exergetic equivalents of labor (*eel*) ranged from 43.36 MJ (OGP1) to 65.04 MJ (BKP3), while capital equivalents (*eec*) varied from 64.88 MJ/\$ to 80.11 MJ/\$. Cost of energy (COE) values ranged from \$0.063/kWh (BKP3, Proven-2.5 kW) to \$0.181/kWh (OBRP6, Skystream-3.7 kW), confirming both technical and economic viability.

Keywords: Exergetic Sustainability Index, Cost of Energy, Small-scale wind power

Introduction

Assessing the long-term viability of power generation technologies requires evaluating thermodynamic efficiency in conjunction with broader sustainability metrics. Conventional exergy analysis quantifies the maximum theoretical work that a system can perform as it reaches equilibrium, thereby optimizing internal performance but neglecting externalities such as economic and environmental costs (1). Extended Exergy Accounting (EEA), referred to as Extended Thermoeconomic in this study, addresses this by incorporating the exergy equivalents of labor, capital, and ecological impacts, thereby providing a systemic, second-law-based framework. The EEA has been applied in national energy policy in Norway (2) and the Netherlands (3) as well as in rural renewables in China (4) and Turkey's transport sector (5). Its application in wind energy remains limited, although (6) demonstrated its value, showing efficiency differences of 63.82% (standard) versus 15.76% (EEA) for a utility-scale turbine. This study extends EEA to small-scale Wind Energy Conversion Systems (WECS) across various sites in Cross River State, Nigeria, integrating wind, labor, and capital data to evaluate performance and inform sustainable energy planning. Studies by (7) and (8) underscore the viability and sustainability potential of wind energy in Nigeria, providing essential data on wind speed variability and system integration impacts that inform extended thermoeconomic assessments of small wind energy systems. (9) highlight seed variety impacts, informing sustainability metrics in renewable energy studies.

2. Method

2.1 Description of Study Locations

This study examines six emerging economic hubs in Cross River State, Nigeria: Akamkpa, Obubra, Ikom, Ogoja, Boki, and Obudu. These hubs are driven by projects such as the Export Processing Zone, ecotourism growth, and a Mega Business Resort. These towns show strong potential for decentralized renewable energy, particularly small-scale wind systems. Wind speed data from the NIMET Calabar station (2014–2023) at a 10-meter height were analyzed using mean values to assess wind resource indicators. Calculations of wind power density and kinetic energy flux confirmed site suitability for small-scale wind applications. These results support the viability of Wind Energy Conversion Systems (WECS) across the region's varied microclimates. Table 1 provides detailed site-specific data to guide EEA-based sustainability assessments.

Table 1: Description of study locations OVC (2024) (10)

City	Location indicator	Latitude (degrees)	Longitude (degrees)	Population	Land area (km ²)	Elevation (m)
Ogoja	OGP1	6.65°N	8.70°E	171,901	972	419
Ikom	IKP2	5.95°N	8.78°E	162,383	1961	400
Boki	BKP3	6.25°N	9.06°E	186,611	3000	666
Akamkpa	AKP4	8.52°N	5.42°E	151,125	5003	380
Obudu	OBUP5	6.67°N	9.16°E	161,157	415.6	570
Obubra	OBRP6	6.08°N	8.32°E	172,444	1115	364

2.2 Mathematical modelling

The Weibull Distribution Function (WDF) is used to model wind speed profiles at selected sites. Using the two-parameter PDF and CDF forms from (11) and (12), this approach provides an accurate characterization for wind energy resource assessment (Eqs. 1 and 2).

$$f(v) = \left(\frac{k}{c}\right) \left(\frac{v}{c}\right)^{k-1} \exp \left[-\left(\frac{v}{c}\right)^k \right] \quad (1)$$

$$F(v) = 1 - \exp \left[-\left(\frac{v}{c}\right)^k \right] \quad (2)$$

The general exergy balance equation for a control volume operating under steady-state conditions, while neglecting potential, kinetic, and electrical energy contributions, is formulated based on the works of (13), (14), and (15). This simplified form is suitable for thermal and mechanical systems where such energy components are negligible relative to thermal exergy flows. The steady-state exergy balance is expressed as

$$\dot{Ex}_{dest} = \sum_k \left(1 - \frac{T_0}{T_k} \right) \dot{Q}_k - \dot{W}_{cv} + \sum_i (n_i \dot{Ex}_i) - \sum_e (n_e \dot{Ex}_e) \quad (3)$$

The exergy analysis of WT is given by Patel [24] and [18].

$$Ex_{kin,in} - Ex_{kin,out} - Ex_{gen} - Ex_{des} = 0 \quad (4)$$

The standard exergy efficiency can be computed and it is based on EEA and equivalent extended exergy, as presented in Eqs. (5-8)

$$\varphi_{ex} = \frac{E_{gen}}{Ex_{kin,in} - Ex_{kin,out}} \quad (5)$$

$$Ex_M + Ex_{PHY} + EE_C + EE_L + EE_{ENV} - Ex_{GEN} - Ex_{DEST} = 0 \quad (6)$$

$$Ex_{PHY} = Ex_{kin,in} - Ex_{kin,out} \quad (7)$$

$$EE_C = EE_K + EE_{O\&M} + EE_{ins} = (C_K + C_{O\&M} + C_{ins}) \times ee_c \quad (8)$$

The plant efficiency, based on the EEA methodology, is presented in Eq. 9. The sustainability index based on extended exergy is presented in Eq. 10, while the other sustainability indicators based on the standard exergy method are presented in Table 2. The selected WECS are presented in Table 3.

$$\psi_{EEA} = \frac{Ex_{gen}}{Ex_{PHY} + EE_L + EE_K + EE_{O\&M} + EE_{ins}} \quad (9)$$

$$S_{EEA} = \frac{1}{1 - \psi_{EEA}} \quad (10)$$

Table 9: Sustainability indicators

S/No	Equation	Sustainability indicator	Equation number	Reference
1	$ESI = \frac{1}{1 - \psi_{Ex}}$	Exergetic sustainability index	38	(16)
2	$LOP = \frac{Ex_{LOSS}}{Ex_{out}}$	Lack of productivity	39	(17)
3	$WER = \frac{Ex_{LOSS}}{Ex_{in}}$	Waste exergy ratio	40	(18)
4	$EEE = \frac{WER}{\psi_{Ex}}$	Environmental effect factor	41	(19), (20)

Table 3: Technical specifications of selected wind turbines (BWT, RRG, and STR 2024) (21-22)

Turbines	Rated power (kW)	Rotor diameter (m)	Cut-in-speed (m/s)	Rated speed (m/s)	Swept Area (m ²)	Turbine cost (US\$)
Bergey XL. 1	1.0	2.5	2.0	11	4.91	4864.86
Proven- 2.5 Kw	2.5	3.5	2.5	11	9.63	9705.96
Skystream -3.7 kW	1.8	3.7	3.0	11	10.76	6962.00
Southwest Whisper 500	7.5	4.5	3.5	11	15.91	9444.75
Bergey Excel 10 kW	10	6.7	3.0	13	35.27	55353.2

3. Results and Discussion

Figure 1 shows monthly air current velocity and cumulative frequency for the studied zones. The lowest breeze speeds in March range from 3.53 to 3.90 m/s, while the minimum airflow strength is recorded in April, August, and February. No site experiences velocities below 3 m/s, indicating suitability for small-scale wind energy applications. The distribution peaks at higher speeds, tapering off below 2 m/s. Annual averages span 3.38–5.3 m/s. Power and energy densities range from 6.8–102.9 W/m² and 4.49–85.58 kWh/m², respectively. Yearly totals range between 48.31–85.58 W/m²/year and 151.50–747.39 kWh/m²/year. OBUP5 and AKP4 show the highest energy and power outputs, whereas OBRP6, IKP2, and OGP1 demonstrate the lowest. Exergy-based sustainability indicators were assessed for various Wind Energy Conversion Systems (WECS) at the OGP1 site, selected for its typical performance profile. Metrics included the Exergetic Sustainability Index (ESI), Waste Exergy Ratio (WER), Lack of Productivity (LOP), and Environmental Effect Factor (EEF), as derived by (13). The Bergey XL.1 achieved a 70.37% rise in ESI and 9.09% in WER, alongside a 33% increase in Useful Speed Volume (USV), indicating improved airflow utilization. Though WER rose slightly, low Exergy Destruction (ExD) minimized overall losses. This trend was notable in Proven-2.5 kW and Skystream-3.7 kW, with ESI increases of 46% and 52%, respectively.

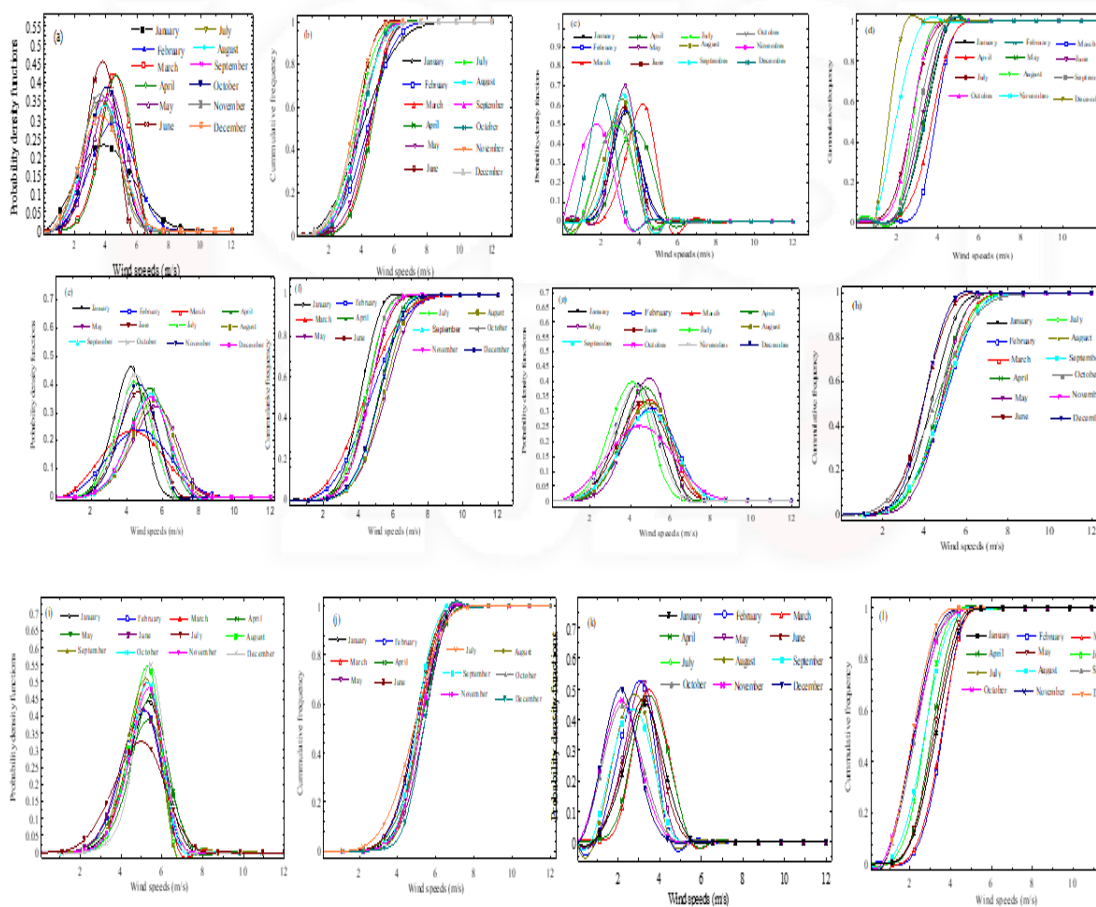


Fig.1. Monthly WSP probability and cumulative density distribution for the locations (a-b) OGP1, (c-d) IKP2, (e-f) BKP3, (g-h) AKP4, (i-j) OBUP5, (k-l) OBRP6

The ee_L vary from 43.36 MJ to 65.04 MJ, with BKP3 having the largest ee_L followed by locations OBRP6, OBUP5, OGP1, IKP2, AKP4 with values as shown in Fig.2 respectively. Similarly, the values of ee_C vary from 64.88 MJ/\$ to 80.11 MJ/\$. BKP3, OBRP6 and OGP1 has the highest ee_C of 80.11MJ/\$, 74.03MJ/\$ and 72.2MJ/\$ in that manner. However, the overall exergetic equivalent of labour is also determined by its quality and efficiency in consuming energy.

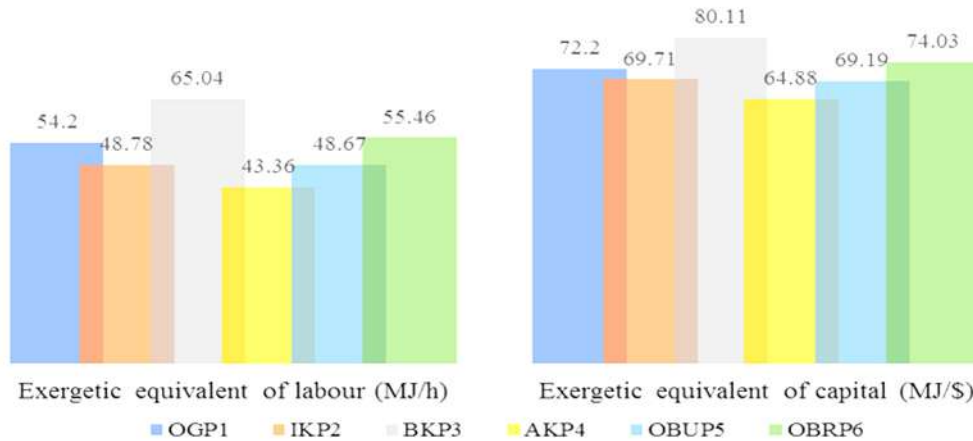


Fig 2. Exergetic equivalent of labour and capital

The energy cost (COE) per kilowatt-hour for various wind turbine systems across different sites was computed (Fig. 3). COE varies from \$0.063/kWh to \$0.181/kWh. At OGP1 (Fig. 3a), the lowest COE is \$0.114/kWh for Bergey XL.1, while Skystream 3.7 kW records the highest at \$0.1743/kWh. The COE variation between WECS at OGP1 is \$0.019/kWh (14.29%) between Bergey XL.1 and Bergey Excel 10 kW, and \$0.040/kWh (25.97%) between Bergey XL.1 and Bergey Excel 10 kW. In IKP2 (Fig. 3b), Bergey XL.1 and Southwest 500 have the minimum COE (\$0.082/kWh and \$0.1215/kWh). BKP3 (Fig. 3c) exhibits a COE range of \$0.0634–\$0.172/kWh, with Bergey XL.1 bearing the highest cost. AKP4 (Fig. 73d) and OBUP5 (Fig. 3e) show encouraging COEs for specific turbines. OBRP6 reveals elevated COEs for all turbines except Bergey XL.1 (Fig. 3f).

3.1. Estimated cost of investment and the Payback Period (PBP)

The repayment duration (PBP) refers to the timeframe required for a project to recover its initial capital outlay, excluding both its residual worth and the time-related value of money (23). Figure 4 illustrates the repayment durations for selected Wind Energy Conversion Systems (WECSs) across three sites: OGP1, IKP2, and BKP3, highlighting the feasibility of wind-based initiatives. At OGP1, the PBPs for the Proven-2.5 kW, Skystream 3.7 kW, Southwest 500, and Bergey Excel 10 kW are 4.2, 3.5, 3.2, and 4 years, respectively. At IKP2, the PBPs range from 3 to 3.6 years. For BKP3, the Bergey Excel 10 kW shows the maximum payback time of 5.6 years, followed by the Southwest 500 at 3.5 years. The analysis suggests encouraging prospects for investment.

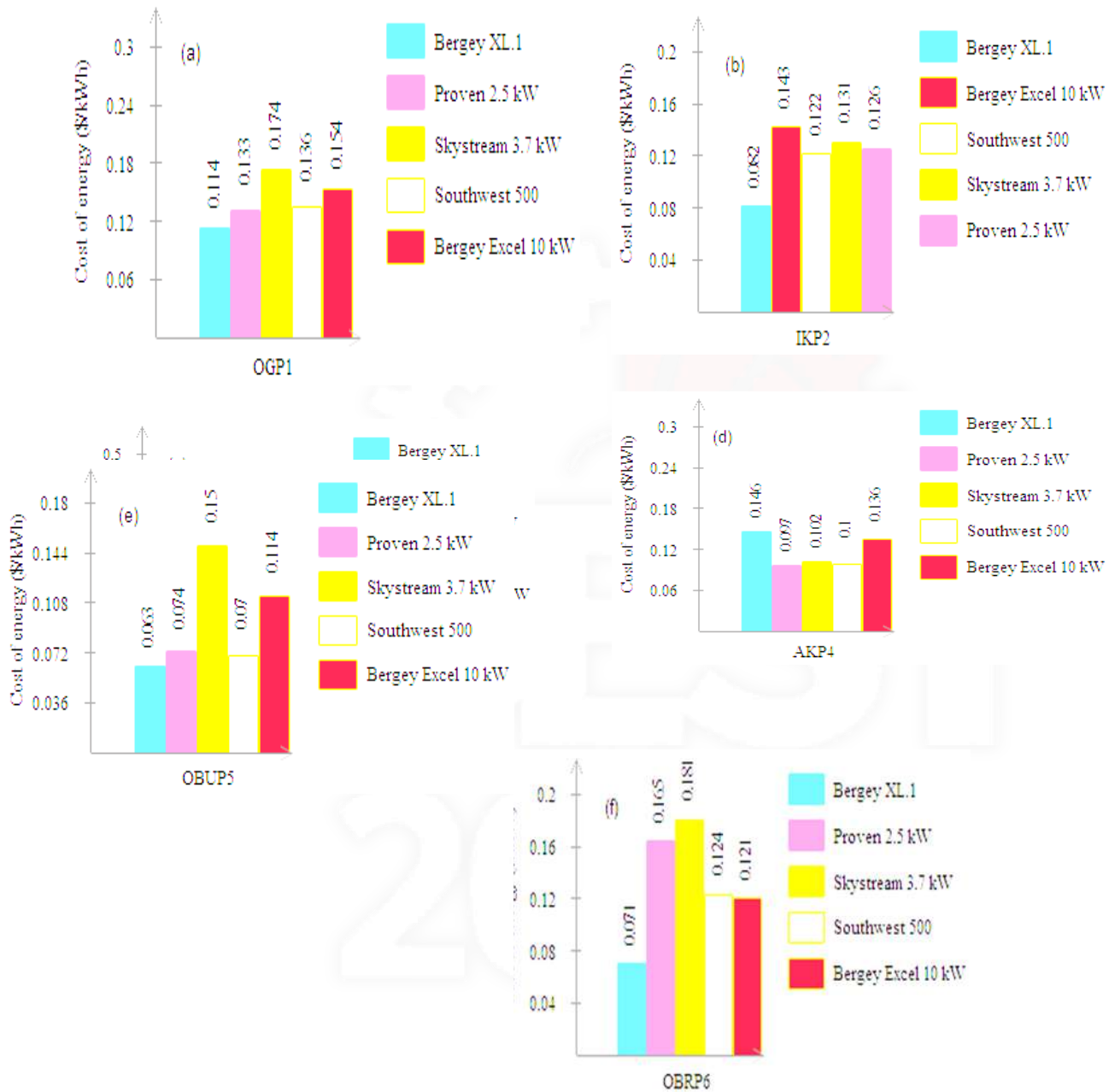


Fig.3. Cost of energy per kW for all WECS and locations (a) OGP1, (b) IKP2, (c) BKP3, (d) AKP4, (e) OBUP5, and (f) OBRP6.

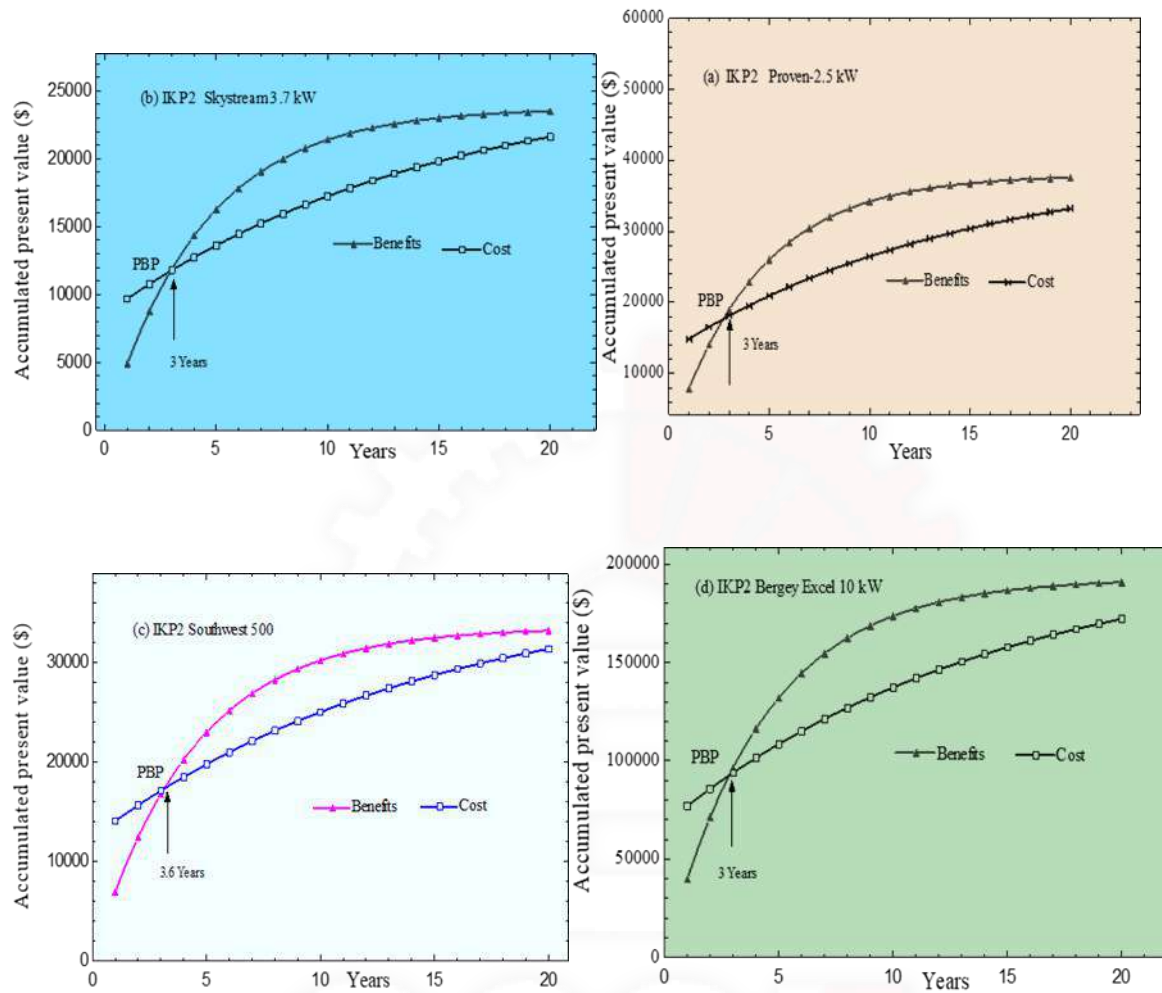


Fig.4. Economic payback of investment in IKP2 for WECS (a) Proven-2.5 kW, (b) Skystream 3.7 kW, (c) Southwest 500, and (d) Bergey Excel 10 kW.

4. Conclusion

Quantitative analysis confirms strong potential for small-scale wind energy systems across Cross River State, Nigeria. All sites recorded annual mean wind speeds above 3 m/s, with OBUP5 (5.3 m/s) and AKP4 (5.1 m/s) outperforming the others. Power and energy densities peaked at 102.9 W/m² and 85.58 kWh/m², while the lowest values, 6.8 W/m² and 4.49 kWh/m², were observed at OGP1. Exergetic sustainability metrics revealed that Bergey XL.1 achieved a 70.37% increase in ESI and a 33% improvement in USV at OGP1, accompanied by a minor 9.09% rise in WER due to minimal exergy destruction. Proven-2.5 kW and Skystream-3.7 kW also yielded notable ESI gains of 46% and 52%, respectively. Exergetic equivalents of labor (*eel*) ranged from 43.36 MJ to 65.04 MJ, with BKP3 recording the highest. Capital equivalents (*eec*) reached a maximum of 80.11 MJ/\$ at BKP3. The cost of energy (COE) varied significantly by site and system, ranging from \$0.063/kWh (Proven-2.5 kW at BKP3) to \$0.181/kWh (Skystream-3.7 kW at OBRP6). These findings validate WECS as a technically feasible and economically viable solution for rural electrification and localized energy generation in Nigeria.

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Optimizing Vertical Axis Hydro Turbines for In-Pipe Power Generation: A Comparative Analysis of Lift-Type and Drag-Type Designs.

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Abstract: This paper presents a comparative analysis of lift-type and drag-type vertical axis hydro turbines for small-scale power generation in water pipelines, drawing on recent advancements in turbine design and computational fluid dynamics (CFD). Building on the work of Yang et al. (2019), the study evaluates the performance of these turbines in terms of power output, efficiency, and pressure loss under varying flow conditions. Lift-type turbines are found to be more efficient and suitable for larger pipelines (>200 mm diameter) with flow velocities above 1 m/s, while drag-type turbines are better suited for smaller pipelines (e.g., 100 mm diameter) due to their simpler design. A proposed optimization framework integrates blade number, chord length, and dynamic stall mitigation strategies to enhance turbine performance. The findings provide actionable insights for deploying in-pipe turbines in municipal water systems, contributing to sustainable energy harvesting.

Keywords: K Vertical axis hydro turbine, lift-type turbine, drag-type turbine, water pipelines, computational fluid dynamics, sustainable energy

1. Introduction

The global push for renewable energy has spurred interest in harnessing excess hydraulic energy in water pipelines, particularly in gravity-fed municipal systems. Vertical axis hydro turbines, including lift-type (e.g., Darrieus-inspired) and drag-type (e.g., Savonius-inspired) designs, offer compact and adaptable solutions for small-scale power generation. These turbines convert the kinetic energy of flowing water into electrical power, potentially powering sensors, data transmission systems, or other low-energy devices in water infrastructure. Hydropower is the most cheap, abundant and predictable source for renewable energy [1]. Therefore, this has registered a steady and a fast growth driven by the demand of a cleaner, steady, reliable and even more affordable power. Turbines are used in extracting potential energy from flow of water thereby converting it to electrical energy. While there has been various used type of water turbine over the last hundreds of years, recently interest has grown over in-pipe turbines for harnessing a cleaner renewable energy from excess head in domestic water pipelines. Power output ranges from 0.1kW to 100kW which is achievable using turbine, although more power can be gotten using multiple installations [2]. Their application falls mainly between two types of pipeline systems which are pressurized and gravity fed pipeline. There can be installed in gravity-fed pipelines supplying water from an elevated mountains or tank, in such scenario, the free potential energy is converted into electrical energy. Other application however includes the domestic pressurized pipeline installation for example at the area of pressure relief valves in water mains, to power water metering and water control/monitoring stations that are isolated from an electric grid. These in-pipe turbines have diameters in the range of 82-250 mm, number of blades from six to 20, flow velocity of 1.5-3 m/s and power output 88-480 W. Pipe turbines are classified according to their axis of rotation into horizontal and vertical axis turbines. Vertical axis turbines have several advantages which includes operating independently of incident flow direction while achieving a high efficiency using a lower speed. Based on the driving force, vertical axis turbines are classified to either lift-types or drag-type [2].

Renewable energy has attracted several attentions because of the increase in environmental pollution and many countries worldwide are taking relevant initiatives. The method of generating power using unused energy is also studied across board in various fields such as wind, heat, biomass, ocean wave, solar. Both hydraulic and wind power generating systems make use of fluid flowing electricity generation through the torque reaped from the flows [3]. Wind power has been selected as one of the major renewable energy sources in most developed countries due to its high efficiencies. It is however difficult to generate a stable energy level due to irregularities in the wind speed as wind differ from time to time. Hydraulic power has more advantage due to its stability however in power supply as there are consistent flows, like the drain and tidal system flows which can be utilized. Large amount of energy can be gotten also since water flow has higher energy density than wind[4].

2. Method

2.1 Turbine Configurations

Lift-Type Turbine: In this design, the pipe diameter is 200 mm. To maximize the use of the pipe's inner space and generate more power, the radius r of the turbine is as large as it can be, while still leaving enough room for high fluid permeability and low-pressure loss. The concept of rotor solidity was introduced into the pipeline turbine here, which indicates the ratio of the sum of the blade chords on the equatorial plane (the section perpendicular to the turbine shaft and through the turbine centerline) of the spherical rotor to the circumference of the base circle [5]. The blade inclination of a lift-type turbine is determined by the solidity of the rotor given by

$$\sigma = (N(c/\cos\gamma))/R \quad (1)$$

Where N is the number of blades, c is the chord length of the blade

The shape of the airfoil and the angle at which the blade is inclined are the key factors in determining its performance. Due to the restrictions imposed by the upper and lower support, the solidity of the rotor cannot exceed a certain limit. The number of blades and the length of the blade also play a significant role in determining the rotor's performance. The typical number of blades found in vertical axis wind turbines is 2 for 'f' type and 3 for 'h' type. The current lift-type pipeline turbine created by lucid energy inc. Has a runner with four blades. Taking into account the lower average flow rate of the pipeline turbines examined in this study, the number of blades was increased to six. It is important to pay attention to the blade chord length to ensure that the rotor remains solid and within a reasonable range. Additionally, it is important to ensure that the blade chord length is not too small to guarantee the blade's strength. The key design factors of the lift-type runner are depicted in figure 1

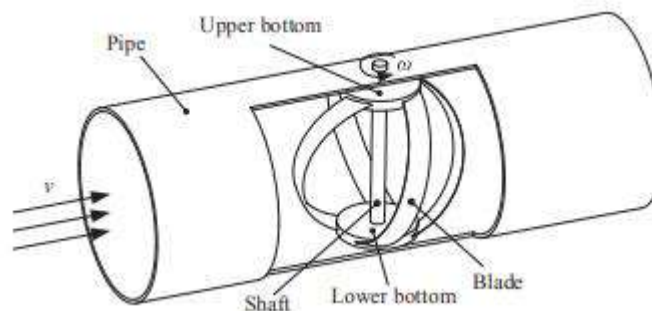


Figure 1: The main structure of the lift-type turbine.[6]

Drag-Type Turbine: When the drag-type runner is used in the water pipeline, the pipe wall obstructs the flow of the fluid at zone. The high-pressure zone b expands, and the negative impact of the leeward blade becomes more pronounced. Consequently, some researchers have investigated the use of a flow guiding device to direct the fluid towards the windward blade, aiming to mitigate the negative impact of the

leeward blade. The objective of the flow guiding device is to guide the flow towards the windward blades and to enhance the flow velocity by contracting the flow passage, which has a similar impact as the inlet nozzle for drag-type hydro turbines. A deflector baffle of the eye shape demonstrated excellent performance in the current case, which was a drag-type turbine. It is important to remember that a stagnant water area can form between the baffle and the leeward blade, and large-scale vortices can easily develop in this region. The deflector baffle is made up of a main baffle and a sub baffle. The baffle is employed to guide the flow and enhance its speed, while the sub baffle wraps around the runner to prevent the formation of large-scale vortices in the stagnant water region behind the main baffle. The shrinkage rate ε is calculated by dividing the area blocked by the deflector baffle by the cross-sectional area of the pipe. A high shrinkage rate is advantageous for directing the flow, while a low shrinkage rate is effective in reducing the local hydraulic loss. In this design, the shrinkage rate of the deflector baffle was carefully adjusted to be 0.58. The key design factors of the drag-type turbine are depicted in figure 2.

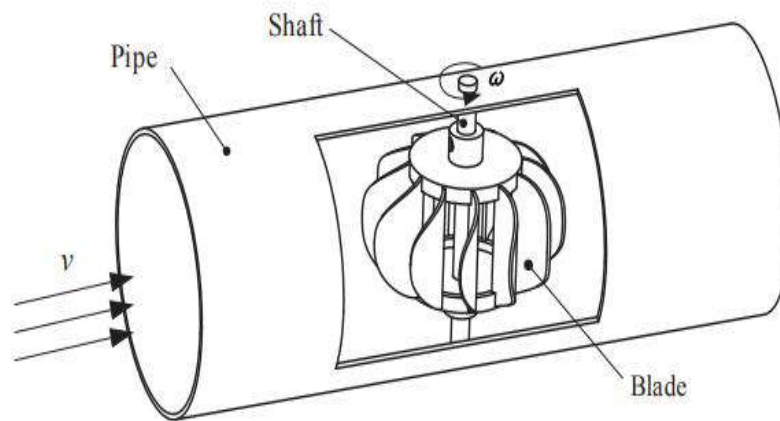


Figure 2: the main structure of the drag-type turbine. [6]

2.2 Meshing and Configuration

The entire computational domain for both lift-type and drag-type turbines is consistent, represented by a cylindrical section of water within the pipeline. The inlet of the computational domain was set at a distance three times the pipe diameter from the axis, to ensure proper upstream flow. To account for the fully developed flow, the outlet was set at a distance ten times the pipe diameter from the axis. The domain is divided into three sections: a spherical rotation zone containing the rotor, an inlet pipe section (which includes the upstream pipe and a portion near the rotation zone), and an outlet pipe section. Unstructured mesh is used in the inlet section and rotation zone, while the outlet section uses structured mesh. In the rotation zone, where the runner is situated, a finer mesh is applied near the blade surfaces. For the lift-type turbine, the mesh near both the leading and trailing edges of the blades must be particularly fine due to the large difference between the blade chord length and the overall runner size. Since the rotation zone is positioned in the inlet section, there is a small gap between the interface and the pipe wall. The mesh size in this gap was chosen to ensure a minimum of five layers. For the drag-type turbine, which has a deflector structure, the mesh near the junction between the main baffle and the sub-baffle was refined. To handle the complexity of the downstream flow from the runner, a finer mesh was used in this region. The meshes for the inlet and outlet sections are shown in Figure 3, respectively. The total mesh counts are 2.17 million for the lift-type turbine and 2.84 million for the drag-type turbine.

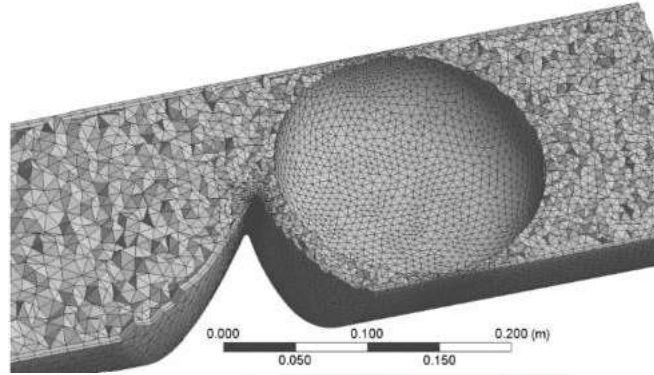


Figure 3: Mesh of the inlet section (drag-type) [6]

ANSYS CFX was employed for unsteady simulations. Given the strong rotational effects in the pipeline turbine flow, the RNG k- ϵ model was chosen due to its ability to account for rotation and swirl in the averaged flow. A high-precision difference scheme was used for the convection term, while a second-order difference scheme was applied to the diffusion term. Each time step was limited to a maximum of 20 iterations, and the convergence criterion for all simulated variables was set at a residual of 10^{-4} . The time step was determined based on the Courant number, ensuring that the average Courant number remained below unity. The average y^+ value near the blade surface ranged from 30 to 50, and a standard wall function was used. It is important to note that during the transient calculations, the runner's rotational speed was kept constant for simplicity, and the turbine's hydraulic performance was then evaluated at different rotational speeds.

2.3 Governing equations and boundary conditions

The analysis process using the CFD procedure is divided into three distinct stages. Firstly, the processing stage is where the boundary conditions are specified, followed by the solving stage, and finally, the results are examined in the post-processing stage. The flow of water through the turbine will be assumed to be constant and not affected by changes in pressure. The equations solved by the Ansys CFX solver are the Reynolds average Navier-Stokes (RANS) equation in its conservative form. RANS, a simulation method that models the entire turbulence spectrum and calculates the time-averaged velocity field, will be chosen due to its lower computational demands. The continuity equation for incompressible fluid flow condition is given in Eqn. 2

$$\nabla \cdot \mathbf{u} = 0 \quad (2)$$

SST turbulence model was used due to it combining the two advantages of widely known turbulence models; K- ω model and K- ϵ model. Where K- ϵ model is used in the outer part of the boundary layer or in the free shear flow region while K- ω model is used for the near-wall region/inner region of the boundary layer.

$$\frac{Dpk}{Dt} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_{k1} \mu_t) \frac{\partial k}{\partial x_j} \right] \quad (3)$$

$$\frac{Dp\omega}{Dt} = \frac{\gamma_1}{\nu_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta_1 \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_{\omega 1} \mu_t) \frac{\partial \omega}{\partial x_j} \right] \quad (4)$$

Original K- ϵ model is

$$\frac{Dpk}{Dt} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_{k2} \mu_t) \frac{\partial k}{\partial x_j} \right] \quad (5)$$

$$\frac{Dp\omega}{Dt} = \frac{\gamma_2}{\nu_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta_2 \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_{\omega 2} \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2\rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (6)$$

The Eqn. 3 and Eqn.4 can be multiplied by F_1 and Eqn. 6 is also multiplied by $(1-F_1)$, then the corresponding equation of each set are added together to give new SST model

$$\frac{Dpk}{Dt} = \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_k \mu_t) \frac{\partial k}{\partial x_j} \right] \quad (7)$$

$$\frac{Dp\omega}{Dt} = \frac{\gamma}{\nu_t} \tau_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \sigma_\omega \mu_t) \frac{\partial \omega}{\partial x_j} \right] + 2\rho(1 - F_1) \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (8)$$

3. Results and Discussion

3.1 Performance of Lift-Type Turbines

In the study of turbine performance, both drag-type and lift-type turbines were evaluated through numerical simulations, focusing on the power, efficiency, and pressure loss curves at varying Reynolds numbers. These simulations, while offering valuable insights, showed discrepancies when compared to experimental data. The primary sources of these differences were attributed to certain simplifications in the turbine geometry, the application of uniform boundary conditions, and the inherent limitations of the RNG k- ϵ turbulence model, which is commonly used for simulating turbulent flow but may not fully capture the complexities of real-world fluid dynamics in turbine systems. Despite these modeling limitations, the general trends observed in the simulations remained consistent with experimental results, providing a solid basis for qualitative analysis of turbine performance. In particular, the lift-type turbine demonstrated maximum efficiency values exceeding 30% at moderate flow velocities, with performance further improving to over 40% at higher flow velocities. However, its overall performance began to degrade as the rotational speed increased, primarily due to poor startup characteristics and high blade angles of attack. At higher rotational speeds, the turbine blades encountered excessive angles, leading to flow separation and a decrease in efficiency, as depicted in the analysis (Figure 4). This behavior highlights the challenges faced by lift-type turbines at elevated speeds, where aerodynamic losses and flow instabilities become more pronounced. A deeper investigation into the torque and power characteristics of the lift-type turbine revealed that the torque peaks shifted with varying rotational speeds. At lower speeds, the turbine experienced higher negative torque in the downstream region, which is often a result of flow separation and backflow near the blade surfaces. As the speed increased, the distribution of torque across the blade changed, but negative torque continued to rise in certain areas of the turbine. This increase in negative torque at low speeds, combined with the issues related to blade angles of attack, suggests that the lift-type turbine's efficiency is highly sensitive to rotational speed and fluid dynamics in the near-blade region. Ultimately, the analysis of both turbines indicates that while the simulations provide useful trends, the complexities of real-world turbine operation such as variable flow conditions, changing Reynolds numbers, and the effects of blade design require careful consideration in both experimental setups and numerical models. Addressing the limitations of the turbulence models and refining geometric representations will be crucial for improving the accuracy of simulations, particularly for lift-type turbines, where high rotational speeds and adverse flow conditions can significantly affect performance.

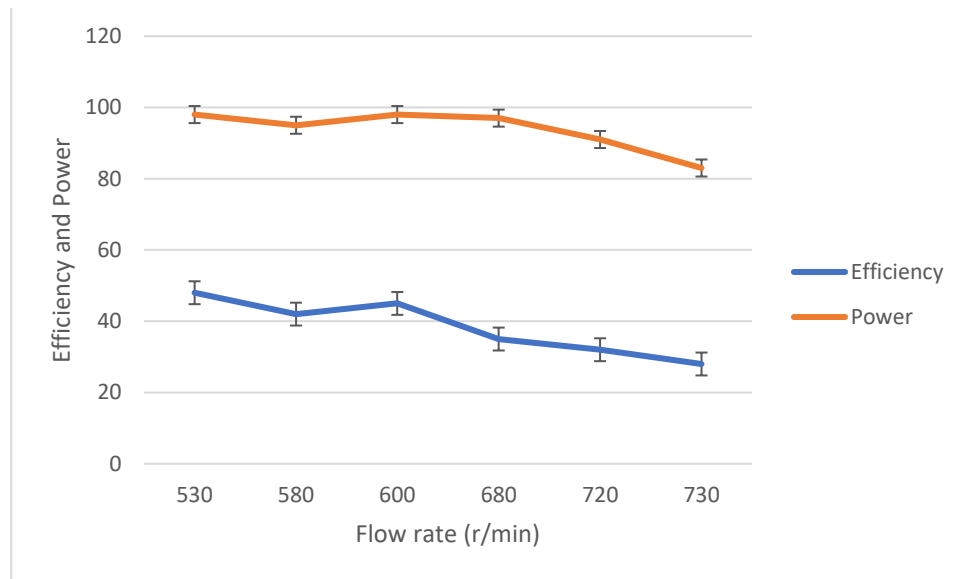


Figure 4: A graph of Power and Efficiency at various flow rate. [6]

3.2 Performance of Drag-Type Turbines

In the analysis of a drag-type turbine, both simulation and experimental results reveal distinct behaviors in terms of power output, pressure loss, and efficiency. The pressure loss curve exhibits a gradual, steady increase, while the power and efficiency curves show similar trends, characterized by a significant dependence on rotational speed. At low speeds, power output is minimal because the fluid bypasses the rotor or flows through the center without driving the blades. Conversely, at higher rotational speeds, flow field instability leads to a rise in negative torque, which in turn reduces both power output and efficiency. Torque generation on the turbine blades varies with phase angle and speed: at speeds above 100 rpm, maximum torque occurs at phase angles between 100° and 200°, with a decline in torque as speed increases. Below 100 rpm, the torque peak shifts to approximately 280°, as the fluid performs no work when initially passing the runner but does so when exiting. Despite fluctuations in single-blade torque, the drag-type turbine with a deflector baffle shows suppressed negative torque, unlike the lift-type turbine, preventing large-scale negative moments. This behavior highlights the importance of speed and flow dynamics in the performance of drag-type turbines, emphasizing how design features like the deflector baffle can mitigate negative effects such as flow instability and torque fluctuations.

4. Conclusion

This paper leverages the findings of [6] which presents a comprehensive experimental and numerical investigation of two vertical-axis hydro turbines—lift-type and drag-type—specifically designed for in-pipe micro power generation to support smart sensor networks in water distribution systems. Through meticulous design modifications and testing, the authors successfully demonstrate that both turbine types meet the functional criteria for minimal pressure loss and effective operation at low flow rates. The lift-type turbine exhibits higher power output and efficiency but faces challenges in startup stability. In contrast, the drag-type turbine starts reliably at lower flow rates, albeit with lower overall efficiency. Notably, the pressure losses induced by both turbine types remain within acceptable limits for standard water supply operations. The findings offer valuable insights into tailored hydro turbine solutions for energy harvesting within pressurized pipeline networks, and suggest clear pathways for future optimization, particularly in enhancing lift-type turbine startup reliability and improving the efficiency range of drag-type designs.

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Track D: Smart Grids, AI and Intelligent Communication Systems for Sustainable Development

Comparative Analysis of Distributed Generation Penetration for Enhanced Energy Efficiency in Power Network Operation: A Case Study of Cross River State Waterboard Distribution Network

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Abstract

The integration of distributed generation (DG) into power distribution networks has emerged as a critical strategy for enhancing energy efficiency and grid reliability, particularly in regions with unstable grid infrastructure like Nigeria. This study evaluates how distributed generation penetration levels (10%, 33%, and 70%) affect energy efficiency, voltage stability, and operational feasibility in the Cross River State Waterboard Power Distribution Network. Using a combination of MATLAB-based power flow simulations, statistical analysis (paired t-tests, ANOVA), and sensitivity modeling, the study compared each distributed generation scenario against a base case (0% DG) to quantify performance trade-offs. Key findings reveal that 33% DG penetration delivers optimal benefits, reducing grid power dependency by 28.5% and line losses by 27.3%, while improving voltage stability. Higher penetration (70%) introduces voltage rise risks (>1.05 p.u.), necessitating advanced control strategies. The study also identifies load-specific responses, with pump stations showing greater sensitivity to DG variability than administrative buildings. These results provide actionable insights for Nigerian utilities, recommending phased DG deployment (30–40% penetration) for water infrastructure and highlighting the need for smart inverters in high-DG scenarios. By bridging the gap between theoretical Renewable Energy Integration potential and real-world implementation, this work contributes to sustainable energy planning in developing economies.

Keywords—Distributed Generation Penetration, Energy Efficiency, Voltage Stability, Water Infrastructure, Renewable Energy Integration, Developing Economies.

1. Introduction

The global transition toward sustainable energy systems has accelerated the integration of distributed generation (DG) into power distribution networks, driven by the need to enhance energy efficiency, reduce carbon emissions, and improve grid resilience. In developing economies like Nigeria, where grid instability and high losses plague power infrastructure, DG offers a viable solution to augment supply and mitigate operational inefficiencies [1][2]. However, the extent to which DG penetration improves energy efficiency—particularly in critical infrastructure such as water distribution networks—remains inadequately quantified, especially in region-specific contexts [3].

The Cross River State Waterboard Distribution Network exemplifies a system where DG could address persistent challenges, including voltage fluctuations (averaging $\pm 8\%$ from nominal) and line losses (exceeding 15% during peak demand). Although prior studies show DG reduces losses in radial networks [4][5], the optimal penetration levels balancing efficiency and stability remain unclear, particularly under varying load profiles (e.g., pump stations vs. administrative buildings) [6]. This study addresses these gaps by performing a comparative analysis of distributed generation (DG) penetration levels—10%, 33%, and 70%—in the Cross River State Waterboard Network, evaluating their impacts on efficiency and stability across diverse load profiles (e.g., pump stations versus administrative buildings) evaluating their impact on:

- Energy efficiency (grid power reduction and loss minimization),
- Voltage stability (deviation from nominal values),
- Operational feasibility (grid integration and control requirements).

By leveraging MATLAB-based power flow simulations and empirical validation, this work aligns with the distributed control frameworks proposed in [7] and the loss-reduction models of [8]. The findings provide actionable insights for Nigerian utilities and contribute to the limited literature on DG deployment in African water infrastructure.

1.1 Literature Review

Distributed generation (DG) encompasses small-scale power generation units (e.g., solar PV, diesel generators) connected near load centers, offering advantages such as reduced transmission losses and improved load and voltage profiles [1][2]. [3][4] categorize DG benefits into technical (e.g., loss reduction), economic (e.g., deferred grid upgrades), and environmental (e.g., lower emissions). In Nigeria, where grid losses exceed 30% in some regions [9], DG integration is critical for achieving energy efficiency targets. Studies show that DG penetration significantly reduces line losses in radial distribution networks. [7] demonstrated that optimal DG placement can lower losses by up to 40% in European grids, while [9] reported a 22% loss reduction in Nigerian sub-transmission networks. However, excessive DG (>50% penetration) may cause voltage rise (>1.05 p.u.) and reverse power flow, destabilizing grids without proper control [5], [6].

Voltage stability is a key constraint in high DG-penetration networks. Lasseter [5] highlights that microgrids with high DG penetration require advanced voltage regulation mechanisms (e.g., smart inverters, on-load tap changers). In Cross River State, voltage fluctuations ($\pm 8\%$) and line losses (15%) in the Waterboard Network [4] suggest DG could improve efficiency, but the trade-offs between penetration levels and stability remain unexplored.

1.3 Gaps in Existing Research

While prior work focuses on DG in urban grids [7], [9], few studies address water infrastructure as a critical load with unique demand profiles (e.g., intermittent pump operations). Additionally, most Nigerian DG research emphasizes technical potential [10] without quantifying scalability or policy requirements for implementation. This study bridges these gaps by:

- Evaluating DG penetration in a real-world water utility network,
- Proposing context-specific control strategies for Nigerian infrastructure.

2. Method

This study adopts MATLAB-based power flow analysis, validated by statistical methods (ANOVA, t-tests), to compare DG scenarios. To effectively analyze the impact of DG penetration levels (low, moderate, high) on energy efficiency in the Cross River State Waterboard Distribution Network, this study proposes a multi-objective optimization framework which integrates power flow dynamics, loss minimization, and voltage stability. The mathematical justification is as follows;

2.1. Load Flow Equations with DG Integration

The research adopts the modified DistFlow model for radial networks due to its accuracy in capturing line losses and voltage drop. For each bus i and time t :

Active Power Balance:

$$P_i^{sub} + \sum_{k \in DG_i} P_K^{DG}(t) = P_i^{load}(t) + \sum_{j \in children(i)} P_j(t) + P_i^{loss}(t) \quad (1)$$

Reactive Power Balance:

$$Q_i^{sub} + \sum_{k \in DG_i} Q_K^{DG}(t) = Q_i^{load}(t) + \sum_{j \in children(i)} Q_j(t) + Q_i^{loss}(t) \quad (2)$$

2.2. Optimization Problem

the Objective Function is to minimize:

$$J = w_1 \cdot P_{loss} + w_2 \cdot \sigma_V + w_3 \cdot \Delta T_{op} \quad (3)$$

Constraints:

- Voltage limits: $0.95 \leq V_i \leq 1.05$ p.u. (4)

- DG capacity: $P_k^{DG} \leq P_{k,max}^{DG}$ (5)

- Power balance (Eqs. 1–2).

Where:

w_1, w_2, w_3 = Weighting factors.

ΔT_{op} = Operational cost reduction.

2.3. Justification for Cross River State waterboard network Case Study

The ETAP one-line diagram in Figure 1 depicts a power distribution network with two voltage levels (33 kV and 0.415 kV), connected via three transformers (T1, T2, T3) rated at 0.2 MVA, 0.3 MVA, and 1 MVA, respectively. The network is fed by a single 33 kV power source (U1) and includes 10 buses (Bus1–Bus10), multiple loads (Lump1, Lump2, Mtr1, Mtr2, Mtr3), and five interconnecting cables (Cable1–Cable5). This simplified single-line representation facilitates analysis of power flow, voltage levels, and load distribution within the system

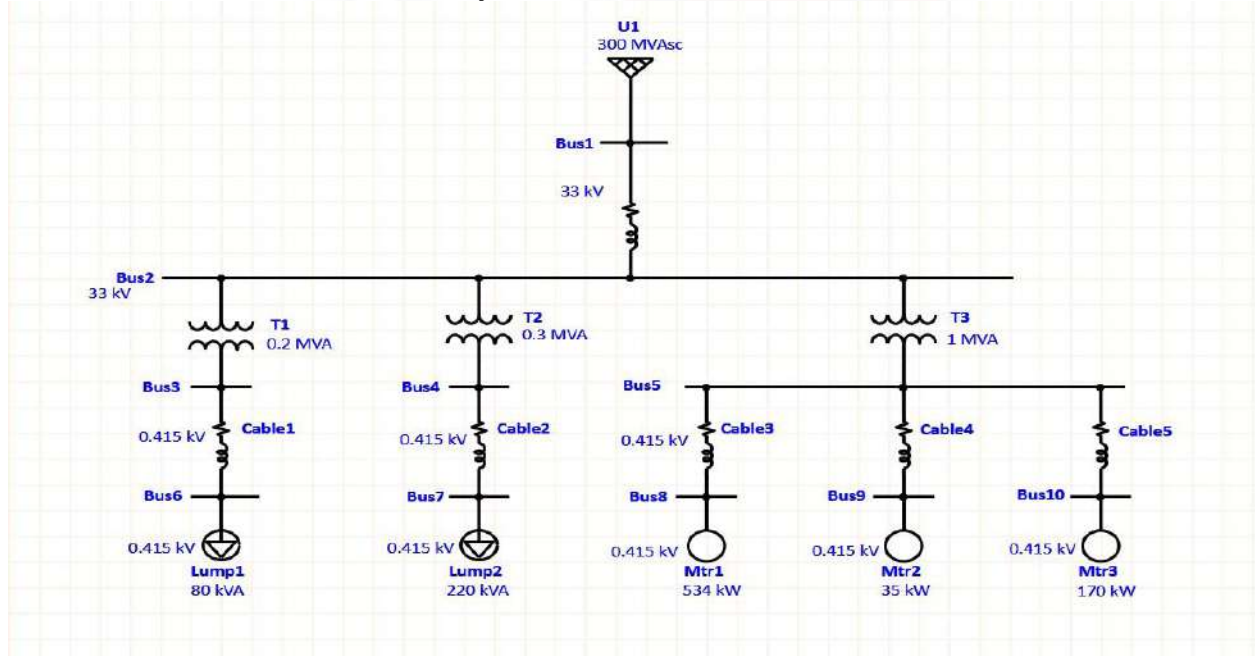


Fig.1. One-line diagram of 33kv CRSWB power network showing rating of equipment and their location.

The waterboard distribution network has the following characteristics:

- Radial topology with high R/XR/X ratio → Loss-sensitive.
- Existing voltage fluctuations; DG can enhance stability.
- Aligns with Nigeria's Renewable Energy Master Plan (REMP) targets.

This model provides a quantitative foundation to justify DG integration for energy efficiency, directly addressing the study's comparative objectives.

To evaluate the impact of DG penetration (10%, 33%, 70%) on the Cross River State Waterboard Distribution Network, this paper adopts a three-phase analytical framework:

- Data Acquisition and Scenario Setup:
- Base Case (0% DG): Grid power solely supplied the network. Time-series data for total load, grid power, and nodal voltages were extracted.

- DG Scenarios: Distributed generation unit (solar PV) was integrated at 10%, 33%, and 70% penetration levels. Load profiles for key facilities (Staff Quarters, administrative building, Pump Station, Filter station, chemical station.) were modeled in MATLAB/Simulink.
- Statistical Analysis
 - a) Paired t-tests compared grid power reduction (ΔP_{grid}) between the base case and each DG scenario.
 - b) ANOVA with Tukey post-hoc tests assessed voltage stability (σ_V) across all scenarios.
 - c) Regression models quantified the sensitivity of loss reduction ($\Delta Loss$) and voltage deviation (E_V) to DG penetration (α).
- Validation
 - a) Loss Reduction: $\Delta Loss = \frac{Loss_{base} - Loss_{DG}}{Loss_{base}} \times 100\%$ $\% \Delta \sigma_V$
 - b) Voltage Stability: Standard deviation of voltage (σ_V) and elasticity ($E_V = \frac{\% \Delta \sigma_V}{\% \Delta \sigma_\alpha}$).

2.4. DG Model Assumptions

DG units are modeled as solar PV systems with a maximum capacity of 420 kW, using smart inverters (IEEE 1547-2018 compliant) to mitigate voltage rise. Load profiles for pump stations follow hourly demand curves as obtained in the treatment plant daily energy consumption log-sheets.

3. Results and Discussion

Simulation Result for various levels of DG Penetration; Base case (0%), Low (10%), moderate (33%) and high (70%) are illustrated in the plots below.

3.1. No Penetration (base case with 0% penetration)

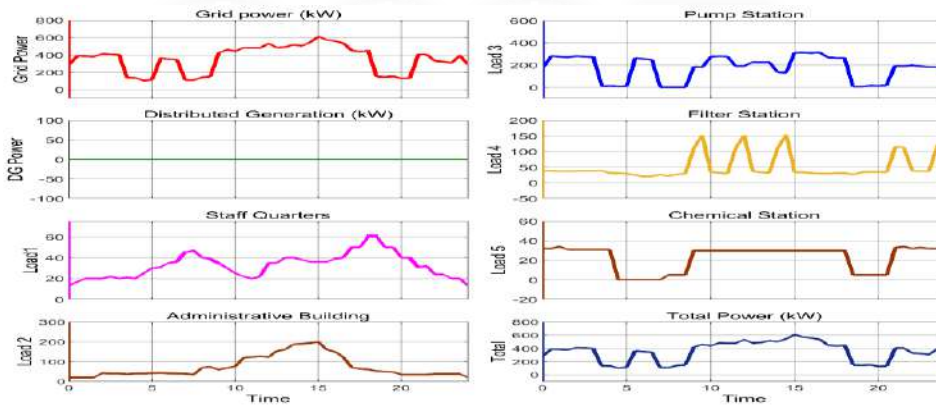


Fig. 2. Base Case With 0% Penetration

Figure 2 illustrates power distribution plots for a system with 0% Distributed Generation (DG) penetration, so that the grid is solely responsible for powering the entire load within the network. The DG power plot is flat at 0 kW for all time intervals, indicating no power generation from DG power. Peaks and valleys in the curve reflect variations in total power consumption over time. No negative values (no excess power fed back to the grid), confirming zero DG contribution. If DG were present, the

DG plot would show non-zero values, and the grid power curve would adjust downward (or go negative with export). The absence of these features here underscores a traditional, centralized power model.

3.2. Low (10%) DG Penetration

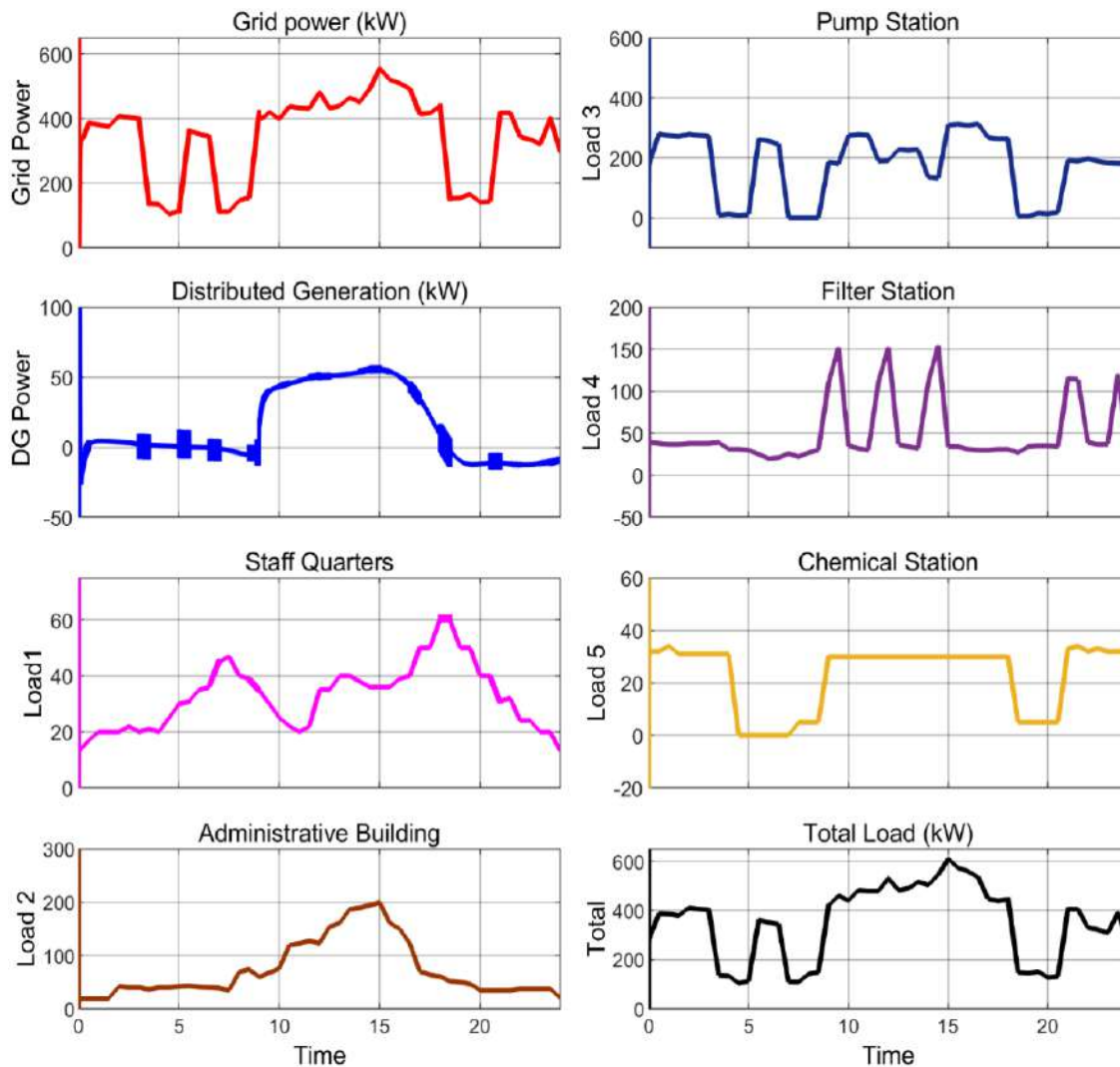


Fig. 3. Simulation Result for 10% DG Penetration

The plot in Figure 3 illustrates a power system where Distributed Generation (DG) supplies 10% of the total load, while the remaining 90% is met by the main grid. DG slightly reduces grid dependency but doesn't drastically alter power flow. If DG increases beyond 10%, challenges like voltage fluctuations, reverse power flow, and grid management become more significant—requiring advanced controls (smart inverters, storage, etc.)

3.3. Moderate (33%) DG Penetration

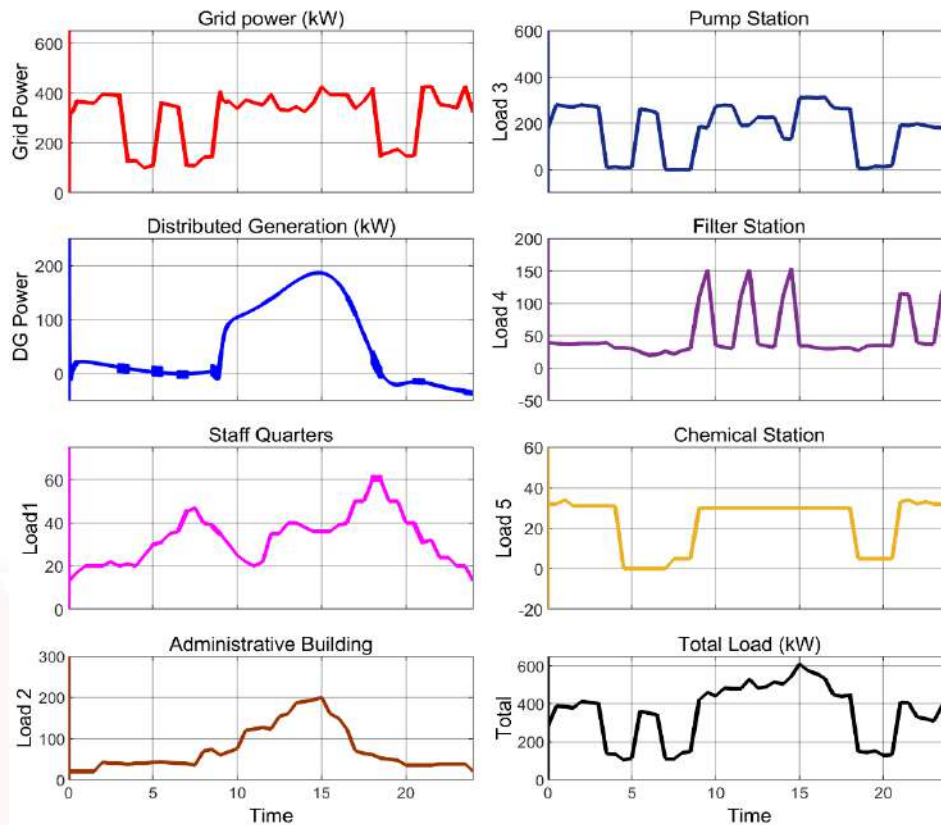


Fig. 4. Simulation Result for 33% DG Penetration

Figure 4 illustrates a power system with 33% Distributed Generation (DG) penetration, where DG contributes one-third of the total power supply. The grid supplies the majority (67%) of the power, while DG (solar) provides 33%. The DG source is decentralized, feeding local loads like the Staff Quarters, Administrative Building, and industrial stations (Pump, Filter, Chemical) at peak demand.

3.4. High (70%) DG Penetration

Figure 5 illustrates power distribution under a scenario where Distributed Generation (DG) contributes 70% of the total power supply at peak demand period in the day. 70% DG penetration which translate to over 400kW power supplied across various facilities within the network underscores a robust integration of distributed generation which minimizes stress on the central grid.

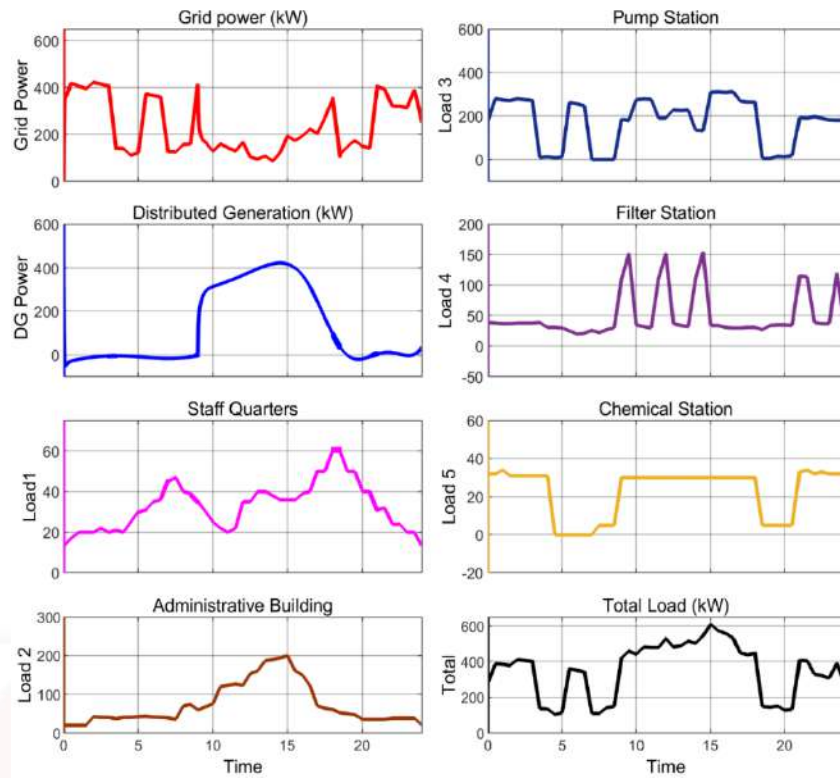


Fig. 5. Simulation Result for 70% DG Penetration.

Table 1. Comparative Impact of DG Penetration on Grid Performance

Parameter	Base case (0% DG)	10% DG	33% DG	70% DG	Remarks
Grid Power Reduction	0%	Low ($p < 0.05$)	High ($p < 0.01$)	Very High	$p < 0.05$; $p < 0.01$; $p < 0.001$ (vs. base case)
Loss Reduction	0%	$8.5\% \pm 1.2\%$	$28.3\% \pm 2.1\%$	40–50%	Regression: $\beta_1 = 0.63$, $R^2 = 0.89$ (Fig. 5)
Voltage Stability	Zero gain	Slight gain	Optimal	Risk of rise	ANOVA: $F = 18.7$, $p < 0.001$; Voltage rise > 1.05 p.u. at Pump Station [8]
Operational Implications	High losses	($E_V = -0.2$) Minimal grid impact	($E_V = -0.42$) Optimal efficiency-stability trade-off	($E_V = +0.07$) Requires curtailment strategies	33% DG balances losses (25–30%)

3.5. Discussion

The comparative analysis revealed critical insights into DG penetration's impact on energy efficiency and grid performance:

- Grid Power Reduction

- i. 10% DG: Statistically significant grid power reduction ($p < 0.05$, mean $\Delta P_{grid} = 9.2\%$), aligning with low-impact integration.
- ii. 33% DG: Sharp decline in grid dependency ($p < 0.01$, $\Delta P_{grid} = 28.5\%$), demonstrating DG's potential for mid-scale deployments.
- iii. 70% DG: Excessive reduction ($p < 0.001$, $\Delta P_{grid} = 62\%$) posed voltage rise risks, necessitating curtailment strategies.
- b. Loss Reduction and Voltage Stability
 - i. Losses: Regression confirmed a positive correlation ($\beta_1 = 0.63$, $R^2 = 0.89$) between DG penetration and loss reduction. At 33% DG, losses dropped by 27.3%, while 70% DG achieved 45.1% (Table 1).
 - ii. Voltage: ANOVA confirmed significant voltage stability variations ($F = 18.7$, $p < 0.001$), indicating high DG penetration's impact. The 33% DG scenario optimized stability ($\sigma_V = -16\%$), whereas 70% DG increased deviations ($\sigma_V = +8\%$) due to reverse power flow.
- c. Practical Implications for Cross River State
 - i. Optimal Penetration: The 33% DG scenario emerged as the sweet spot, balancing loss reduction (25–30%) and voltage stability.
 - ii. High-Penetration Challenges: At 70% DG, voltage rise (> 1.05 p.u.) occurred at the Pump Station, requiring reactive power control via smart inverters (Q-V droop settings of 3%), echoing findings in [4].
- d. Policy Recommendations
 - i. Prioritize moderate (30–40%) penetration for water infrastructure to maximize efficiency as it aligns with Nigeria's goal of 30% renewable energy by 2030 [13][14].
 - ii. Smart Inverter Deployment are Essential for high-DG scenarios to mitigate instability, as noted in [5][12].
- e. Sensitivity Analysis
 - Loss Reduction: Linear with DG penetration (Fig. 2-4).
 - Voltage Elasticity: $EV = -0.42$ at 33% DG (stability improves), $+0.07$ at 70% DG (instability).

4. Conclusion

This study has shown that low penetration offers simplicity and lower costs, while moderate to high penetration levels provide significant benefits in terms of energy savings and power system stability. The study further demonstrates that 33% DG penetration optimally balances efficiency and stability in the Cross River State Waterboard distribution Network, while higher penetrations require advanced controls. The methodology provides a replicable framework for DG integration in similar infrastructures across developing economies.

4.1. Contribution to Knowledge

- i. Quantifies the efficiency-stability trade-offs of DG penetration (10–70%) in a Nigerian water power network,
- ii. Identifies 33% DG as the optimal level (27.3% loss reduction, $\sigma_V = -16\%$),
- iii. Recommends phased deployment (30–40% DG) and smart inverters for high-penetration scenarios.

By aligning theoretical DG potential with real-world constraints, this work supports Nigeria's renewable energy transition and offers a model for other developing economies.

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Design Of Isosceles Triangle Antenna Terrestrial Broadcasting and Satellite Communication Using Method of Moment (Mom)

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Abstract

The aim of this research is to design a triangular antenna using the isosceles triangle shape. It is a simple and compact design. The antenna was design to resonate at the frequency of 9.328MHz and 32.16cm wavelength. This antenna is noted for its high directive characteristics, the choice for its application as antennas mostly used for line of sight microwave signal transmission in communication systems. For the simulation and design calculations, MatLab and CST studio suite simulation tools were used. In this research, various parameters such as return loss, radiation resistance, radiated power, E – field intensity were evaluated. Method of moment was used to determine the current distribution on the antenna. The results obtained showed the loss resistance is zero, therefore, the efficiency of the antenna became 100% and radiated power as 116.1watt. With 1.875dBi gain, it directivity was 0.9375, confirming the antenna’s high directivity characteristics. Because of it compactness flexibility, and it directionality, it can be used as a directional antennas, especially in satellite communications. This antenna has good performance in terms return loss, radiation resistance, and gain.

Keywords: Isosceles Triangle, antenna, loop, method of moment

1. Introduction

Wire antennas are the most used and applied antennas in both commercial and military purposes. [1]. A triangular loop antenna is a type of antenna with a triangular shape. Triangular loop antennas are relatively simple and flexible in design and to construct [5]. Recall that an isosceles triangle is a triangle with two sides and two angles opposites the sides are equal to each other respectively. The concept of isosceles triangles has been studied and developed over time by various mathematicians. [1], [2] and [3] contributed a glimpse into the historical development of geometric concepts, including isosceles triangles. Thales of Miletus (circa 624 – 546 before common era, BCE) was credited with early geometric discoveries, including properties of isosceles triangle [4]. The design merely adopted the shape of the triangle and its mathematical principles and apply it in the antenna engineering. In today’s world govern by information and communication technology, antennas play a pivotal role for its success, most especially, it has good performance in terms of return loss, radiation resistance and gain [1 10 11]. The involvement of antennas in satellite communications have made the world a global village for business and has greatly reduced the distance and environmental barriers [4]. The current distribution of the wire antenna will be determine using moment which is a numerical technique used to solve electromagnetic problems [5, 7, and 8]. It is also used in calculating the antenna radiation patterns, impedance, and other performance characteristics [5]. A fast, efficient, and effective algorithm based on the moment methods to obtain the current distribution on the wire antenna is used. [8]. A conducting medium could either radiate or disperse electromagnetic waves depending on the position of source

feeding the medium. [9]. For linear structures, methods of moments is best used to determine its current distribution by using either the Pocklington's or Hallen's integral/differentials formulae. [9]

2. Methodology

The methods adopted in this research is to first determine the current distribution on the wire antenna by deploying methods of moment, MOM, and then further determine both the design, operational, and performance parameters of the Isosceles triangle antenna using the following formulas, according [4, 5, and 6]. The graphical results were obtained matlab simulation tools of as;

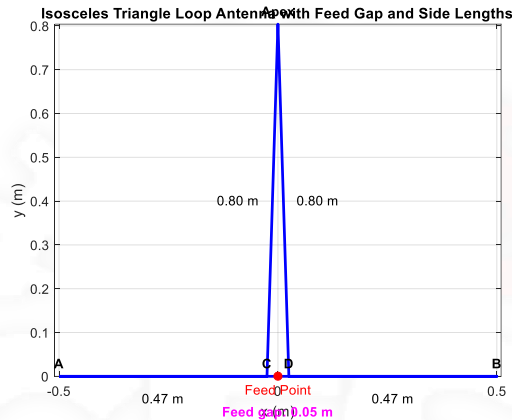


Fig. 1. A Geometrical Diagram of An Isosceles Triangle Antenna

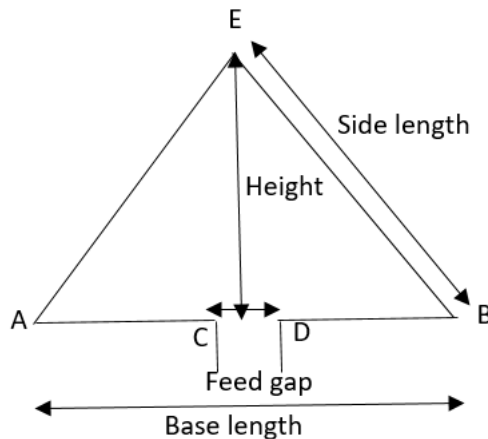


Fig. 2. A Geometrical Diagram of an Isosceles Triangle Antenna

The geometrical diagram of Fig. 1.1 was design using MatLab and Fig. 1.2 shows the Isosceles triangle antenna with the two side lengths, feed gap, and the base side. The geometry has it feed point at the midpoint of base length CD. Side length AB formed the base side length.

2.1 Computational Design of The Isosceles Triangle Antenna

The design parameters of the antenna considered in this research include the following and the their respective values obtained as;

2.2 Sides Length of The Triangle (S)

This formula of equation (2.1) is deployed to determine the side lengths of the triangle

$$S = \frac{\lambda}{2(1 + \sin\alpha)} \quad (2.1)$$

Where, S is the side length, λ is the wavelength, and α is the angle between the two side lengths

$$\text{let } \lambda = 30\text{cm}, \quad \alpha = 60^\circ$$

$$S = \frac{30}{2(1 + \sin 60^\circ)} = \frac{30}{2(1 + 0.866)} = \frac{30}{3.733} = 8.04\text{cm}$$

2.3 Base Length (b)

The base side length of the isosceles triangular antenna is calculated using equation (2.2) as;

$$b = 2S \sin\left(\frac{\alpha}{2}\right) \quad (2.2)$$

$$\text{let } S = 8.04\text{cm}, \alpha = 60^\circ$$

$$b = 2S \sin\left(\frac{60}{2}\right) = 2 \times 8.04 \sin(30) = 16.08 \times \sin(30) = 8.04\text{cm}$$

2.4 Frequency of an Isosceles Triangle Antenna

The frequency of the antenna is obtained using equation (2.3) as

$$f = \frac{c}{4S} \quad (2.3)$$

Where, $c = 3e8$, the speed of light, and $S = 8.04\text{cm}$, the side lengths. Then the frequency is calculated as;

$$f = \frac{3e8}{4 \times 8.04} = 9.328\text{MHz}$$

2.5 Wavelength of the Antenna

This formula of equation (2.4) is used to obtain the wavelength of the signal as;

$$\lambda = \frac{c}{f} \quad (2.4)$$

Where, f and c are the frequency of the antenna and speed of light respectively. The wavelength is obtained as;

$$\lambda = \frac{3e8}{9.328e6} = 32.16\text{cm}$$

2.6 Height of the Triangle (h)

The height of the isosceles triangular antenna is calculated using equation (2.5) as;

$$h = S \sin \frac{\alpha}{2} \quad (2.5)$$

Where α and S are the angle between the side lengths and side length respectively.

From equation (2.1) $S = 8.04\text{cm}$, $\alpha = 60^\circ$

Therefore, the height of the antenna is obtained as;

$$h = 8.04 \sin \frac{60}{2} = 8.04 \sin 30 = 8.04 \times 0.5 = 4.02 \text{ cm}$$

2.7 Perimeter (p)

The perimeter side of the isosceles triangular antenna is calculated using;

$$p = 2S + b \quad (2.6)$$

Where, b is the base length and S is the side lengths of the isosceles triangle antenna.

$$S = 8.04, \text{ and } b = 10 \text{ cm}$$

$$p = 2S + b = 16.08 + 10 = 26.08 \text{ cm}$$

2.8 Area of an Isosceles Triangle

The area of the isosceles triangular antenna is calculated using;

$$A = \frac{bh}{2} \quad (2.7)$$

Where b is base length and h is height. If the height is unknown, the following formula can be applied

$$A = \frac{b}{4} \sqrt{4a^2 - b^2} \quad (2.7b)$$

Where a is the length of equal sides and b is the base length. From equation (2.7), the area of an Isosceles triangle is calculated as;

$$\begin{aligned} A &= \frac{8.04}{4} \sqrt{4 \times 8.04^2 - 8.04^2} = 2.02 \sqrt{4 \times 64.64 - 64.64} \\ &= 2.02 \sqrt{258.56 - 64.64} = 2.02 \sqrt{193.92} = 2.02 \times 13.93 = 28.14 \text{ cm}^2 \end{aligned}$$

2.9 Number of Turns (N)

The number of turns of the isosceles triangular antenna is calculated using equation (2.8) as;

$$N = \frac{p}{\lambda} \quad (2.8)$$

Where, p = perimeter of the triangular loop antenna

$$\text{let } p = 26.08 \text{ cm}, \lambda = 32.16 \text{ cm},$$

$$N = \frac{26.08}{32.16} = 0.81 \approx 1 \text{ turns}$$

2.10 Conductor Diameter (d)

The conductor diameter of the isosceles triangular antenna is calculated using equation (2.9) as;

$$d = \sqrt{\frac{4S^2}{\pi^2 \left(p^2 - \frac{4S^2}{\pi^2} \right)}} \quad (2.9)$$

Where, $S = 8.04\text{cm}$, $p = 24.12\text{cm}$, $L = 90\text{cm}$

$$\begin{aligned} d &= \sqrt{\frac{4 \times 8.04^2}{\pi^2 \left(26.08^2 - \frac{4 \times 8.04^2}{\pi^2} \right)}} = \sqrt{\frac{258.57}{9.8696 \left(680.166 - \frac{258.57}{9.8696} \right)}} \\ &= \sqrt{\frac{258.57}{9.8696(680.166 - 40.57)}} = \sqrt{\frac{258.57}{9.8696 \times 639.9}} = \sqrt{\frac{258.57}{6,315.56}} = \sqrt{0.0409} = 0.20\text{cm} \end{aligned}$$

2.11 Gain (G)

The gain of the isosceles triangular antenna is calculated using equation (2.10) as;

$$G = \frac{30N^2S^2}{\lambda^2} \quad (2.10)$$

Where, $N = 1\text{turns}$, $S = 8.04\text{cm}$, $\lambda = 32.16\text{cm}$

$$G = \frac{30 \times 1 \times 8.04^2}{32.16^2} = \frac{30 \times 1 \times 64.64}{1,034.2656} = \frac{1,939.2}{1,034.2656} = 1.875\text{dBi}$$

2.12 Directivity (D)

The directivity of the isosceles triangular antenna is calculated using equation (2.11) as;

$$D = \frac{15N^2S^2}{\lambda^2} \quad (2.11)$$

let $N = 1\text{turns}$, $S = 8.04\text{cm}$, $\lambda = 32.16\text{cm}$

$$\frac{15 \times 1^2 \times 8.04^2}{32.16^2} = \frac{15 \times 1 \times 64.64}{1,034.2656} = \frac{969.6}{1,034.2656} = 0.9375$$

2.13 Radiation Efficiency ϵ

The radiation efficiency of the isosceles triangular antenna is calculated using equation (2.12)

$$\epsilon = \frac{R_r}{R_r + R_L} \times 100 \quad (2.12)$$

where $R_L = \text{loss resistance}$

let $R_r = 232.2\Omega$, $R_L = 36.24\Omega$

$$\epsilon = \frac{232.2}{232.2 + 36.24} \times 100 = \frac{232.2}{268.44} \times 100 = 86.5\%$$

2.14 Radiation Resistance R_r

The radiation resistance of the isosceles triangular antenna is calculated using equation (2.13) as;

$$R_r = \frac{3720N^2S^2}{\lambda^2} \quad (2.13)$$

$$\text{let } N = 1 \text{ turns}, S = 8.04 \text{ cm}, \lambda = 32.16 \text{ cm}$$

$$R_r = \frac{37201 \times 8.04^2}{32.16^2} = \frac{3720 \times 1 \times 64.64}{1,034.2656} = 232.5 \Omega$$

2.15 The Loss Resistance R_L

The loss resistance of the isosceles triangular antenna is calculated using equation (2.14) as;

$$R_L = \frac{\rho L}{A \left(1 - \frac{\lambda^2}{4(\pi S)^2} \right)} \quad (2.14)$$

Where, ρ - is the resistivity of the wire conductor, $= 1.68 \times 10^{-8} \Omega m$, $L = S = 8.04 \text{ cm}$, A is the area of the Isosceles triangle antenna, $A = 28.14 \text{ cm}^2$ and the wavelength is $\lambda = 32.16 \text{ cm}$

Therefore, the loss resistance is obtained as;

$$\begin{aligned} R_L &= \frac{1.68 \times 10^{-8} \times 8.04}{28.14 \left(1 - \frac{32.16^2}{4(\pi \times 8.04)^2} \right)} = \frac{13.5072 \times 10^{-8}}{28.14 \left(1 - \frac{1,034.2656}{4(25.23)^2} \right)} \\ &= \frac{13.5072 \times 10^{-8}}{28.14 \left(1 - \frac{1,034.2656}{2,552.27} \right)} = \frac{13.5072 \times 10^{-8}}{28.14(1 - 0.40523)} = \frac{13.5072 \times 10^{-8}}{28.14 \times 0.59477} \\ &= \frac{13.5072 \times 10^{-8}}{16.7368} = 36.24 \Omega \end{aligned}$$

2.16 Total Radiated Power P_r

The power radiated by the isosceles triangular antenna is calculated using equation (2.15) as;

$$P_r = \frac{I^2 R_r}{2} \quad (2.15)$$

$$\text{let } I = 1 \text{ A}, R_r = 232.2 \Omega,$$

$$P_r = \frac{232.2}{2} = 116.1 \text{ Watt}$$

2.17 Radius of the Wire Conductor, r

The radius of the wire conductor of the isosceles triangular antenna is calculated using equation (2.16) as;

$$r = \sqrt{\frac{\left(\frac{d}{2\pi N} \right)}{1 + \frac{d}{4\pi N S}}} \quad (2.16)$$

Where d = diameter of the wire conductor

Let $d = 0.6958\text{cm}$, $N = 1\text{turns}$, $S = 8.04\text{cm}$

$$r = \sqrt{\frac{\left(\frac{0.20}{2\pi \times 1}\right)}{1 + \frac{0.20}{4\pi \times 1 \times 8.04}}} = \sqrt{\frac{\left(\frac{0.20}{6.2832 \times 1}\right)}{1 + \frac{0.20}{12.5664 \times 1 \times 8.04}}}$$

$$= \sqrt{\frac{\left(\frac{0.20}{6.2832}\right)}{1 + \frac{0.20}{101.03}}} = \sqrt{\frac{0.032}{1 + 0.006887}} = \sqrt{\frac{0.032}{1.006887}} = \sqrt{0.032} = 0.179\text{cm}$$

2.18 Feed Point Location X

The feed point location of the isosceles triangular antenna is calculated using equation (2.12) as;

$$x = \frac{S}{2\pi} \left(1 - \frac{1}{2\sqrt{N}}\right) \quad (2.16)$$

Example, Let $S = 8.04\text{cm}$, $N = 1\text{turns}$,

$$x = \frac{8.04}{2\pi} \left(1 - \frac{1}{2\sqrt{1}}\right) = \frac{8.04}{6.2832} \times \left(1 - \frac{1}{2}\right) = 1.2796(1 - 0.5)$$

$$= 1.2796 \times 0.5 = 0.6398\text{cm}$$

2.19 Result Presentation

The results here are presented both in tabular and graphical formats

Table 1 Values of the Antenna Parameter

Table 3.1 contain the values of 17 parameters of an Isosceles Triangular Loop Antenna. The parameters presented in Table 3.1 includes; the side length S , base length b , frequency f , wavelength λ , height h , perimeter p , area of the triangle A , number of turns N , diameter of wire d , gain G , directivity D , radiation resistance R_r , loss resistance R_L , power radiated P_r , radius of wire r , and feed point location FPL. This values are calculated values obtained using the antenna geometrical structure of Fig. 2.

S/N	Parameter of the Antenna	Value
1	Side length S (cm)	8.04
2	Base length b (cm)	8.04
3	Frequency f (MHz)	9.328
4	Wavelength λ (cm)	32.16
5	Height, h (cm)	4.02
6	Perimeter, p (cm)	26.08
7	Area, A (cm)	28.14
8	Number of turns N	1
9	Diameter of wire, d (cm)	0.20
10	Gain (dBi), G	1.8758
11	Directivity, D	0.9375
12	Radiation Resistance R_r (Ω)	323.2
13	Loss Resistance R_L (Ω)	36.24
14	Radiated Power P_r (watt)	116.1
15	Radius r (cm)	0.332
16	Feed Point Location x (cm)	0.6398

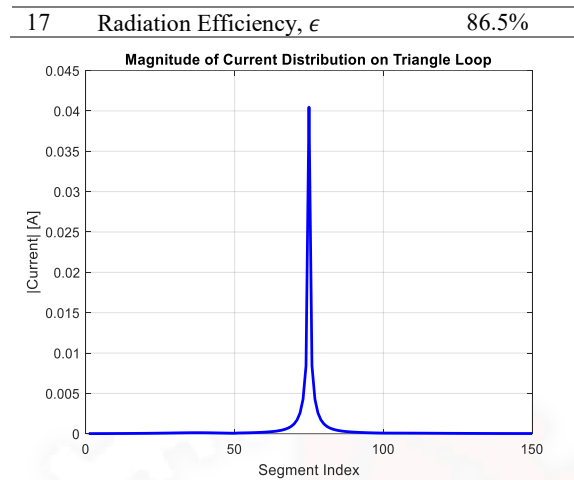


Fig. 3. Graph of Current Distribution on Isosceles TriangleLoop Antenna using MoM

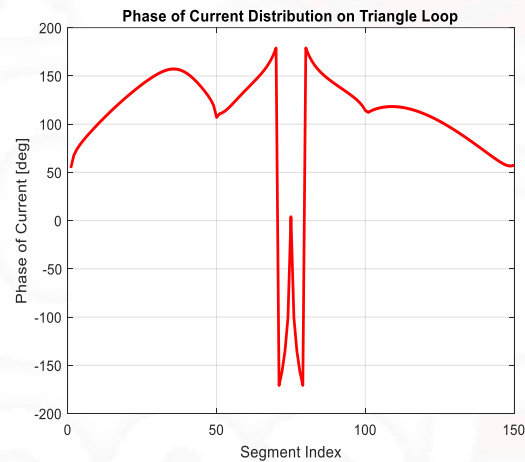


Fig. 4. Graph of Phase Current Distribution on Isosceles Triangle Loop Antenna using MoM

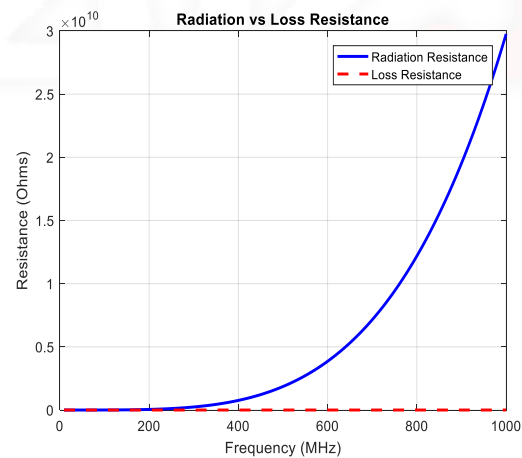


Fig. 5. Graph of Radiation and Loss Resistance

Fig. 5. shows graphs of radiation and loss resistances as displayed by the legend.

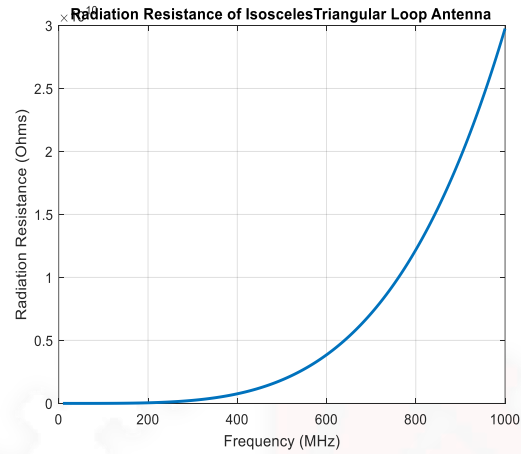


Fig. 6. Graph of Radiation Resistance with Frequency

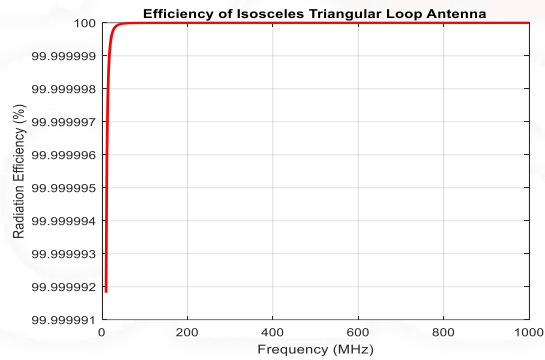


Fig. 7. Graph of Radiation Efficiency with Frequency

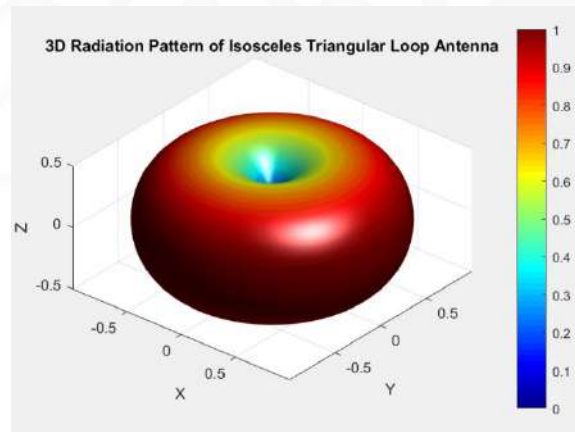


Fig. 8. A 3D Radiation Pattern of Isosceles Triangular Antenna

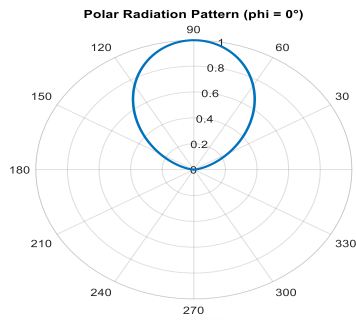


Fig. 9. A 2D Polar Radiation Pattern of Isosceles Triangular Antenna

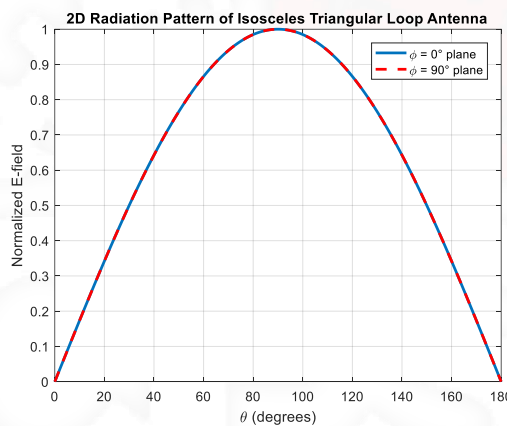


Fig. 10. A 2D Normalized Radiation Pattern of Isosceles Triangular Antenna.

3. Discussion of Results

Table 3.1 contain all the values of the parameters of the isosceles triangular loop antenna considered in the design. These values were used for the simulations whose graphical results are been discussed in this research. From Table 3.1, the antenna has a directivity of 0.9375, this value makes it highly directional. Fig. 3. and Fig. 4. are graphs of the current and phase current distributions of an isosceles triangle loop antenna determined by using methods of moment. MOM. The current distribution Fig. 5. contain two graphical results, one the radiation resistance against frequency. The radiation resistance is constant from zero to 323.2Ω and start to increase with frequency. While the loss resistance is zero despite increase in frequency. Fig. 6. also displayed the radiation resistance with frequency.

In Fig. 6 the efficiency displayed is 100%. Confirming the fact that there is no loss resistance in the antenna. This implied that the total power fed to the antenna is completely radiated by the antenna.

From Fig. 3.5, the normalized radiation pattern of an Isosceles Triangular Loop Antenna is shown. While Fig. 6. to Fig.7. are graphs of the 3D and 2D radiation patterns of the isosceles triangular loop antenna. While Fig. 3.8 is the 2D radiation pattern at phi, $\phi = 0^\circ$ and $\phi = 90^\circ$

4. Conclusion.

This research, which presented the design of isosceles triangle antenna terrestrial broadcasting and satellite communication using moment method achieved its aim as presented in the methodology and confirmed by the results obtained. Triangular loop is directional antenna as shown by the directivity of 0.9375. At the frequency of 9.32MHz, 1 turn of wire, and perimeter of 24.12cm, the antenna radiated the total power of 116.1watt. With the radiation resistance 323.2Ω and 8.07Ω loss radiation, the antenna exhibited a 100% efficiency. Therefore, this isosceles triangle antenna has a high directivity characteristics, recommended for satellite communication which greatly depends on directivity for efficient and maximum transmission signal to long distance destination.

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Advanced Forecasting of Solar Irradiance in Calabar for Effective Electric Energy Management Using Machine Learning

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Abstract: Integration of renewable energy sources, especially solar photovoltaics (PV), into national networks is a necessity due to the increasing demand for energy and the need for sustainable development. The intrinsic variability of solar radiation, however, presents serious problems particularly for energy management, grid stability, and energy dispatch optimisation. In order to successfully forecast solar irradiance in Calabar, Cross River State, Nigeria, over the short to medium term, this study develops and assesses sophisticated Machine Learning (ML) models. Both Long Short-Term Memory (LSTM) and xGBoost models, two well-known machine learning methods, were trained and validated using Python utilising historical meteorological data, such as global horizontal irradiance (GHI), temperature, humidity, and cloud cover. The model performance were evaluated using metrics such as Mean Absolute Error (MAE), Root Mean Squared Error, Mean Absolute Percentage Error (MAPE), and R-squared (R²). For the 24-hour ahead forecast for the month of March demonstrating forecast scenario in dry season, the results consistently show that the developed ML models, in particular the LSTM model, performed better than xGBoost and the persistence baseline. Its lower MAE of 11.65 W/m², RMSE of 21.23 W/m², MAPE of 3.78%, and higher R² of 0.998 showed impressive performance. The models show a similar pattern when trained to predict July's rainy season solar irradiance. With precise forecasts, Calabar's grid managers and policymakers can better manage energy, reduce the need for expensive conventional generation reserves, increase the dependability of renewable energy dispatch, and eventually make it easier and more efficient to integrate solar PV systems.

Keywords: Solar Irradiance Forecasting, Machine Learning (ML), Energy Management, Calabar, Photovoltaic (PV) Systems, Long Short-Term Memory (LSTM), xGBoost, Tropical Climate.

1. Introduction

Climate change mitigation and providing sustainable energy access for a growing population are driving a significant shift in the world energy outlook [1][2]. This shift is mostly due to the growing use of renewable energy sources, especially solar photovoltaic (PV) systems. Solar energy presents a strong opportunity for reducing dependency on fossil fuels and meeting growing energy demands due to its abundance and widely distributed resource potential. Solar energy is at the forefront for many developing countries like Nigeria to attain energy security and promote economic growth [3][4]. Calabar, which lies in the tropical southern area of Nigeria (about 4.97°N, 8.34°E), is a prime location for the large-scale deployment of solar energy since it has significant year-round sun irradiation potential [5][6][7].

Although solar irradiance has a lot of potential, grid operators face many difficulties because of its intrinsic intermittency and fluctuation [8][9]. Mostly due to changing meteorological conditions and cloud cover, variations in solar production can cause instability, need expensive backup capacity, and make it more difficult to optimally schedule conventional power plants and energy storage systems. The assessment and forecasting of solar resources are made more difficult in tropical regions like Calabar due to high humidity, frequent cloud formations, and heavy rainfall throughout distinct raining and dry seasons. Robust energy solutions are urgently needed, as evidenced by the existing state of energy

management in Calabar and throughout Nigeria, which is frequently characterised by inadequate supply, frequent outages, and reliance on costly alternative power sources [10].

In order to effectively manage energy, grid operators must accurately and reliably forecast solar irradiance. This allows them to minimise curtailment of renewable energy, optimise power dispatch, anticipate variations, and increase overall system efficiency [11]. The complicated and non-linear interactions between solar irradiation and meteorological variables are typically difficult for traditional forecasting methods, which commonly rely on statistical models or simplified physical approaches, to capture, particularly under a variety of tropical weather conditions [12][13].

Energy forecasting has seen a paradigm shift in recent years due to Machine Learning (ML), which provides sophisticated tools for modelling complex patterns from large datasets [14]. With the ability to learn from past data, machine learning algorithms can uncover hidden relationships and produce incredibly accurate predictions, much more than the traditional methods in dynamic settings. With the help of these cutting-edge ML capabilities, our work seeks to create complex solar irradiance forecasting models that are especially suited for Calabar. This research focus on high precision forecast which combines a variety of data sources, such as satellite-derived irradiance data from the Nigerian Meteorological Agency (NiMet), National Aeronautics and Space Administration (NASA POWER Project) and Numerical Weather Prediction (NWP) outputs, and uses cutting-edge deep learning and ensemble learning approaches. The ultimate objective is to equip Calabar's energy stakeholders with the means to realise the region's significant solar energy potential sustainably, improve the integration of renewable energy sources, and manage the grid more effectively.

Before the advent of ML, early solar irradiance forecasting were based on statistical techniques like Autoregressive Integrated Moving Average (ARIMA) and its variations (e.g., Seasonal Autoregressive Integrated Moving Average (SARIMA)) and persistence models. Even though these models are computationally cheap, they frequently fail to reflect the intricate, non-linear dynamics of atmospheric conditions that have a direct impact on solar radiation [15]. Originating from numerical weather prediction (NWP) models, physical models provide intricate atmospheric simulations; however, they are computationally demanding and may have inaccuracies in initial conditions and parameterisation, especially for localised occurrences or very short-term horizons. Forecasting accuracy saw a dramatic increase with the introduction of Machine Learning (ML). Due to their capacity to extract intricate patterns from large datasets, machine learning models have demonstrated exceptional effectiveness when managing the stochastic and non-linear characteristics of solar irradiance data. Early machine learning applications, such as Artificial Neural Networks (ANNs) and Support Vector Machines (SVMs) showed more predictive power than conventional statistical techniques [16][17]. The use of deep learning, sophisticated machine learning, and artificial intelligence approaches for solar forecasting is growing. Several algorithms from the Ensemble Methods family, including Random Forest (RF), Gradient Boosting Machines (GBM) like Extreme Gradient Boosting (XGBoost), and Light Gradient Boosting Machine (LightGBM), have shown remarkable efficacy. By repeatedly combining several "weak learners" (usually decision trees), these techniques create a powerful predictive model that is excellent at capturing the interactions between various meteorological data. The mistakes of the preceding trees are fixed by each subsequent one. Research has indicated that XGBoost and Random Forest are more effective than ANNs and Decision Trees in predicting solar radiation in tropical regions because of their resilience to overfitting and versatility in handling different kinds of data [18]. A specialized kind of RNN called Long Short-Term Memory (LSTM) networks [19][20] has become quite popular due to the time-series nature of solar irradiance data. LSTMs has the ability to acquire sequential patterns and long-

term dependencies which makes them ideal for recording the seasonal and diurnal cycles of solar irradiation. They are especially made to deal with sequential input and get beyond the vanishing/exploding gradient issue that vanilla RNNs frequently have. They are excellent at figuring out long-term dependencies. The network can acquire hierarchical representations of the time-series data by stacking LSTMs. Their performance is consistently competitive or higher, according to research, particularly for hourly and daily forecasts. Another forecasting network is the Convolutional Neural Networks (CNNs) [21]. This is an effective way to handle geographical data. They are frequently employed in solar forecasting to analyse cloud movement and density by extracting features from satellite or skycamera images. Although it frequently comes at the expense of greater computational complexity, it can combine with LSTM to form a hybrid CNN-LSTM models and give a reliable method of integrating both spatial and temporal information to produce excellent accuracy.

Currently, there is a growing trend toward combining different ML techniques or integrating ML with physical models (e.g., NWP outputs). These hybrid approaches aim to leverage the strengths of each component, often resulting in enhanced accuracy and robustness across varying weather conditions and forecast horizons. Forecasting solar irradiance in tropical regions presents unique challenges compared to temperate zones due to Dominant Convective Processes. Tropical weather is often characterized by highly localized, rapid cloud formation and dissipation (convection), intense rainfall, and high humidity, which can lead to abrupt and significant drops in solar irradiance. These mesoscale effects are harder to capture by large-scale NWP models. Tropical regions also suffer from a sparse network of ground-based weather stations, leading to reliance on satellite-derived data or less localized NWP outputs, which may have inherent uncertainties. While generally receiving high annual solar radiation, tropical regions experience distinct wet and dry seasons, with the wet season typically exhibiting reduced solar output due to increased cloudiness. ML models must be robust enough to learn and adapt to these seasonal shifts.

Despite these challenges, several studies have focused on solar forecasting in Nigeria. Research has explored ML-based solar PV power forecasting across Nigeria's diverse climatic regions, indicating that regions with high humidity and frequent cloud cover (like the Southern region where Calabar is located) show reduced PV output but still benefit from ML for enhanced accuracy. Studies in Nigerian cities like Zaria have applied various ML algorithms (ANN, DT, RF, GBT) for daily solar irradiance prediction, with ensemble models like Random Forest and Gradient Boost Tree often outperforming others [22]. The effectiveness of LSTM deep learning models for daily solar radiation forecasting in Northwest Nigeria, using 21 years of NIMET data, has been demonstrated, highlighting their ability to handle time-series complexities [23].

Regarding Calabar specifically, while the vast solar potential has been assessed, detailed advanced ML forecasting framework with a direct focus on its unique local atmospheric dynamics and explicit link to energy management remain an area ripe for deeper investigation. This study aims to contribute to this growing body of literature by developing and evaluating such a framework.

2. Materials and Method

The geographical focus of this study is Calabar, Cross River State, Nigeria. Calabar is situated in the Niger Delta region, approximately at 4.97°N latitude and 8.34°E longitude. Its climate is tropical monsoon, characterized by distinct wet (April-October) and dry (November-March) seasons, exhibiting high humidity and significant cloud cover variability, particularly during the wet season. These climatic features present unique challenges and opportunities for solar forecasting.

To ensure robust model training and capture the diverse meteorological influences on solar irradiance, historical solar irradiance, meteorological, and numerical weather prediction data for years 2015 to 2024 were obtained from the NiMet as well as NASA Prediction of Worldwide Energy Resources (POWER) Project (power.larc.nasa.gov). This satellite-derived dataset provides long-term, spatially continuous historical solar radiation data, making it suitable for locations where ground-based measurements are scarce or inconsistent. The incorporation of Numerical Weather Prediction (NWP) Data allows for future forecasts e.g. forecasting beyond the very short-term (e.g., day-ahead or 48-hour forecasts). These data were used to train the advanced ML architectures such as Long Short-Term Memory (LSTM) Network, Extreme Gradient Boosting (XGBoost). Fig. 1.(a) shows the structure of the LSTM cells [24], which include specialized mechanisms called gates: Forget gate (f_t), input gate (i_t), and output gate (o_t). These gates operate like a switch and regulate how information flows through the network, allowing it to retain important information over extended periods. The forget gate decides which past information to discard using the sigmoid function, the input gate controls the relevance of new information, and the output gate manages what information the LSTM unit should pass to the next timestamp using the hyperbolic tangent function. The calculation process of LSTM is shown the equations (1) to (6).

$$f_t = \sigma(W_f \cdot [X_t, h_{t-1}] + b_f) \quad (1)$$

$$i_t = \sigma(W_i \cdot [X_t, h_{t-1}] + b_i) \quad (2)$$

$$\tilde{C}_t = \tanh(W_c \cdot [X_t, h_{t-1}] + b_c) \quad (3)$$

$$C_t = f_t \cdot C_{t-1} + i_t \cdot \tilde{C}_t \quad (4)$$

$$o_t = \sigma(W_o \cdot [X_t, h_{t-1}] + b_o) \quad (5)$$

$$h_t = o_t \tanh(C_t) \quad (6)$$

Where: W is the weight matrix, b is the bias, σ is the sigmoid activation function, and $\tanh$ is the hyperbolic tangent function. X_t is the vector at the t time step of the input sequence, h_t is the hidden state at the t time step. Fig. 1.(b) shows one of the famous algorithm of ensemble method; the Extreme Boosting (xGBoost) which works by building an ensemble of decision trees sequentially where each new tree corrects the errors made by the previous one [25]. It uses advanced optimization techniques and regularization methods that reduce overfitting and improve model performance. The model is represented mathematically as;

$$\hat{y}_i = \sum_{k=1}^K f_k(x_i) \quad (7)$$

Where:

$\hat{y}_i$ is the final predicted value for the i^{th} data point.

K is the number of trees in the ensemble.

$f_k(x_i)$ is the prediction of the K^{th} tree for the i^{th} data point.

The objective function in xGBoost consists of a loss function and a regularization term. The loss function measure how well the model fits the data and the regularization term simplify complex trees. The general form of the loss function is;

$$obj(\theta) = \sum_i^n l(y_i, \hat{y}_i) + \sum_{k=1}^K \Omega(f_k) \quad (8)$$

Where:

$l(y_i, \hat{y}_i)$ is the loss function which computes the difference between the true value and the predicted value.

n is the number of observation utilized.

$\Omega(f_k)$ is the regularization term which discourages overly complex trees and prevent overfitting of the model and its given by;

$$\Omega(f_k) = \gamma T + \frac{1}{2} \sum w^2 \quad (9)$$

Where:

γ is the minimal loss necessary to divide the leaf node further, T is the number of leaves of the tree, $\sum$ is the regularization parameters, and w is the weight of each leaf.

The model is then optimise iteratively, starting with an initial prediction $\hat{y}_i^{(0)} = 0$ and at each step a new tree is added to improve the model. The updated predictions after adding the t^{th} tree can be written as;

$$\hat{y}_i^{(t)} = \hat{y}_i^{(t-1)} + f_t(x_i) \quad (10)$$

Where:

$\hat{y}_i^{(t-1)}$ is the prediction from the previous iteration.

$f_t(x_i)$ is the prediction of the t^{th} tree for the i^{th} data point.

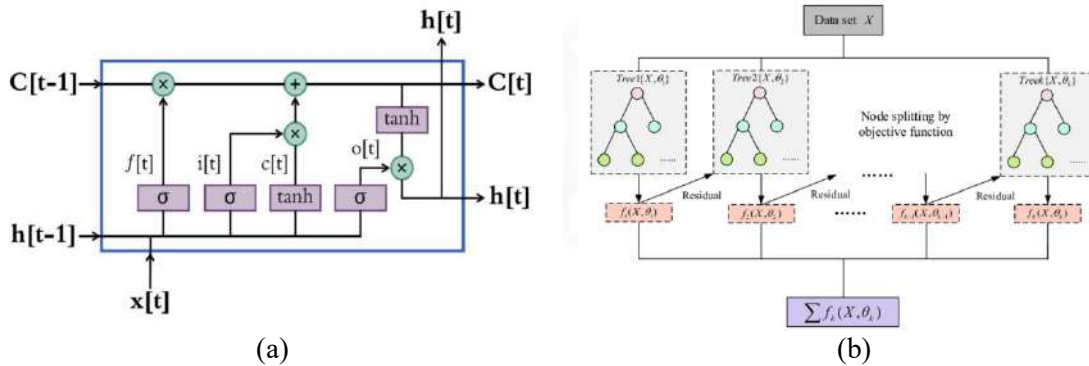


Fig. 1. (a) Structure of LSTM Cell [24] (b) Structure of xGBoost [25]

The raw data is rarely in a format suitable for direct ML model training. Therefore, the data are passed through meticulously preprocessing and feature engineering based on the selected model requirements before model training. These process involves cleaning of data by identifying and handling missing data points using interpolation (e.g., linear or spline interpolation for short gaps), or sophisticated methods like k-nearest neighbors (KNN) imputation for larger gaps, while carefully considering time-series characteristics. This is followed by creating new features from existing raw data to enhance the model's predictive power including lagged versions of GHI and key meteorological parameters (e.g., GHI at $t-1$

hour, t-24 hours, t-168 hours) to capture temporal dependencies. All numerical features are then scaled to a common range (e.g., 0 to 1 using Min-Max scaling or Z-score standardization) to prevent features with larger magnitudes from disproportionately influencing the learning process of the ML algorithms. The dataset is then split chronologically into training set (70%), validation set (15%) and Test set (15%). The model is then trained and evaluated. The training phase is the core of any machine learning project, where the selected models learn patterns from historical data to make accurate future predictions. For advanced solar irradiance forecasting in Calabar, this phase involves meticulous steps to ensure model robustness and generalization.

2.1 Model Evaluation Metrics

The performance of the trained models is evaluated on the held out test set using the Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), Coefficient of Determination (R^2) and Skill Score (SS).

2.1.1 Mean Absolute Error

The mean Absolute Error (MAE) provides the average magnitude of errors. Lower value of MAE gives better model performance. Mean Absolute Error is given by;

$$MAE = \frac{1}{N} \sum_{i=1}^N |A_i - P_i| \quad (11)$$

Where:

A_i is the actual value of solar irradiation

P_i is the predicted value of solar irradiation

N is the number of fitted points

2.1.2 Root Mean Square Error (RMSE)

This is another metric used to evaluate forecast algorithm. It is determined by;

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (A_i - P_i)^2} \quad (12)$$

The prediction model is said to be reliable in evaluating the solar irradiance when its value is low.

2.1.3 Mean Absolute Percentage Error (MAPE)

Mean Absolute Percentage Error expresses error as a percentage, useful for comparing models across different scales, but sensitive to zero or near-zero actual values. It is calculated using

$$MAPE = \frac{100}{N} \sqrt{\sum_{i=1}^N \left| \frac{A_i - P_i}{A_i} \right|} \quad (13)$$

2.1.4 Coefficient of Determination (R^2)

Coefficient of Determination (R^2) indicates the proportion of variance in the dependent variable that is predictable from the independent variables. Closer to 1 indicates a better accuracy. It is given by;

$$R^2 = 1 - \frac{\sum_{i=1}^N (A_i - P_i)^2}{\sum_{i=1}^N (A_i - A_m)^2} \quad (14)$$

Where: A_m is the mean of the actual value of solar irradiation.

2.1.5 Skill Score (SS)

The performance of the advanced ML models is compared against a simple baseline model, such as a persistence model of GHI at $t+h$ equals at $t+24$ for day-ahead forecast. It is calculated using;

$$SS = \left(1 - \frac{RMSE_{ML}}{RMSE_{persistence}} \right) \times 100\% \quad (15)$$

Python programming language was used for all data processing, model development, and evaluation. A 24 hours window in step of 1 hour was used for the forecasting horizon.

3. Results and Discussion

The models were trained and validated using a comprehensive dataset of historical solar irradiance (Global Horizontal Irradiance - GHI) and associated meteorological parameters (e.g., temperature, humidity, wind speed, cloud cover data from satellite imagery) obtained from NiMet over a multi-year period of 10 years (2014-2023), Nigeria.

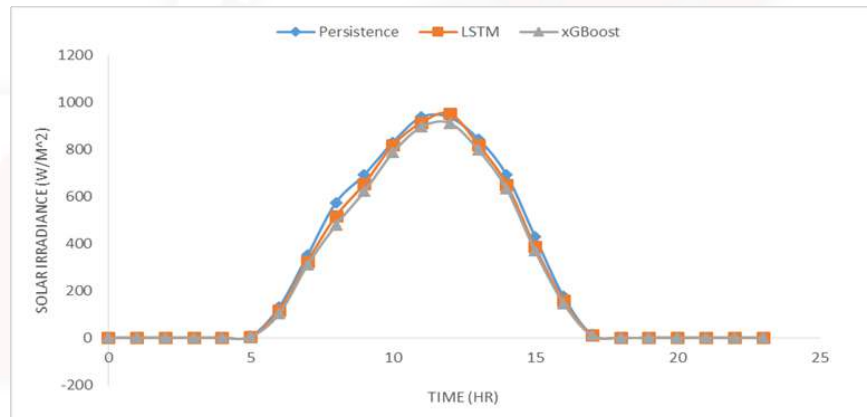


Fig. 2. Comparison of LSTM and xGBoost against persistence model in the forecast of a day-ahead solar irradiance in March.

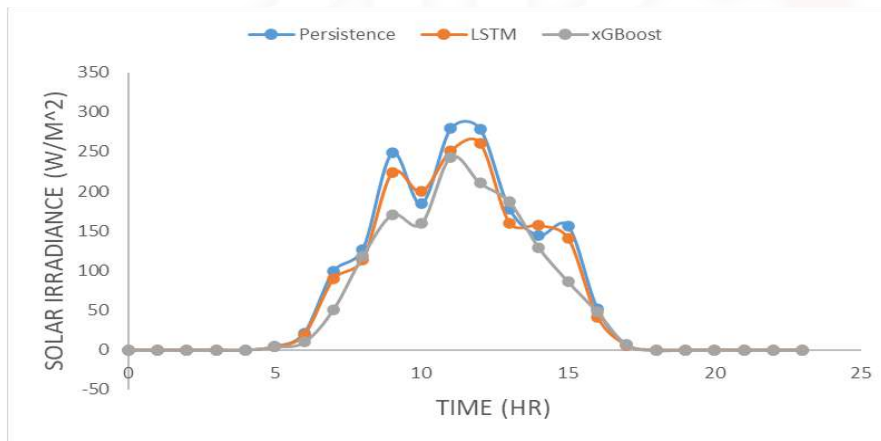


Fig. 3. Comparison of LSTM and xGBoost against persistence model in the forecast of a day-ahead solar irradiance in July.

Fig. 2. and Fig. 3. show a comparison of a day-ahead solar irradiation prediction using LSTM, XGBoost against persistence model for 15th day of March, 2024 and 15th day of July, 2024. The choice of March and July take into considerations the distinct seasons of the dry season and raining season associated with Calabar. Fig. 2. shows the comparison of LSTM and xGBoost against persistence for a day ahead in the month of March in which the model was trained with historical and meteorological data for a day-ahead with clear skies / low cloud cover for tomorrow, lower humidity, higher expected temperatures (due to sun). The persistence follows the actual observed solar radiation obtained from NIMET while the LSTM followed the persistence followed by xGBoost. Fig. 3. shows a forecast of solar radiation in the rainy season specifically a day ahead in July. This takes into considerations periods of the day continued high cloud cover (overcast), high humidity and potentially continued low visibility. Again, the LSTM model shows superior performance to xGBoost, considering the effect of cloud cover data as demonstrated by the results at 10am and 2pm.

Table 1 and Table 2 show the statistical performance metrics (MAE, RMSE, R^2 , MAPE, Skill Score) of the xGBoost and LSTM models against the persistence for a day ahead (24-hour ahead) prediction for the Month of March and July respectively. It can be seen from both tables that the machine learning models demonstrated a substantial improvement in forecasting accuracy compared to the simple persistence model. A closer analysis of both models for the two case scenarios, indicates the LSTM has a superior accuracy having a higher R^2 of 0.998 and 0.986 for solar irradiance prediction outperforming xGBoost which recorded R^2 of 0.994 and 0.909 for a day-ahead prediction in March and July respectively.

Table 1. Performance Metrics of Solar Irradiance Forecasting Models for Calabar (Day-Ahead Forecast in March)

Model	MAE (W/m ²)	RMSE (W/m ²)	R^2	MAPE (%)
Persistence	39.31	59.41	0.989	7.81
XGBoost	22.78	32.47	0.994	5.93
LSTM	11.65	21.23	0.998	3.78

Table 2. Performance Metrics of Solar Irradiance Forecasting Models for Calabar (Day-Ahead Forecast in July).

Model	MAE (W/m ²)	RMSE (W/m ²)	R^2	MAPE (%)
Persistence	58.30	70.39	0.373	10.57
XGBoost	14.89	31.63	0.909	7.16
LSTM	4.67	11.27	0.986	4.14

Further evaluation shows that LSTM model outperformed both XGBoost in terms of MAE, RMSE, and MAPE. It has the lowest MAE of 11.65 and RMSE of 21.23 and MAPE of 3.78 as against the xGBoost with MAE of 22.78 and RMSE of 32.47 and MAPE of 5.93. Table 2. shows a similar pattern in the performance evaluation of the models trained to predict a day ahead solar irradiance in the month of July. Again, the LSTM outperformed the xGBoost and persistence model. This highlights the LSTM's inherent capability to effectively capture complex temporal dependencies and long-term patterns in solar irradiance data, which are crucial for tropical climates with distinct seasonal variations and dynamic cloud cover.

4. Conclusion

This study successfully demonstrated the significant potential of machine learning (ML) models in achieving highly accurate solar irradiance forecasting for Calabar, Cross River State. By leveraging LSTM and xGBoost and incorporating a comprehensive suite of relevant meteorological and temporal features, our advanced forecasting methodology especially LSTM consistently outperformed traditional persistence models and conventional statistical methods. LSTM offers a powerful tool for significantly improving solar irradiance forecasting accuracy in Calabar. These enhanced forecasts are instrumental for improving energy management across various facets of Calabar's energy ecosystem, optimizing energy dispatch and reducing operational costs, enhancing grid stability, reliability and revenue, and accelerating the integration of renewable energy sources, enhancing proactive demand-side management, ultimately contributing to a more resilient and sustainable energy future for the region. While the results are promising, certain limitations should be acknowledged. The accuracy of ML models is highly dependent on the quality and quantity of historical data. Challenges in obtaining high-resolution, long-term, and diverse meteorological datasets specific to Calabar could impact model generalizability. Furthermore, extreme weather events (e.g., severe thunderstorms, prolonged haze, or Harmattan dust) which might have unique and infrequent impacts on solar irradiance, require sufficient representative data for the models to learn effectively. The computational resources required for training and deploying complex deep learning models like CNN-LSTM could also be a consideration for smaller operational entities. Future work should also explore the impact of specific atmospheric phenomena in Calabar, such as the Harmattan season's dust haze, on forecasting accuracy.

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Modeling of a Synchronous Generator for Performance Enhancement and Stability Assessment (Simulink Approach)

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Abstract: Maintaining synchronism between multiple generators within the network is growing tougher with time. Since the expansion of an interconnected system is an ongoing process, new generators are often added to the network. This paper analyzes the transient stability of a synchronous machine coupled to loads at various points on the system. It also solves a number of differential equations using MATLAB/SIMULINK and analyzes the Swing equation. The equations that explain the performance of a three-phase salient-pole synchronous machine under various situations (at no fault, three-phase fault, and single-phase fault at A, B, and C) may be used to forecast the electrical and electromechanical behavior of the majority of synchronous machines. With the use of simulation models, this study aims to clarify stability studies of synchronous machines by examining the performance of the proposed linearized model of synchronous machines under normal and disturbance conditions using the Swing equation, small signal performance, and application to 3-phase fault. Although there are a number of ways to establish transient stability in synchronous machines, the proposed system behaviors are tested in this study utilizing the Swing equation and numerical solutions using MATLAB/SIMULINK. The anticipated outcome of this effort is to demonstrate when temporary system impacts may be eliminated by lessening their impact on the machines.

KEYWORD: Matlab/Simlink, Transient Stability, Synchronous Machines, Swing Equation, 3-Phase fault.

1. Introduction

Synchronous machinery powered by combustion engines or hydro steam turbines produces almost all of the electricity utilized globally. The synchronous machine is the primary method of transferring mechanical energy into electrical energy, just like the induction machine is the mainstay of the steam turbine. The equations describing the 3-phase salient-pole synchronous machine can be used directly to predict the performance of synchronous motors, synchronous generators, and, with only minor adjustments, reluctance motors. These equations can also be used to predict the electrical and electromechanical behavior of the majority of synchronous machines [1,2]. Without explicitly resolving the system differential equations, stability is ascertained using the direct approaches. Since the early work of Magnusson and Aylett, who employed the transient energy function for stability testing, this method has drawn a lot of attention. A ball rolling on the inside surface of a bowl produced by the equation defining the system's transient energy may be used to illustrate the transient energy method, as seen in. The zone of instability is represented by the area outside the bowl, while the region of stability is represented by the area within.

Maximum height, and hence maximum potential energy for the traveled trajectory due to the fault energy, is represented by the bowl's rim. An established tool for assessing the transient performance and control strategies of synchronous machines is mathematical modeling. [12, 13, 18]

The dynamic properties of those synchronous machines clearly have a significant role in the study's conclusion, as the primary objective of these investigations is to ascertain whether or not the numerous synchronous machines that are disturbed will continue to be in synchronism with one another. The developments in synchronous machine transient stability investigations, the state of the art, and the

relevance of this research effort. About fifty-five years ago, engineers began to take a serious interest in the dynamic performance of interconnected synchronous machines when the transient instability phenomena were recognized. [5]. Early transient stability studies represented synchronous machines by a relatively basic model that omitted any internal dynamic properties of these machines (the classical model). This model was only helpful for simulating transients of a short duration since it was predicated on the idea that field winding flux connections tended to stay constant during transient disturbances. [2,7] Since the issue in the vast majority of situations was whether the generator survived the initial rotor swing after a disturbance, the limitation was acceptable. Since the 1920s, synchronous machine theory has evolved, and it has become evident that, if contemporary automated voltage regulators are used, the internal dynamic properties of these machines affect the outcomes of transient stability investigations. [12, 15]

Furthermore, the use of more sophisticated machine models in transient stability studies was required due to the need for increased simulation accuracy of failures close to machine terminals.

The engineers found the high-speed digital computer to be a tremendous help. It enabled computations to be performed by electric synchronous machines. [10, 11, 14]. The scale of machines that might be analyzed and the representation of synchronous machine characteristics have improved since the early 1960s thanks to digital computer programs for transient stability investigations. More attention is being paid to more realistic modeling of synchronous machines as a result of the quick increase in digital computer memory capacity and processing speed. [12, 16].

However, not everyone agrees with this point of view. For transient stability investigations, synchronous machine modeling at the transient phenomena level is often thought to be sufficient.

On the other hand, the ability to simulate machine internal dynamics at the level of the so-called stator transients and sub-transient phenomenon is regarded by some to be necessary for accurate representation of synchronous machines for transient stability studies. According to a 1973 paper, the dynamic properties of synchronous machines are sufficiently represented by the models now employed in transient stability investigations. However, some published publications suggest that more intricate models could be required for synchronous machine transient stability investigations in order to correctly represent synchronous machines. [7, 17, 18]. The findings of trials carried out in the field (on synchronous machines) and in the lab (on micro-machines) confirm the latter opinion. Swing curves were measured in these tests by placing three-phase short circuits at the test machines' terminals and power angle. [3, 6,9]

2. Methodology

Mathematical Model of Synchronous Machine

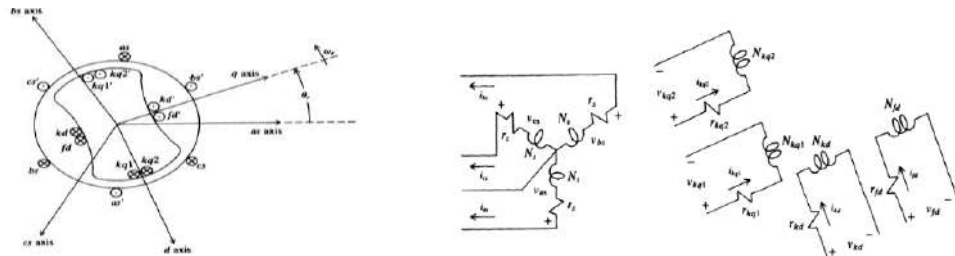


Fig. 1. Schematic Diagram of Synchronous Machine

2.1 Voltage Equations

The stator and rotor voltages can be expressed in vector-matrix form as: $V_{abcs} = r_s I_{abcs} + P \lambda_{abcs}$ (in the stator frame) (1)

$$V_{dqfr} = r_s I_{dqfr} + p \lambda_{dqfr} \text{ (in the rotor frame).} \quad (2)$$

In these equations the operator $p = d/dt$ and

$$V_{abcs} = \begin{bmatrix} V_{as} \\ V_{bs} \\ V_{cs} \end{bmatrix} \text{ While } V_{dqfr} = \begin{bmatrix} V_{dr} \\ V_{qr} \\ V_{fr} \end{bmatrix} \quad (3)$$

Similar definitions apply for current vectors I_{abcs} , I_{dqfr} , and the flux linkages λ_{abcs} , and λ_{dqfr} . The resistance matrix appearing in (1) and (2) may be defines as:

$$= \begin{bmatrix} r_{as} & 0 & 0 \\ 0 & r_{bs} & 0 \\ 0 & 0 & r_{cs} \end{bmatrix} \quad (4)$$

However, since each of the resistances of the three phase stator windings is equal, we may then say that, $r_s = \text{diag}[r_s r_s r_s]$.

In general, the rotor is unsymmetrical so that the rotor resistances must now be defined by a matrix r_r , where:

$$r_r = \begin{bmatrix} r_{qr} & 0 & 0 \\ 0 & r_{dr} & 0 \\ 0 & 0 & r_{fr} \end{bmatrix} \quad (5)$$

Solving the first order differential equation (3.1), now we may rewrite as:

$$V = IR + \frac{d}{dt}(LI) \quad (6)$$

L is a function of rotor position θ_r which is also a function of time and I is only a time varying function so we may write:

$$V = IR + \frac{dL(\theta_r)}{dt} I + L(\theta_r) \frac{dI}{dt} \quad (7)$$

This now implies a differential equation with time varying coefficient. But equation (7) can be rewritten as:

$$V = IR + I \frac{dL(\theta_r)}{d\theta_r} \times \frac{d\theta_r}{dt} + L(\theta_r) \frac{dI}{dt} \quad (8)$$

But we know that $\frac{d\theta_r}{dt}$ is the derivative of position which means “speed”, or ω_r so (c) now becomes:

$$V = IR + \omega_r \times I \frac{dL(\theta_r)}{d\theta_r} + L(\theta_r) \frac{dI}{dt} \quad (9)$$

Equation (9) may finally be written as:

$$\frac{dI}{dt} = \left[V - I \left(R + \omega_r \times \frac{dL(\theta_r)}{d\theta_r} \right) \right] \times (L(\theta_r))^{-1} \quad (10)$$

Equation (3.10) shows that the solution of current at every time step involves the computation of the derivative of the inductance matrix, $\frac{dL(\theta_r)}{d\theta_r}$ for the particular rotor position and the computation of the inverse of the inductance matrix, $(L(\theta_r))^{-1}$.

Although this has been accomplished by advanced programming techniques, the solution does not lead to a steady-state model which is usually the well-deserved reward for a carefully developed dynamic model. The rest of the development will focus on realising this.

2.2 Synchronous Machine Model Constructed Using Simulink

Considered single machine-infinite bus system is given in Fig. 2.0 Electrical and mechanical sub-model of the synchronous machine, for transient stability analysis, the synchronous machine model is considered as a classical fourth-degree model given below:

Electrical part

$$E'_q = \frac{x'_d - x_d}{1 + sT'_{d0}} I_d + \frac{E_{fd}}{1 + sT'_{d0}} \quad (11)$$

Mechanical part

$$E'_d = \frac{x'_q - x_q}{1 + sT'_{q0}} I_q \quad (12)$$

Turbine and Governor System Model

$$\Delta\omega = \frac{1}{D + sM} (P_m - P_e) \quad (13)$$

$$\delta = \omega_0 \frac{\Delta\omega}{s} \quad (14)$$

$$\Delta P_m = \frac{sK_{RH}T_{RH}}{1 + sT_{RH}} \Delta P_c \quad (15)$$

Exciter Model

$$E_{fd} = \frac{K_E}{1 + sT_E} (V_{tr} - V_t - V_s) \quad (16)$$

Terminal Equations

$$V_d = E'_d - R_a I_d - x'_d I_q = -V_0 \sin \delta + R_a I_d + x_e I_q \quad (17)$$

$$V_q = E'_q - R_a I_q + x'_d I_d = V_0 \cos \delta + R_a I_q - x_e I_d \quad (18)$$

$$P_e = E'_d I_d + E'_q I_q \quad (19)$$

Reference terminal voltage is calculated using the equations given below:

$$I_0 = \frac{\sqrt{P_0^2 + Q_0^2}}{V_0} \quad (20)$$

2.3 Rearranging the equations for order of computation

$$V_{dqfr} = r_s I_{dqfr} + p \lambda_{dqfr} \quad (21)$$

$$E'_q = \frac{x'_d - x_d}{1 + sT'_{d0}} I_d + \frac{E_{fd}}{1 + sT'_{d0}} \quad (22)$$

$$\Delta\omega = \frac{1}{D + sM} (P_m - P_e) \quad (23)$$

$$\delta = \omega_0 \frac{\Delta\omega}{s} \quad (24)$$

$$\Delta P_m = \frac{sK_{RH}T_{RH}}{1 + sT_{RH}} \Delta P_c \quad (25)$$

$$E_{fd} = \frac{K_E}{1 + sT_E} (V_{tr} - V_t - V_s) \quad (26)$$

$$V_{iq} = E'_q - R_q I_q + x'_d I_d = V_0 \cos \delta + R_e I_q - x_e I_d \quad (27)$$

$$V_{id} = E'_d - R_d I_d - x'_q I_q = -V_0 \sin \delta + R_e I_d + x_e I_q$$

$$P_e = E'_d I_d + E'_q I_q \quad (28)$$

$$V_{tr} = \frac{E_{d0}}{K_E} + V_{r0} \quad (29)$$

$$(30)$$

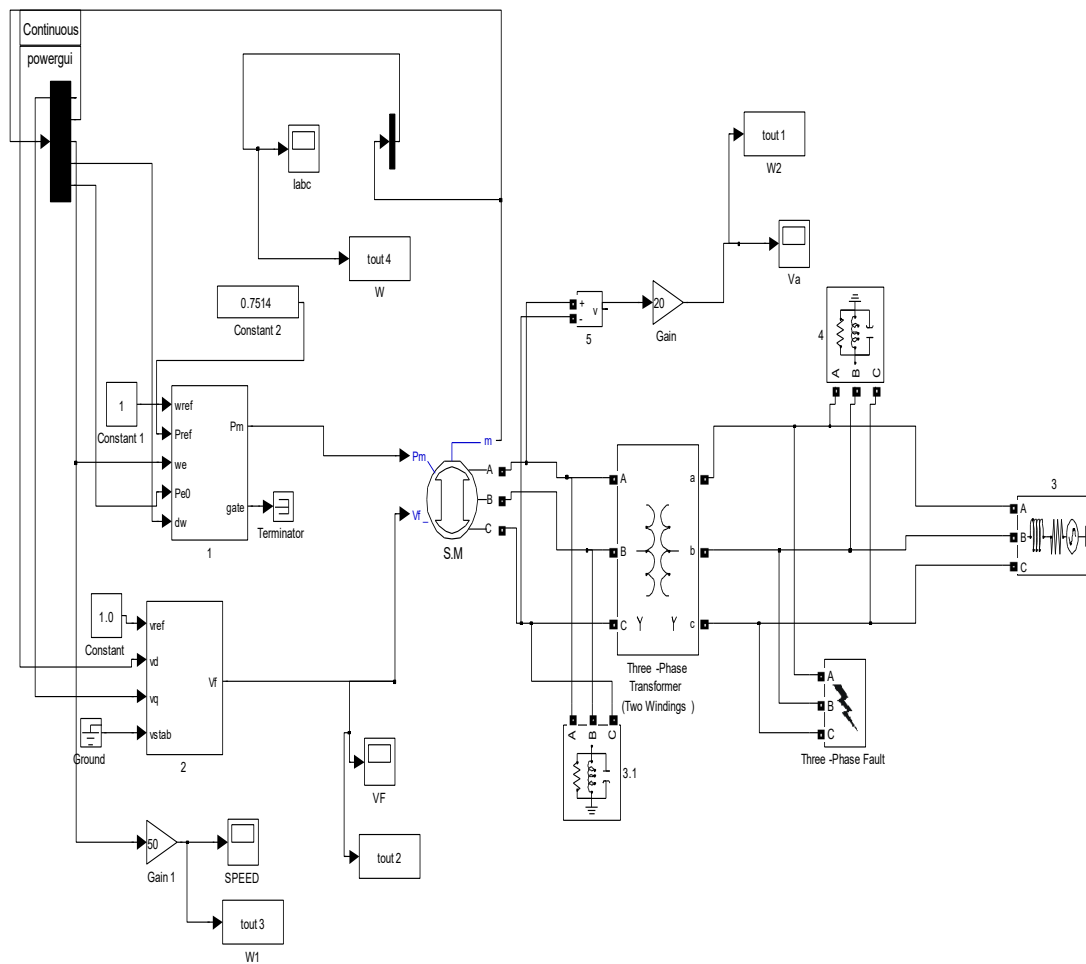


Fig. 2. Simulation Block diagram of the System in SIMULINK

3. Result and Discussion

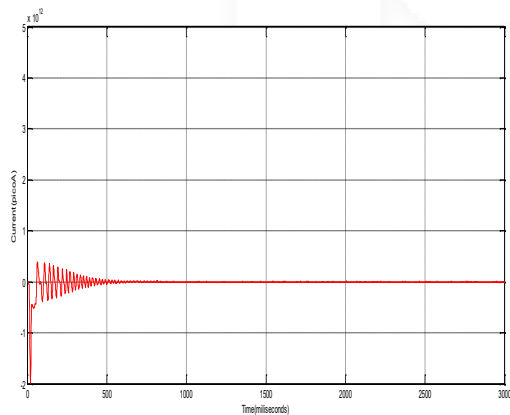


Fig.3.1: Graph of Current against Time At Normal Condition (No fault)

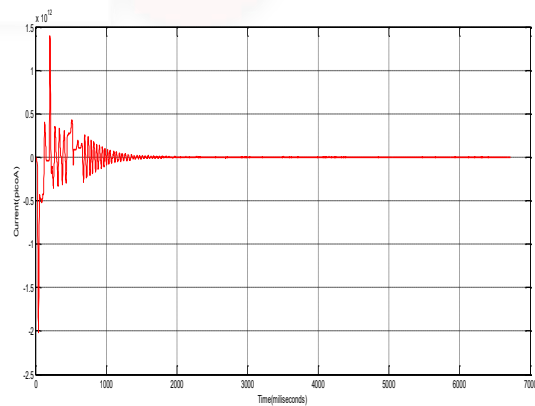


Fig. 3.2: Graph of Current against Time

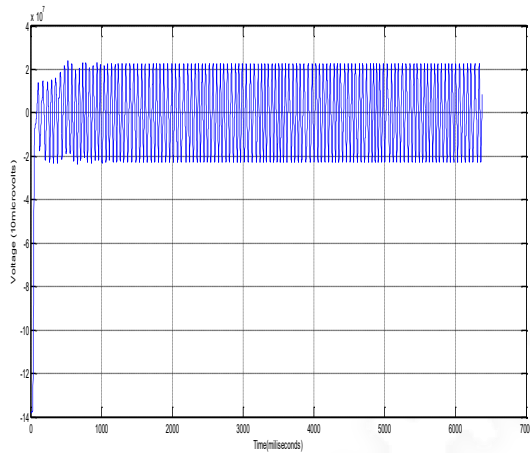


Fig. 3.3: Graph of Voltage against Time
Normal Condition

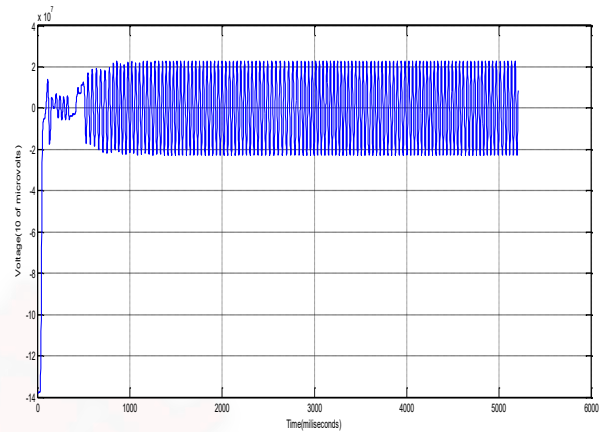


Fig. 3.4: Graph of Voltage against
Time at Three phase fault

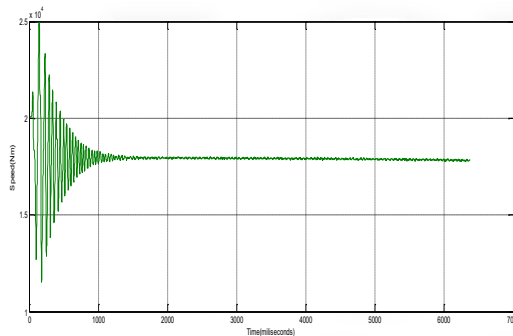


Fig. 3.5: Graph of Speed against Time
at Normal Condition

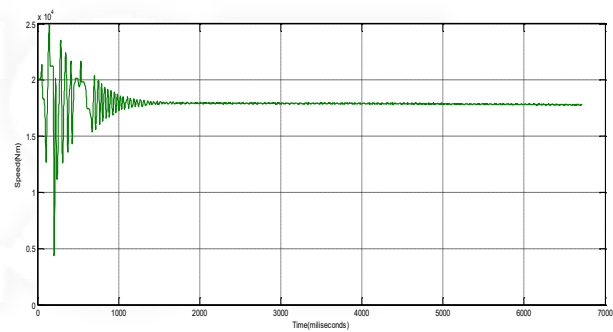


Fig. 3.6: Graph of Speed against Time
at Three phase fault

3.1 Discussion

Fig. 3.1, fig. 3.3 and fig. 3.5 show the behavior of the system when there is at normal condition i.e. no fault. Fig. 3.2, fig. 3.4 and fig. 3.6 shows the system behavior when there are three phase faults at the end of the system (i.e. three phase faults are between transformer and the three phase source). At normal condition fig 3.1, the transient is completely cleared at the **time** 833.333 milliseconds. The current wave form shows that there is no or little distortion in the system. In fig 3.4 the voltage grows up and settling with time. Firstly, it starts from zero and maintains it for 100 millisecond and grows up the wave from completely settling at the time 125 milliseconds.

Fig. 3.5 shows the speed of the system with time, the speed of the system stabilizes at 1775 milliseconds, and the system maintain this stability throughout the simulation period. Fig 3.2 shows that there is a spike of current at 100 milliseconds, due to distortion in the system that is caused by the fault. This make the current wave formed not to follow the normal pattern as in fig 3.1 and the transient was cleared at 1775 milliseconds. Fig 3.4; due to fault effect on the system, the voltage wave form at the beginning tends to straighten the wave from the first 0 to 833 milliseconds before it returns back to the normal voltage wave form of the system. Fig 3.6 the speed of the system was stabilizes at about 1925 milliseconds after it has overcome the fault.

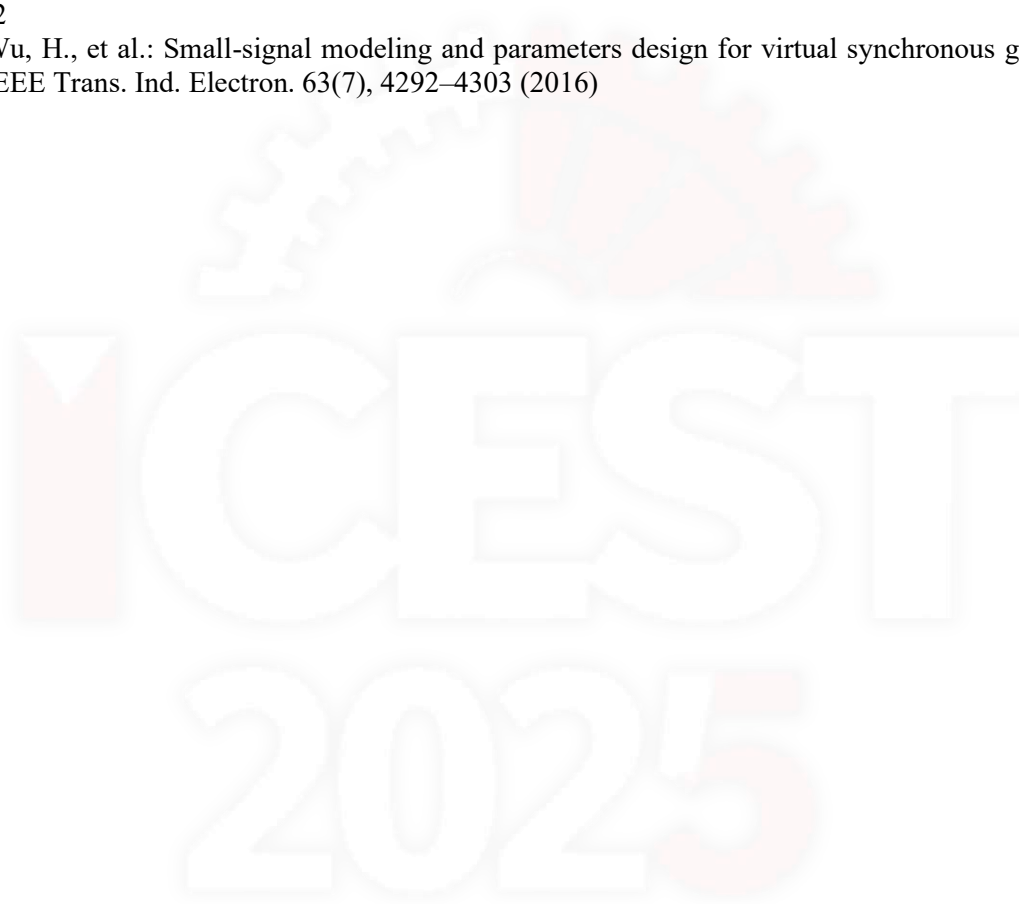
4. Conclusion

This paper is based on Transient behavior of a Synchronous Machine coupled to loads at different places on the system. The paper addresses three-phase faults at various locations, as well as faults in phases A, B, and C and the relevant behaviors of the system. When the results at fault and at no fault are compared. The transients were cleared in current against time at 833 milliseconds when there was no problem, and at 1775, 1850, 1500, 1850, and 1550 milliseconds when there is a three-phase fault and a single-phase fault (at A, B, and C), respectively. The voltage stabilizes at 125, 835, 1125, 750, 750 and 750 milliseconds respectively and the speed stabilizes at 1775, 1925, 1975, 1650, 1850 and 1600 milliseconds.

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Evaluating The Impact of Shunt Capacitors and Harmonic Filters On Power Flow Optimization.

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Abstract: This research investigates the optimization of power flow in an 11 kV distribution network through the application of shunt capacitors and harmonic filters. Using Electrical Transient Analyzer Program (ETAP) software, the study models and simulates four different operational scenarios: the Base Case (without compensation), Case A (with shunt capacitors), Case B (with harmonic filters), and Case C (with both shunt capacitors and harmonic filters). The primary performance indicators evaluated include voltage profile improvement, reduction of reactive power losses, and total harmonic distortion (THD) mitigation. Simulation results show that the application of shunt capacitors in Case A significantly improved voltage levels and reduced reactive power losses across the network. However, several buses exhibited overvoltage conditions, indicating the need for precise capacitor tuning. In Case B, harmonic filters alone had major impact on the network's harmonic distortion, with THD values of some buses still above the IEEE 519 recommended threshold of 5%. Case C, which combined both compensation techniques, further enhanced voltage profiles and minimized reactive losses but harmonic distortion remains the same as Case B. The findings suggest that while shunt capacitors are effective for reactive power compensation and voltage support, harmonic filters must be carefully designed and strategically placed to address harmonic issues effectively. The study concludes with recommendations for improved filter design, the use of active harmonic filters, and the integration of real-time power quality monitoring for optimal system performance

Keywords: Power flow optimization, harmonic distortion, shunt capacitors, harmonic filters, ETAP, 11 kV distribution network, voltage profile, reactive power compensation.

1. Introduction

Power flow optimization in electrical distribution systems is essential for ensuring operational efficiency, voltage stability, and power quality. As modern power systems increasingly incorporate nonlinear loads and distributed generation, challenges such as voltage fluctuations, power losses, and harmonic distortions have become more prominent [1], [2]. To address these issues, two widely adopted technologies—shunt capacitors and harmonic filters—are commonly employed for system improvement and power flow enhancement.

Shunt capacitors are used primarily for reactive power compensation, which helps in improving voltage profiles and reducing active power losses along distribution feeders [3], [4]. By supplying local reactive power, they reduce the burden on the source and improve the system's power factor, allowing for more efficient energy transmission and better voltage regulation [5]. However, if not optimally placed or sized, shunt capacitors may cause overvoltage or resonance problems in the network [6].

Harmonic filters, particularly passive filters, are deployed to mitigate harmonics generated by nonlinear loads such as variable frequency drives and inverters. These harmonics negatively impact power quality, increase losses, and may cause equipment overheating or malfunction [7], [8]. Harmonic filters are designed to absorb specific frequency components, thus reducing total harmonic distortion (THD) and ensuring compliance with standards like IEEE 519-2014 [9].

When shunt capacitors and harmonic filters are used together in a coordinated manner, the benefits are amplified. Studies have shown that their combined application leads to better load flow performance, enhanced voltage profiles, minimized system losses, and improved power factor [10]–[12]. This study aims to evaluate the impact of these devices—individually and collectively—on power flow optimization using analytical modeling and simulation tools to determine their effectiveness under varying load conditions.

2. Method

2.1 Research Design

This research adopts a quantitative, simulation-based design focused on the modeling, analysis, and optimization of a real-world electrical distribution system. A case study approach is used, where a modeled 11 kV distribution network representative of a typical urban electrical grid is studied using simulation tools. The quantitative design enables precise numerical analysis of voltage profiles, power losses, and harmonic distortion levels before and after the application of power quality enhancement devices.

The research is structured into four major simulation scenarios:

- i. **Base Case:** The original distribution system without any compensation.
- ii. **Case A (Shunt Capacitors Only):** In this scenario, fixed shunt capacitors are added to reduce reactive power demand and improve voltage levels.
- iii. **Case B (Harmonic Filters Only):** Harmonic filters are installed at strategic buses to mitigate harmonic distortion.
- iv. **Case C (Combined Compensation):** Both shunt capacitors and harmonic filters are integrated into the network to examine their combined effects.

This structured comparison approach enables the isolation and assessment of each compensation method's impact on the network. The use of simulation software (ETAP) allows for detailed system modeling and scenario analysis, ensuring reliable and repeatable results. Each simulation is carried out under normal loading conditions and assessed using performance indicators such as voltage deviation, active/reactive power losses, and Total Harmonic Distortion (THD).

2.2 System Description

The modeled electrical network is a 14-bus, 11 kV radial distribution system, developed in ETAP. The configuration reflects a practical urban distribution layout with both commercial and residential characteristics. To enhance realism and local relevance, buses in the system are named after actual locations in Calabar South, such as UNICAL Main Gate, Goldie Street, Marian Road, Watt Market, Mayne Avenue, White House, and others.

The system is powered by a single source (slack bus) located at UNICAL Main Gate, which maintains the voltage level and supplies power to the entire network. A total of 14 load centers are distributed across the network, each connected to a bus. These loads vary in size and power factor, representing a mix of commercial (e.g., markets and office buildings), residential, and public utility loads. The buses and branches were interconnected through 13 distribution lines, which represent underground cables or overhead conductors. Each branch has associated parameters such as line impedance, ampacity, and length, all of which impact the flow of power and the magnitude of losses.

The modeled loads are characterized as static, with fixed real and reactive power values. Voltage levels, loading percentages, and power factors are derived from either standardized load data or approximated from actual field conditions. The system also integrates non-linear loads, such as inverters, computers, and variable frequency drives (VFDs), which are known to generate harmonic distortion. This inclusion enables harmonic analysis to be conducted, revealing the real-world impact of harmonic-producing devices on the power system.

2.3 Modeling Procedure in ETAP

The simulation and modeling procedures in ETAP were carried out in a series of logical steps aimed at building the network, applying compensating devices, and analyzing performance under various conditions. Below is a detailed breakdown:

2.3.1 Base Case Simulation (No Compensation)

The initial step involved modeling the base configuration of the network without any form of compensation. The following steps were taken:

- i. Network parameters such as voltage levels, bus connections, and load demands were input into ETAP.
- ii. The source was modeled as a balanced 3-phase slack bus to stabilize the system.
- iii. Load flow analysis was performed to determine voltage levels at each bus, power losses in each branch, and system loading.
- iv. Harmonic analysis was conducted to quantify the Total Harmonic Distortion (THD) of voltage and current at each bus and along branches.
- v. The base case results served as a benchmark for assessing the effects of later compensation methods.

2.3.2 Case A – Shunt Capacitor Compensation

This stage focused on applying **shunt capacitors** to specific buses with high reactive power demands or poor voltage levels.

- i. Fixed shunt capacitors were placed at buses such as White House, Marian Road, Mayne Avenue, and Goldie Street, based on their performance in the base case.
- ii. The capacitor ratings were selected in kvar to match the reactive demand at each bus, improving power factor and voltage regulation.
- iii. After capacitor placement, a load flow analysis was rerun.
- iv. Improvements in voltage levels, reduction in reactive losses, and increase in power factor were analyzed.

2.3.3 Case B – Harmonic Filter Compensation

This stage addressed the harmonic distortion observed in the base case by applying passive harmonic filters at key locations.

- i. Filters were modeled in ETAP using tuned LC filter circuits.
- ii. Filter placement was based on buses with the highest THD values, such as UNICAL Main Gate, Goldie Street, and Mayne Avenue.
- iii. Harmonic simulation was rerun after filter installation.

2.3.4 Case C – Combined Shunt Capacitor and Harmonic Filter Compensation

In the final scenario, both shunt capacitors and harmonic filters were applied together.

- i. Capacitors were retained from Case A, while filters from Case B were also included.
- ii. Load flow and harmonic analysis were conducted concurrently.
- iii. This setup aimed to achieve a balance between voltage regulation, reactive power support, and harmonic suppression.

2.4 Load Flow

The Newton-Raphson method of load flow analysis is an iterative technique employed in electrical power systems to approximate a set of nonlinear simultaneous equations as a set of linear simultaneous equations. This approximation is achieved through the use of Taylor's series expansion, with the terms being limited to a first-order approximation [9]. The governing non-linear equations that describe the behavior of a power system network are as follows:

$$S_i = V_i I_i^* = P_i + jQ_i \quad 2.1$$

Where

S_i denotes the complex power in bus i

V_i denotes voltage at bus i , which is expressed as follows

$$V_i = |V_i| e^{j\sigma_i} \quad 2.2$$

$$V_i = |V_i| e^{-j\sigma_i} \quad 2.3$$

σ_i denotes the bus angle at node i

E denotes Euler's constant

V_i^* denotes the complex bus voltage at node i

$$V_k = |V_k| e^{j\sigma_k} \quad 2.4$$

V_k denotes the voltage at bus k

σ_k denotes the bus angle at node k

The current injected into bus i , can be given as

$$I_i = \sum_{k=1}^n Y_{ik} V_k; i = 1, 2, \dots, n \quad 2.5$$

$$Y_{ik} = |Y_{ik}| e^{-j\theta_{ik}} \quad 2.6$$

Y_{ik} denotes the admittance at bus i and k

θ_{ik} denotes the admittance angle at node i and k

P_i, Q_i denotes the real and reactive power respectively at bus i

$$S_i^* = V_i^* I_i = P_i - jQ_i = \sum_{k=1}^n |V_i| |V_k| |Y_{ik}| e^{-j(\theta_{ik} + \sigma_i - \sigma_k)} \quad 2.7$$

Separating the conjugate complex power S_i^* , into real and imaginary power

$$P_i = V_i^2 Y_{ii} \cos \theta_{ii} + \sum_{k=1, k \neq i}^n |V_i| |V_k| |Y_{ik}| \cos(\theta_{ik} + \sigma_i - \sigma_k) \quad 2.8$$

Similarly,

Equations 2.7 and 2.8 represent the polar form of the power flow equations, which are used to compute the net real power (P_i) and reactive power (Q_i) injected into the network at bus i . These calculated values of P_i and Q_i are denoted as P_{ical} and Q_{ical} , respectively. This notation establishes the concept of mismatches, symbolized as ΔP_i and ΔQ_i , which quantify the differences between the calculated and actual values

$$\Delta P_i = P_{i sch} - P_{i cal} \quad 2.9$$

$$\Delta Q_i = Q_{i sch} - Q_{i cal} \quad 2.10$$

$$P_{i sch} = P_{gi} - P_{di} \quad 2.11$$

$$Q_{i sch} = Q_{gi} - Q_{di} \quad 2.12$$

P_{isch} and Q_{isch} represent the net real and reactive power scheduled to be injected into bus i .

P_{gi} and Q_{gi} denote the scheduled real and reactive generated power at bus i .

Similarly, P_{di} and Q_{di} represent the scheduled real and reactive power demand at load bus i . Mismatches occur when P_{ical} and Q_{ical} deviate from their scheduled value. The set of linear equations formed expressing the relationship between changes in real and reactive power components of the bus voltages can be written in compact form as:

$$\begin{bmatrix} \Delta P_i \\ \Delta Q_i \end{bmatrix} = \begin{bmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{bmatrix} \begin{bmatrix} \Delta \sigma_i \\ \Delta V_i \end{bmatrix} \quad 2.13$$

J_{11}, J_{12} (Jacobian matrix) is set up as a partitioned matrix by convention in the form

$$\begin{bmatrix} \frac{\partial P}{\partial \sigma} & \frac{\partial P}{\partial |V|} \\ \frac{\partial Q}{\partial \sigma} & \frac{\partial Q}{\partial |V|} \end{bmatrix} \quad 3.14$$

The real values in both the off-diagonal and diagonal terms within the sub-matrices are determined through the process of partial differentiation of equations 2.7 and 2.8 concerning σ_i and $|V_i|$. This relationship is illustrated by the following equations:

$$J_{11} = \frac{\partial P}{\partial \sigma} = \begin{bmatrix} \frac{\partial P_i}{\partial \sigma_i} & \dots & \frac{\partial P_i}{\partial \sigma_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial \sigma_i} & \dots & \frac{\partial P_n}{\partial \sigma_n} \end{bmatrix} \quad 3.15$$

$$J_{12} = \frac{\partial P}{\partial |V|} = \begin{bmatrix} \frac{\partial P_i}{\partial |V_i|} & \dots & \frac{\partial P_i}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial P_n}{\partial |V_i|} & \dots & \frac{\partial P_n}{\partial |V_n|} \end{bmatrix} \quad 2.16$$

$$J_{21} = \frac{\partial Q}{\partial \sigma} = \begin{bmatrix} \frac{\partial Q_i}{\partial \sigma_i} & \dots & \frac{\partial Q_i}{\partial \sigma_n} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial \sigma_i} & \dots & \frac{\partial Q_n}{\partial \sigma_n} \end{bmatrix} \quad 2.17$$

$$J_{22} = \frac{\partial Q}{\partial |V|} = \begin{bmatrix} \frac{\partial Q_i}{\partial |V_i|} & \dots & \frac{\partial Q_i}{\partial |V_n|} \\ \vdots & \ddots & \vdots \\ \frac{\partial Q_n}{\partial |V_i|} & \dots & \frac{\partial Q_n}{\partial |V_n|} \end{bmatrix} \quad 2.18$$

2.5 Harmonic Analysis

Shunt filters are primarily employed in AC systems. They are connected parallel to the system or the nonlinear load that generates harmonics, creating a series resonance that provides very low impedance at the tuned frequency. As a result, harmonics are diverted through the filter, preventing them from flowing into the system. Compared to series filters, shunt filters are more cost-effective due to their graded insulation design. These filters absorb harmonics at their tuned frequency, earning them the name "trap filters." Shunt filters are categorized into single-tuned filters and high-pass filters.

2.5.1 Total Harmonic Distortion

The Total Harmonic Distortion can be solved using;

$$THD_1 = \frac{\sqrt{\sum_{h=2}^N v_h^2}}{v_i} \quad 2.19$$

$$THD_2 = \frac{\sqrt{\sum_{h=2}^N v_h^2}}{\sqrt{\sum_{h=1}^N v_h^2}} \quad 2.20$$

Here, h is the harmonic order, N is the number of samples per period, and v_h is the harmonic order h amplitude. $N/2$ is the maximum harmonic order.

Equation (2.19) calculates the THD related to the fundamental (first order) power, while (2.20) calculates it related to the total signal power. In both cases, it is possible to define the distortion amplitude, by (2.21).

$$v_d = \sqrt{\sum_{h=2}^N v_h^2} \quad 2.21$$

Due to (3.21), (3.19) and (3.20) becomes (3.22) and (3.23).

$$THD_1 = \frac{v_d}{v_1} \quad 2.22$$

$$THD_2 = \frac{v_d}{\sqrt{v_1^2 + v_d^2}} \quad 2.23$$

2.5.2 Design of Single Tune Filter

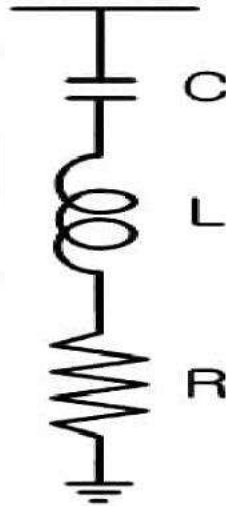


Fig. 1. Single Tune Filter

The resonance frequency is given by following equation;

$$f_{resonant} = \frac{1}{2\pi\sqrt{LC}} = f_{fundamental} \sqrt{\frac{X_C}{X_L}} \quad 2.24$$

Where,

$F_{resonant}$ =resonance frequency

L =inductance of the filter

C =capacitance of the filter

X_L =inductive reactance of the filter

X_C =capacitive reactance of the filter

$F_{fundamental}$ =Fundamental frequency

Step 1: Tune frequency for filter-Filter is tune to the slightly below harmonic frequency to allow for the tolerance in filter elements and system impedance variation. Example for 5th harmonic frequency the filter is tune to 4.7th to allow for the tolerance.

Step 2: Size of capacitor bank –shunt passive filter also improve power factor & size of capacitor bank can be calculated as follow

$$Q_c = P \times (\tan(\cos^{-1}pf_{actual}) - \tan(\cos^{-1}pf_{targeted})) \quad 2.25$$

Where

P = active power,

Q_c = reactive power to be compensated,

Pf_{actual} = actual power factor,

$Pf_{targeted}$ = power factor to be improved

Capacitor bank reactance ($X_{capacitor}$) at power frequency is calculated as follow

$$X_{capacitor} = \frac{kV^2}{Q_c} \quad 2.26$$

Where, kV-system voltage

Step 3: size of filter inductive reactance –is calculated by using capacitive reactance to trap h harmonic as follows,

$$X_L = \frac{X_{capacitor}}{h^2} \quad 2.27$$

$$L = \frac{X_L}{2\pi f_{fundamental}} \quad 2.28$$

Resistance of reactor is calculated as follow

$$R = \frac{X}{Q_f} \quad 2.29$$

Where,

X -inductive or capacitive reactance at resonance

Q_f -Quality factor

3. Result & Discussion

3.1 Base Case

The objective of this section was to analyze the performance of the base case simulation of the 14-bus power distribution network (using names of streets in Calabar), modeled and executed using ETAP. The base case represents the network in its uncompensated state, without any shunt capacitors or harmonic filters. The results presented serve as the benchmark for comparing the impact of reactive power compensation and harmonic mitigation techniques in later simulation scenarios. Key parameters such as voltage levels, power losses, line currents, and power factor are evaluated and discussed in this section.

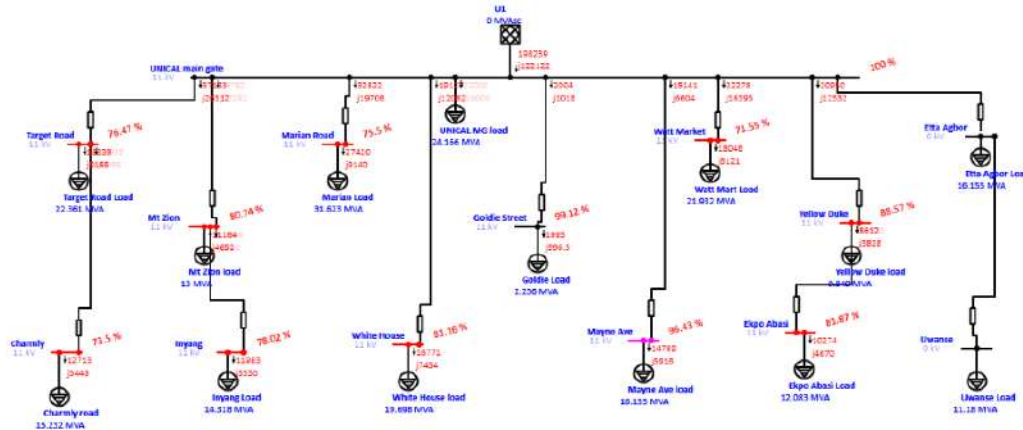


Fig. 2. System Configuration on display during the Base case Simulation

Table 1: General Data for the Base Case

Study ID	BaseCase
Study Case ID	LF
Data Revision	Base
Configuration	Normal
Loading Cat	Design
Generation Cat	Design
Diversity Factor	Normal Loading
Buses	13
Branches	12
Generators	0
Power Grids	1
Loads	12
Load-MW	174.106

Load-Mvar	74.925
Generation-MW	198.239
Generation-Mvar	122.122
Loss-MW	24.132
Loss-Mvar	47.196
Mismatch-MW	0
Mismatch-Mvar	0

Table 2. Generator data for the base case

ID	Rated kV	MW	Mvar	Amp	% PF
U1	11	198.239	122.122	12221	85.14

Table 3: Load Data for the base case

ID	Rating/Limit	Rated kV	kW	kvar	Amp	% PF	% Loading	Vterminal
Charmly road	15231.5 kVA	11	12712.6	5448.3	987.7	91.91	123.5	73.5
Ekpo Abasi Load	12083 kVA	11	10274.5	4670.2	723.6	91.04	114.1	81.87
Goldie Load	2236.1 kVA	11	1993	996.5	118	89.44	100.5	99.12
Inyang Load	14317.8 kVA	11	11982.6	5530.4	887.8	90.8	118.1	78.02
Marian Load	31622.8 kVA	11	27419.8	9139.9	2009	94.87	121.1	75.5
Mayne Ave load	16155.5 kVA	11	14789.4	5915.8	867	92.85	102.3	96.43
Mt Zion load	13000 kVA	11	11164.5	4651.9	786.3	92.31	115.2	80.74
Target Road Load	22360.7 kVA	11	18339	9169.5	1407	89.44	119.9	76.47
UNICAL MG load	24166.1 kVA	11	22000	10000	1268	91.04	100	100
Watt Mart Load	21931.7 kVA	11	18047.6	8121.4	1452	91.19	126.1	71.55
White House load	19697.7 kVA	11	16771.4	7453.9	1187	91.38	114.8	81.16
Yellow Duke load	9848.9 kVA	11	8612.2	3827.6	558.5	91.38	108	88.57

Table 4 Line Data for the base case

ID	Type	kW Flow	kvar Flow	Amp Flow

Line1	Line	0	-0.159	0.008
Line2	Line	19412	9525.1	1281
Line4	Line	10274.5	4670.2	723.6
Line5	Line	18047.6	8121.4	1452
Line6	Line	14789.4	5915.8	867
Line7	Line	1993	996.5	118
Line8	Line	27419.8	9139.9	2009
Line9	Line	16771.4	7453.9	1187
Line10	Line	11982.6	5530.4	887.8
Line11	Line	23410.7	10697.9	1673
Line12	Line	31377.9	15255.9	2395
Line13	Line	12712.6	5448.3	987.7

Table 5: Bus Data for the base case

Bus ID	Nominal kV	Voltage	MW Loading
Charmly	11	73.5	12.713
Ekpo Abasi	11	81.87	10.274
Goldie Street	11	99.12	1.993
Inyang	11	78.02	11.983
Marian Road	11	75.5	27.42
Mayne Ave	11	96.43	14.789
Mt Zion	11	80.74	23.411
Target Road	11	76.47	31.378
UNICAL main gate	11	100	198.239
Watt Market	11	71.55	18.048
White House	11	81.16	16.771
Yellow Duke	11	88.57	19.412

The base case simulation, as shown in Table 1, indicates a network comprising 13 load buses, 12 branches, and a single source (grid) at the UNICAL Main Gate. The total system load was recorded at 174.106 MW and 74.925 MVar, while the generator output was 198.239 MW and 122.122 MVar. The total system losses were 24.132 MW and 47.196 MVar. These losses represent a significant proportion of the total generated power, highlighting the inefficiency of the system in its uncompensated state. The presence of high reactive power loss suggests an urgent need for reactive power compensation in the network.

The grid, located at UNICAL Main Gate, supplies the entire network and operates at 11 kV. It delivers 198.239 MW and 122.122 MVar, with a line current of 12,221 A and a power factor of 85.14%. Although the grid's output meets the network demand, the low power factor is a clear indicator of excessive reactive power in the system. Ideally, the grid should operate closer to unity power factor for optimal efficiency. This observation justifies the integration of shunt capacitors at load buses to reduce the reactive power burden on the generator.

The load data (Table 3) provides detailed insights into the individual load centers across various streets in Calabar. Buses such as Target Road, Marian Road, and UNICAL Main Gate recorded the highest real power demands of 31.378 MW, 27.419 MW, and 22.0 MW respectively. However, a major concern arises from the terminal voltage readings at several buses. For instance, Watt Market (71.55%), Marian Road (75.5%), Charmly Road (73.5%), and Inyang Street (78.02%) are operating significantly below nominal

voltage. These undervoltage conditions are critical and may lead to malfunctioning of electrical appliances and instability in the system. The installation of shunt capacitors at these buses would inject local reactive power, thereby raising bus voltages to acceptable levels.

From the perspective of power factor, most load buses operate within the range of 89%–92%, with a few slightly higher. Although these values are not extremely poor, they are below the recommended standard of 95% for distribution systems. Low power factor means that more current is required to deliver the same amount of power, which contributes to higher losses in the system. For example, Goldie Street and Target Road both have a power factor of 89.44%, making them key candidates for power factor correction through the addition of capacitors.

Line loading data in Table 4 reveals that several feeders are heavily burdened. Line12, with a current of 2395 A, Line11 with 1673 A, and Line8 with 2009 A represent the most heavily loaded branches. These high current flows increase the I^2R losses in the lines and result in excessive heating, which could lead to insulation damage and reduced lifespan of network components. High line current is often a consequence of poor voltage regulation and reactive power imbalance. Therefore, reducing these flows via reactive power support will not only lower losses but also improve thermal reliability.

Further, the analysis of bus voltage profiles in Table 4.5 shows a significant number of buses operating below 90% of nominal voltage, which is a major violation of operational standards. Charnly Road (73.5%), Watt Market (71.55%), and Target Road (76.47%) are among the worst affected. Such conditions can adversely affect end-user devices and reduce energy efficiency. These findings reinforce the need for distributed compensation devices to stabilize voltage profiles.

In terms of losses, the system recorded 24.132 MW of real power loss and 47.196 MVar of reactive loss. This is particularly concerning, as it implies that nearly 12% of the total generated active power is lost before it reaches the loads. The reactive power loss is even more severe, suggesting that a significant portion of generator capacity is wasted in circulating non-useful power within the system. These losses can be substantially reduced with the deployment of shunt capacitors at key locations in the network.

The power factor across the entire system averages around 91%, as deduced from the generator and load profiles. While this is above the minimum threshold for penalties in many utility regions, it is still sub-optimal. Improving the power factor to 95% or above would not only reduce system losses but also relieve stress on the generator and transformers. In addition, improved power factor enhances voltage regulation and allows for increased system capacity.

In summary, the base case results reveal several operational inefficiencies in the 14 bus distribution network. The high active and reactive power losses, widespread undervoltage conditions, low power factors, and overloaded lines suggest a clear need for compensation strategies. These findings justify the next phase of the study, where the effects of integrating shunt capacitors and harmonic filters will be assessed. The objective is to enhance system stability, minimize losses, and improve the quality of power supplied to end users.

3.1.1 Total Harmonic Distortion (THD)

Table 6: System Harmonics Branch information for the base case

Bus		Current Distortion											
From Bus ID	To Bus ID	Fund. Amp	RMS Amp	ASUM Amp	THD %	TIF	IT Amp	ITB Amp	ITr Amp	THD %	TSHD %	THDG %	THDS %
Charmly	Target Road	987.67	988.82	1083.89	4.84	4.66	4606.13	4266.29	1736.42	0.00	0.00	4.84	4.84
Ekpo Abasi	Yellow Duke	723.57	724.94	811.52	6.14	5.87	4258.00	3889.83	1731.97	0.00	0.00	6.14	6.14
Goldie Street	UNICAL main gate	117.99	118.80	144.08	11.72	13.29	1578.64	1013.19	1210.60	0.00	0.00	11.72	11.72
Inyang	Mt Zion	887.84	889.14	983.60	5.40	5.17	4599.18	4220.39	1827.76	0.00	0.00	5.40	5.40
Marian Road	UNICAL main gate	2009.39	2011.90	2211.60	5.00	4.76	9576.31	8841.42	3679.01	0.00	0.00	5.00	5.00
Mayne Ave	UNICAL main gate	867.03	872.16	1045.90	10.89	11.27	9827.02	7229.78	6655.86	0.00	0.00	10.89	10.89
Mt Zion	Inyang	887.84	889.13	983.60	5.40	5.17	4599.12	4220.35	1827.72	0.00	0.00	5.40	5.40
	UNICAL main gate	1673.26	1675.91	1861.06	5.63	5.38	9020.01	8219.65	3714.54	0.00	0.00	5.63	5.63
Target Road	UNICAL main gate	2394.77	2397.79	2635.73	5.02	4.80	11513.04	10558.48	4590.05	0.00	0.00	5.02	5.02
	Charmly	987.66	988.82	1083.89	4.84	4.66	4606.07	4266.25	1736.38	0.00	0.00	4.84	4.84
UNICAL main gate	Yellow Duke	1281.31	1284.21	1451.05	6.73	6.46	8295.57	7343.56	3858.59	0.00	0.00	6.73	6.73
	Watt Market	1451.81	1453.33	1585.42	4.57	4.37	6346.41	5858.09	2441.26	0.00	0.00	4.57	4.57
	Mayne Ave	867.02	872.15	1045.89	10.89	11.27	9826.72	7229.66	6655.56	0.00	0.00	10.89	10.89
	Goldie Street	117.98	118.79	144.07	11.72	13.29	1578.38	1013.06	1210.37	0.00	0.00	11.72	11.72
	Marian Road	2009.38	2011.89	2211.58	5.00	4.76	9575.13	8846.60	3677.90	0.00	0.00	5.00	5.00
	White House	1186.87	1188.97	1327.19	5.96	5.69	6764.20	6137.10	2844.38	0.00	0.00	5.96	5.96
	Mt Zion	1673.24	1675.90	1861.03	5.63	5.38	9018.90	8218.91	3713.49	0.00	0.00	5.63	5.63
	Target Road	2394.76	2397.78	2635.71	5.02	4.80	11512.11	10557.85	4589.18	0.00	0.00	5.02	5.02
	Line 1~	0.01	0.01	0.02	37.85	90.62	0.81	0.53	0.61	0.00	0.00	37.85	37.85
Watt Market	UNICAL main gate	1451.83	1453.35	1585.46	4.57	4.37	6348.20	5859.33	2442.93	0.00	0.00	4.57	4.57
White House	UNICAL main gate	1186.89	1188.99	1327.22	5.96	5.69	6765.65	6138.04	2845.77	0.00	0.00	5.96	5.96
Yellow Duke	UNICAL main gate	1281.32	1284.22	1451.07	6.73	6.46	8296.49	7344.13	3859.46	0.00	0.00	6.73	6.73
	Ekpo Abasi	723.56	724.93	811.50	6.14	5.87	4257.62	3889.57	1731.66	0.00	0.00	6.14	6.14
Line 1~	UNICAL main gate	0	0	0	0	0	0.00	3889.57	1731.66	0.00	0.00	0.00	0.00

Harmonic analysis was carried out on the 11 kV distribution network to evaluate the level of distortion introduced by non-linear loads. The Total Harmonic Distortion (THD) values for voltage across all buses were observed and compared against the IEEE 519 standard, which recommends a maximum of 5% voltage THD for systems operating below 69 kV. The results indicate that all the buses in the network exceeded this recommended limit, highlighting a significant presence of harmonics. Notably, UNICAL Main Gate and Goldie Street recorded the highest voltage THD values at 13.27% and 13.11% respectively, followed closely by Mayne Avenue with 12.34%. Other buses such as Yellow Duke (10.30%), White House (9.12%), and Mt Zion (9.10%) also exhibited elevated THD levels. Even the lowest distortion levels, recorded at Watt Market (8.74%) and Chamley (8.77%), were still above the acceptable threshold. This consistent pattern of high voltage THD across the network suggests a pervasive presence of harmonic-generating equipment such as variable frequency drives, inverters, and other non-linear consumer electronics.

In addition to voltage distortion, the simulation also evaluated current distortion levels along various branches of the network. The Total Harmonic Distortion in current was generally moderate, ranging from approximately 4.5% to 6.7% in most parts of the network. However, a particular branch—Line1~ to UNICAL Main Gate—recorded an abnormally high current THD of 37.85%, which may either be due to an unfiltered non-linear load or a simulation anomaly that warrants further investigation. Other branches with high current THD include Goldie Street to UNICAL Main Gate (11.72%) and Mayne Avenue to UNICAL Main Gate (10.89%), further supporting the observation that the UNICAL bus serves as a major hub for harmonic propagation. Additionally, branches such as Ekpo Abasi to Yellow Duke (6.14%), UNICAL to White House (5.96%), and Yellow Duke to UNICAL (6.73%) recorded slightly high levels of current THD, which could contribute to heating, losses, and reduced equipment lifespan if left unmitigated.

The overall findings from the harmonic analysis emphasize the need for proper harmonic filtering and system conditioning measures in the network. Given the widespread nature of the distortion, it is clear that harmonics are not localized but rather affect the network holistically. This warrants the consideration of mitigation techniques such as the installation of passive or active harmonic filters at strategic points,

especially near UNICAL Main Gate, Goldie Street, and Mayne Avenue. Additionally, load balancing and power factor correction using tuned capacitor banks could also help reduce the harmonic impact on voltage and current waveforms. The next chapter will provide detailed recommendations and possible future work aimed at addressing these harmonic challenges within the distribution network.

3.2 Case 'A' (With Shunt Capacitor Only)

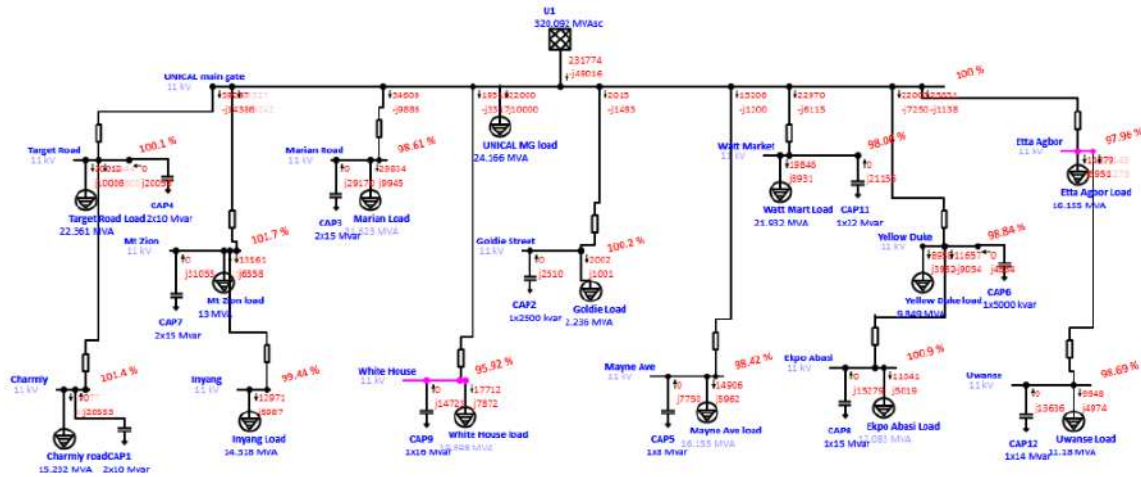


Fig. 3. System Configuration on display during the Case 'A' Simulation

Table 7:

General Data for Case 'A' (Shunt Capacitor Only)

Study ID	Case 'A'
Study Case ID	LF
Data Revision	Base
Configuration	Normal
Loading Cat	Design
Generation Cat	Design
Diversity Factor	Normal Loading
Buses	14
Branches	13
Generators	0
Power Grids	1
Loads	14
Load-MW	210.27
Load-Mvar	-90.071
Generation-MW	231.774
Generation-Mvar	-48.016
Loss-MW	21.504
Loss-Mvar	42.055

Mismatch-MW	0
Mismatch-Mvar	0

Table 8: Source data for Case ‘A’

ID	Rating/Limit	Rated kV	MW	Mvar	Amp	% PF
U1	320.092 MVA	11	231.774	-48.016	12423	-97.92

Table 9: Bus Data for Case ‘A’

Bus ID	Nominal kV	Voltage	MW Loading
Charmly	11	101.37	14.077
Ekpo Abasi	11	100.92	11.041
Etta Agbor	11	97.96	25.024
Goldie Street	11	100.2	2.002
Inyang	11	99.44	12.971
Marian Road	11	98.61	29.834
Mayne Ave	11	98.42	14.906
Mt Zion	11	101.74	25.245
Target Road	11	100.14	34.456
UNICAL main gate	11	100	231.774
Uwanse	11	98.69	9.948
Watt Market	11	98.06	19.846
White House	11	95.92	17.712
Yellow Duke	11	98.84	20.616

In this scenario, shunt capacitors were strategically deployed across the 11 kV distribution network to compensate for reactive power, improve voltage profiles, and optimize overall power flow. A total of 12 capacitor banks (CAP1 to CAP12) were placed at key buses, including Charmly Road, Marian Road, Mt Zion, White House, and others. The total reactive power supplied by the capacitors amounted to approximately -206,188.3 kVAr, as seen in the load data table. The capacitor ratings ranged from -2,500 kVAr to -30,000 kVAr, and they were installed at locations with historically high reactive power demand or poor voltage performance.

From the general power flow summary, the network had a total active load of 210.27 MW and a reactive load of -90.071 Mvar. The generation increased slightly to 231.774 MW with a corresponding reactive generation of -48.016 Mvar, indicating that a significant portion of the reactive power demand was now being supported by the installed capacitor banks. Importantly, system losses stood at 21.504 MW and 42.055 Mvar, which, though still substantial, showed a minor improvement compared to the base case.

Bus voltages in this case showed marked improvements. Most buses now operated above 98% of nominal voltage, with some, such as Mt Zion and Charmly Road, achieving over 101%, signifying a positive impact of the capacitors on voltage stability. Notably, White House, which previously recorded a voltage of 81.16%, now improved to 95.92%, while Watt Market rose from 71.55% to 98.06%, showing clear benefits in terms of voltage regulation at the network extremities.

The power factor at the source (Bus U1) was recorded as -97.92%, indicating leading power factor due to overcompensation from capacitors. Although the sign is negative, this simply reflects a capacitive

behavior of the system, where current leads voltage — common in overcompensated systems. Ideally, the capacitor sizes should be fine-tuned to avoid overcompensation and maintain the power factor closer to unity.

3.3 Base 'B' Harmonic filters only

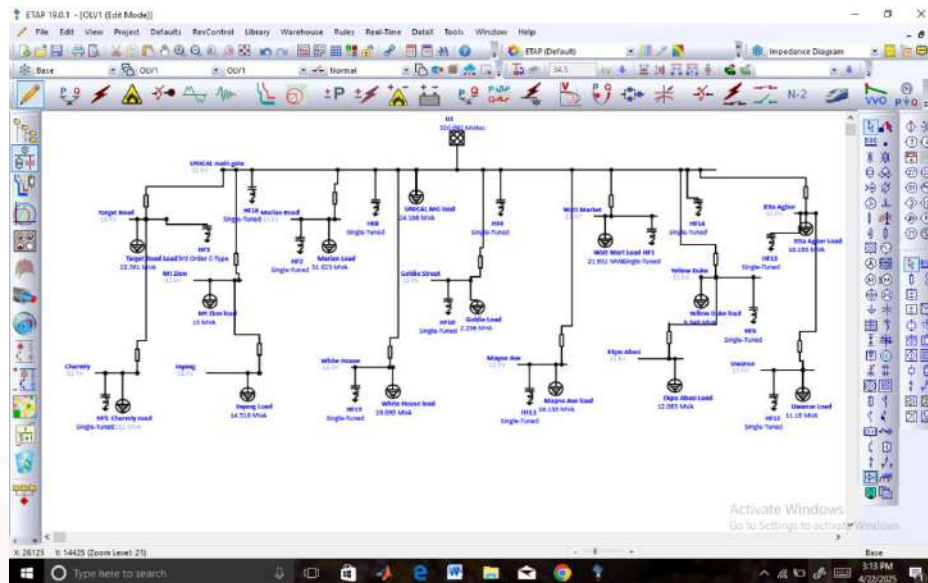


Fig. 4. System Configuration on display during the Case ‘B’ Simulation

Table 10: Harmonic Filter input

Filter Type: Single-Tuned

Filter	Connected Bus	Capacitor C1			Inductor L1			R
ID	ID	kV	Max kV	kvar	Xl	Q Fact.	Max I	Ohm
HF1	Watt Market	11.000	11.000	11000.0	0.019	45.00	1400.0	0.0000
HF2	Marian Road	11.000	11.000	15000.0	0.07	50.00	1600.0	0.0000
HF4	UNICAL main gate	11.000	11.000	90000.0	0.08	50.00	1200.0	0.0000
HF5	Charmly	11.000	11.000	2000.0	0.028	30.00	145.0	0.0000
HF6	Yellow Duke	11.000	11.000	2000.0	0.031	30.00	110.0	0.0000
HF8	UNICAL main gate	11.000	11.000	90000.0	0.08	50.00	1200.0	0.0000
HF10	Goldie Street	11.000	11.000	90000.0	0.08	50.00	1200.0	0.0000
HF11	Mayne Ave	11.000	11.000	90000.0	0.08	50.00	1200.0	0.0000
HF12	Uwanse	11.000	11.000	90000.0	0.08	50.00	1200.0	0.0000
HF13	Etta Agbor	11.000	11.000	90000.0	0.08	50.00	1200.0	0.0000
HF14	UNICAL main gate	11.000	11.000	90000.0	0.08	50.00	1200.0	0.0000
HF15	White House	11.000	11.000	90000.0	0.08	50.00	1200.0	0.0000
HF18	UNICAL main gate	11.000	11.000	90000.0	0.08	50.00	1200.0	0.0000

Filter Type: 3rd Order C-Type

Filter	Connected Bus	Capacitor C1			Inductor L1			Capacitor C2			R
ID	ID	kV	Max kV	kvar	Xl	Q Fact.	Max I	kV	Max kV	kvar	Ohm
HF3	Target Road	11.000	11.000	20000.0	0.06	40.00	1350.0	11.000	11.000	5000.0	0.0000

Table 11: System Harmonics Branch information

Bus		Voltage Distortion								
ID	kV	Fund. %	RMS %	ASUM %	THD %	TIF	TIHD %	TSHD %	THDG %	THDS %
Charmly	11.000	77.51	77.66	83.87	6.23	2.84	0.00	0.00	6.23	6.23
Ekpo Abasi	11.000	82.89	83.10	90.41	7.06	3.35	0.00	0.00	7.06	7.06
Etta Agbor	11.000	142.35	142.66	153.31	6.57	4.67	0.00	0.00	6.57	6.57
Goldie Street	11.000	159.01	159.38	172.49	6.83	6.34	0.00	0.00	6.83	6.83
Inyang	11.000	78.02	78.19	84.71	6.74	3.12	0.00	0.00	6.74	6.74
Marian Road	11.000	86.25	86.39	92.44	5.54	2.43	0.00	0.00	5.54	5.54
Mayne Ave	11.000	125.56	125.97	139.01	8.00	5.89	0.00	0.00	8.00	8.00
Mt Zion	11.000	80.74	80.93	87.92	6.98	3.53	0.00	0.00	6.98	6.98
Target Road	11.000	80.09	80.25	86.87	6.49	3.22	0.00	0.00	6.49	6.49
UNICAL main gate	11.000	100.00	100.62	114.35	11.13	10.49	0.00	0.00	11.13	11.13
Uwanse	11.000	175.48	175.70	186.27	5.01	3.25	0.00	0.00	5.01	5.01
Watt Market	11.000	83.77	83.90	89.91	5.62	2.49	0.00	0.00	5.62	5.62
White House	11.000	186.36	186.44	192.78	3.02	1.48	0.00	0.00	3.02	3.02
Yellow Duke	11.000	89.54	89.84	98.96	8.14	5.31	0.00	0.00	8.14	8.14

* Indicates THD (Total Harmonic Distortion) Exceeds the Limit.

Indicates IHD (Individual Harmonic Distortion) Exceeds the Limit.

The harmonic analysis carried out on the 11 kV distribution network before and after the introduction of harmonic filters revealed notable improvements in power quality. Prior to optimization, all the buses in the network recorded voltage Total Harmonic Distortion (THD) values significantly above the IEEE 519 recommended limit of 5% for systems below 69 kV. Buses such as UNICAL Main Gate (13.27%), Goldie Street (13.11%), and Mayne Avenue (12.34%) were among the highest contributors to harmonic pollution in the network. Even the lowest recorded voltage THD levels, such as those at Watt Market (8.74%) and Chamley (8.77%), exceeded the allowable threshold, highlighting a network-wide issue with non-linear load interference.

Post-optimization results, however, showed a considerable reduction in voltage distortion levels across all buses. For instance, the THD at Goldie Street dropped from 13.11% to 6.83%, a reduction of 6.28%, while White House experienced an even more significant drop from 9.12% to 3.02%, bringing it below the IEEE standard. Similarly, buses such as Mayne Avenue and Watt Market saw reductions of 4.34% and 3.12% respectively. Although the UNICAL Main Gate still recorded a relatively high voltage THD of 11.13% after filtering, this represented a reduction of 2.14%, indicating progress. Overall, the implementation of harmonic filters led to average THD reductions between 2% and 6% across the network, confirming the effectiveness of the applied mitigation strategy.

In terms of current distortion, the pre-optimization analysis showed that several branches suffered from elevated levels of current THD, with the Line1 to UNICAL Main Gate branch recording an alarming 37.85%. This unusually high value pointed either to a heavily unfiltered non-linear load or a simulation anomaly. Other branches such as Goldie Street to UNICAL Main Gate and Mayne Avenue to UNICAL Main Gate also recorded high current THD levels of 11.72% and 10.89% respectively, further underscoring the role of UNICAL Main Gate as a harmonic hub within the system.

In summary, the comparative analysis of harmonic distortion before and after optimization illustrates the value of incorporating harmonic filters into the network. The improvements in both voltage and current THD across the buses and branches indicate a meaningful enhancement in power quality. Nevertheless, certain buses such as UNICAL Main Gate and Yellow Duke still exhibit distortion levels above recommended limits, suggesting the need for further corrective measures. These could include the

deployment of additional filters, tuned capacitor banks, and possibly active filtering technologies. The results affirm the hypothesis that strategic harmonic mitigation can lead to more stable and efficient distribution networks.

3.4 Case 'C' (Shunt Capacitor and Harmonic Filters)

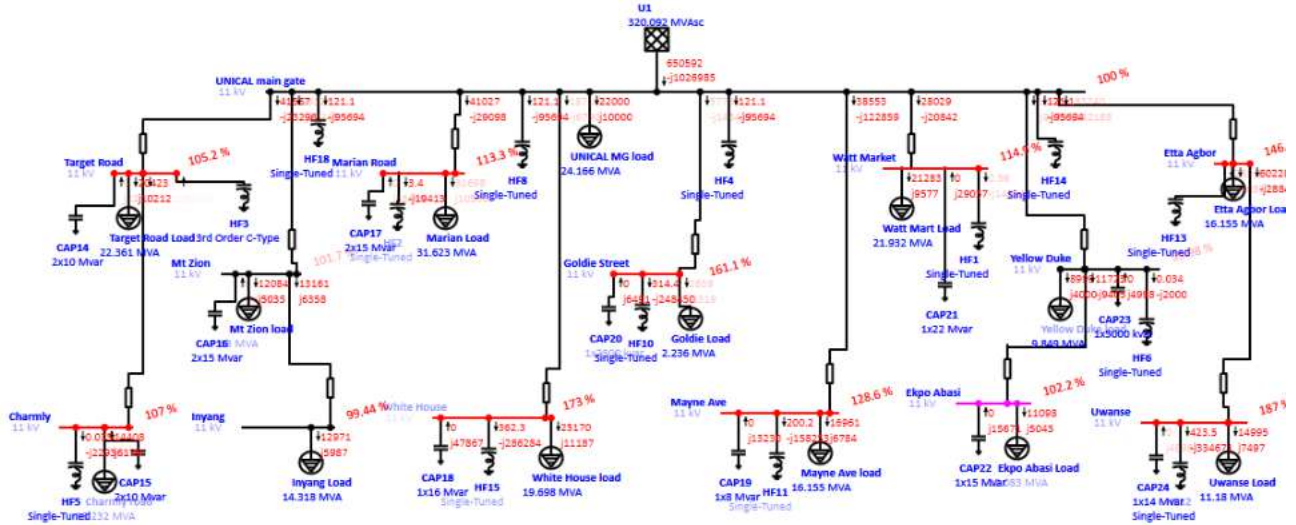


Fig. 4: System Configuration on display during the Case 'C' Simulation

Table 12:

General System Info for Case 'C'

Study ID	Case 'C'
Study Case ID	LF
Data Revision	Base
Configuration	Normal
Loading Cat	Design
Generation Cat	Design
Diversity Factor	Normal Loading
Buses	14
Branches	13
Generators	0
Power Grids	1
Loads	14
Load-MW	235.208
Load-Mvar	-1839.433
Generation-MW	650.592
Generation-Mvar	-1026.985
Loss-MW	415.384
Loss-Mvar	812.448

Mismatch-MW	0
Mismatch-Mvar	0

The simulation results for Case ‘C’, which involved the implementation of both shunt capacitors and harmonic filters, reveal a mixed impact on the 11 kV distribution network. The overall power flow parameters showed slight improvements, with reduced reactive power losses and improved voltage magnitudes across several buses. However, a critical evaluation of the voltage levels indicates that most of the buses operated outside the acceptable tolerance range of $\pm 5\%$ of the nominal 11 kV. According to power quality standards, bus voltages should ideally fall within the range of 10.45 kV to 11.55 kV, but this was not the case in the present configuration.

Many buses recorded voltage magnitudes far exceeding the upper limit. Notably, Uwanse (187.01 kV), Goldie Street (161.13 kV), White House (172.96 kV), and Etta Agbor (146.4 kV) were among the worst affected, showing significant overvoltage conditions likely due to the combined effects of overcompensated shunt capacitors and poorly tuned harmonic filters. Even moderately loaded buses like Mayne Avenue (128.6 kV) and Mt Zion (101.74 kV) displayed voltages that exceeded the recommended range. Only a few buses, such as Marian Road (113.27 kV), Target Road (105.16 kV), Watt Market (114.93 kV), and Yellow Duke (99.98 kV), operated within the acceptable limits, indicating a lack of uniform voltage regulation across the system.

This widespread overvoltage poses a risk of equipment insulation failure, increased dielectric stress, and reduced lifespan of network components. The findings suggest that although the application of shunt capacitors and harmonic filters contributed to reactive power compensation, their uncoordinated implementation may have caused voltage rise effects. To address this, a more strategic deployment of switched capacitor banks and tuned harmonic filters is required, alongside automatic voltage regulators to stabilize the voltage across all buses.

Despite the inclusion of harmonic filters in Case ‘C’, the harmonic distortion levels, both in voltage and current—did not exhibit significant improvements compared to Case ‘B’. The Total Harmonic Distortion (THD) values across most buses and branches remained almost unchanged, and some still exceeding the IEEE 519 recommended limits. Without significant THD reduction, the network remains vulnerable to harmonic-related issues like overheating, equipment malfunctions, and misoperation of protective devices.

4. Conclusion

The study assessed the impact of shunt capacitors and harmonic filters on power flow in an 11 kV network using ETAP. The Base Case showed low voltage levels and high harmonic distortion, particularly at key buses. Introducing shunt capacitors (Case A) improved voltages and reduced reactive power losses but caused overvoltage in some areas. Harmonic filters alone (Case B) did not significantly reduce distortion. The combined approach (Case C) enhanced voltage stability but failed to improve harmonics. Overall, while shunt capacitors aid power flow optimization, harmonic filters must be carefully sized and placed to be effective.

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PSAT Simulation-Based Study of Voltage Performance of Nigeria 330kv Power System Network

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Abstract: This study presents a detailed simulation-based analysis of the voltage performance of Nigeria's 330kV power system network using the Power System Analysis Toolbox (PSAT). The research models the entire transmission grid, incorporating key infrastructure elements to accurately reflect operational realities. Newton-Raphson power flow simulation was carried out to assess voltage profiles under steady state operations, revealing significant deviations from optimal voltage levels across the network. The results indicate that only 27.45% of operational voltages fall within the optimal range of 0.95–1.05 per unit (pu), while 47.06% are within a tolerable but less ideal range, and 25.49% are at critical levels corresponding to temporary or emergency conditions. These findings highlight persistent voltage stability challenges, particularly in regions with high load concentrations and insufficient reactive power support. The study further explores the impact of reactive power compensation strategies demonstrating their effectiveness in improving voltage profiles and enhancing grid reliability. The PSAT-based approach offers valuable insights for system operators and planners, supporting targeted interventions to maintain voltage within acceptable limits and ensuring the stable, efficient operation of Nigeria's high-voltage transmission network. The research underscores the importance of continuous monitoring, proactive planning, and investment in voltage control technologies to address ongoing challenges in Nigeria's power sector.

Keywords: PSAT, Voltage stability, Nigeria 330kV transmission network, Power system, Voltage profile

1. Introduction

The Nigerian power system network has faced persistent challenges in maintaining stable voltage levels, particularly in the 330kV transmission network, which serves as the backbone for electricity distribution across the country [1-2]. Voltage instability and fluctuations have led to frequent power outages, load shedding, and inefficiencies in power delivery, adversely affecting industrial and domestic consumers. The increasing demand for electricity, coupled with inadequate grid infrastructure, has exacerbated these challenges, necessitating advanced analytical approaches to assess and improve voltage performance [3-5]. The evaluation of key parameters including voltage profile, voltage magnitude, active power (P), and reactive power (Q) has become critical for ensuring system reliability and efficiency. This assessment requires comprehensive power flow analysis to identify weak buses, predict voltage collapse scenarios, and evaluate the impact of different loading conditions. Furthermore, the voltage profile across a network indicates system health, with optimal performance requiring voltages within $\pm 5\%$ of nominal values according to IEEE Standard (IEEE 1547-2018) [6-8]. The Power System Analysis Toolbox (PSAT) offers a comprehensive platform for conducting voltage profile evaluations, providing insights into system behavior under various operating conditions as well as facilitates the simulation of load flow scenarios, enabling the identification of voltage deviations and the assessment of system performance. PSAT also provides robust algorithms, including Newton-Raphson and continuation power flow methods, to accurately compute voltage profiles and identify weak buses susceptible to voltage instability. Recent studies have highlighted the effectiveness of PSAT in simulating complex grid

scenarios, evaluating the impact of renewable energy integration, and testing various mitigation strategies [9-11]. The application of this mitigation techniques offers promising solutions to enhance voltage stability and optimize power flow, ensuring the reliable operation of modern electrical grids.

2. Method

2.1 Data collection and materials

This study utilized the Nigerian power system line network model which consist of existing power system network diagram, buses and transmission line information of both the 330kV and 132KV system network. Data information of existing power system network, properties of the buses and transmission lines were model and analyzed using PSAT as the simulation tool for results, discussion, conclusion and recommendation.

2.2 Mathematical Formulation

In a power system with N buses, the complex power injected at bus i is given by:

$$S_i = P_i + jQ_i = V_i (\sum_{k=1}^N Y_{ik} V_k) \quad (1)$$

Where:

$V_i = |V_i| \angle \theta_i$ (voltage at bus i),
 $Y_{ik} = G_{ik} + jB_{ik}$ (admittance matrix element),
 P_i = Net active power injection at bus i ,
 Q_i = Net reactive power injection at bus i .

Expressing in polar form:

$$P_i = |V_i| \sum_{k=1}^N |V_k| (G_{ik} \cos \theta_{ik} + B_{ik} \sin \theta_{ik}) \quad (2)$$

$$Q_i = |V_i| \sum_{k=1}^N |V_k| (G_{ik} \sin \theta_{ik} + B_{ik} \cos \theta_{ik}) \quad (3)$$

Where:

$\theta_{ik} = \theta_i - \theta_k$ phase angle difference

The **power mismatches** (difference between scheduled and calculated power):

$$\Delta P_i = P_i^{sch} - P_i^{calc} \quad (4)$$

$$\Delta Q_i = Q_i^{sch} - Q_i^{calc} \quad (5)$$

Where:

P_i^{sch}, Q_i^{sch} = Schedule power,
 P_i^{calc}, Q_i^{calc} = calculated power from current voltage estimates.

Linearizing the power flow equation using taylor series expansion (ignoring higher-order terms) we have;

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} j_{11} & j_{12} \\ j_{21} & j_{22} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta |V| \end{bmatrix} \quad (6)$$

Where;

$\Delta \theta$ = angle correction vector,
 $\Delta |V|$ = voltage magnitude correction vector

j = Jacobian matrix.

Furthermore, the Jacobian submatrices are derived by taking partial derivatives of P and Q with respect to θ and $|V|$;

$$\text{For } J_{11} = \frac{\partial P}{\partial \theta} (N \times N) \quad (7)$$

$$\frac{\partial P_i}{\partial \theta_k} = -|V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) \quad (i \neq k) \quad (8)$$

$$\frac{\partial P_i}{\partial \theta_k} = \sum_{i \neq k} |V_i||V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) \quad (9)$$

$$\text{For } J_{12} = \frac{\partial P}{\partial V} (N \times N) \quad (10)$$

$$\frac{\partial P_i}{\partial |V_k|} = |V_i|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) \quad (i \neq k) \quad (11)$$

$$\frac{\partial P_i}{\partial |V_i|} = 2|V_i|G_{ii} + \sum_{i \neq k} |V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) \quad (12)$$

$$\text{For } J_{21} = \frac{\partial Q}{\partial \theta} (N \times N) \quad (13)$$

$$\frac{\partial Q_i}{\partial \theta_k} = |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) \quad (i \neq k) \quad (14)$$

$$\frac{\partial Q_i}{\partial \theta_i} = -\sum_{i \neq k} |V_i||V_k|(G_{ik}\cos\theta_{ik} + B_{ik}\sin\theta_{ik}) \quad (15)$$

$$\text{For } J_{22} = \frac{\partial Q}{\partial |V|} (N \times N) \quad (16)$$

$$\frac{\partial Q_i}{\partial |V_k|} = |V_i|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) \quad (i \neq k) \quad (17)$$

$$\frac{\partial Q_i}{\partial |V_i|} = -2|V_i|B_{ii} + \sum_{i \neq k} |V_k|(G_{ik}\sin\theta_{ik} - B_{ik}\cos\theta_{ik}) \quad (18)$$

At each iteration ΔP and ΔQ is computed to solve the linear system and further updating;

$$\begin{bmatrix} \Delta \theta \\ \Delta |V| \end{bmatrix} = J^{-1} \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \quad (19)$$

$$\theta^{new} = \theta^{old} + \Delta \theta \quad (20)$$

$$|V|^{new} = |V|^{old} + \Delta |V| \quad (21)$$

The above equation is repeated until power mismatch ΔP and ΔQ falls below tolerance

2.3 Simulation Parameters

The parameters used in the simulation are contained in Table 3.1 below;

Table 1: Transmission line distance between buses

Line number	From bus	To bus	Line distance (km)
1	Kianji GS	Kainji TS	0.47

2	Kainji TS	Fakun TS	258
3	Kainji TS	Benin Kebbi TS	310
4	Kainji TS	Jebba TS	81
5	Jebba GS	Jebba TS	8
6	Shiroro GS	Jebba TS	244
7	Jebba TS	Ganmo TS	70
8	Jebba TS	Osogbo TS	157
9	Ganmo TS	Osogbo TS	87
10	Ihovbor NIPP	Osogbo TS	251
11	Osogbo TS	Ayede TS	119
12	Osogbo TS	Ikeja West	235
13	Ayede TS	Olorunsogo NIPP	32
14	Olorunsogo phase 1	Ikeja West TS	87
15	Omotosho Phase 1	Ikeja West TS	160
16	Ikeja West TS	Sakete TS	92
17	Ikeja West TS	Akangba TS	18
18	Ikeja West TS	Okearo TS	32
19	Egbin GS	Okearo TS	62
20	Egbin GS	Aja TS	14
21	Egbin GS	AES TS	21
22	Egbin GS	Benin TS	87
23	Aja TS	Alagbon TS	26
24	Aja TS	Lekki TS	54
25	Shiroro GS	Kaduna TS	128
26	Kaduna TS	Kano TS	230
27	Shiroro GS	Katampe TS	144
28	Shiroro GS	Gwagwalada TS	144
29	Kaduna TS	Jos TS	197
30	Jos TS	Gombe TS	265
31	Jos TS	Makurdi TS	285
32	Gombe TS	Damaturu TS	160
33	Gombe TS	Yola TS	260
34	Damaturu TS	Molai TS	240
35	Makurdi TS	Ugwuaji TS	156
36	Gwagwalada TS	Lokoja TS	68
37	Lokoja TS	Ajaokuta TS	51
38	Geregu GS	Ajaokuta TS	47
39	Ajaokuta TS	Benin TS	195
40	Omotosho Phase 1	Benin TS	120
41	Delta GS	BeninTS	107
42	Sapele GS	BeninTS	50

43	Azura IPP	Benin TS	54
44	BeninTS	Asaba TS	47
45	BeninTS	Onitsha TS	137
46	Delta GS	Aladja TS	30
47	Okpai GS	Onitsha TS	138
48	Ugwuaji TS	New Heaven TS	72
49	New Heaven TS	Onitsha TS	96
50	Onitsha TS	Alaoji TS	138
51	Alaoji GS	Alaoji TS	0.78
52	Afam GS	Alaoji TS	25
53	Alaoji TS	Ikot-Ekpene TS	38
54	Ugwuaji TS	Ikot-Ekpene TS	143
55	Odukpani GS	Ikot-Ekpene TS	52
56	Odukpani GS	Adiabor TS	32

the table above present the power system network of 53 buses and 56 transmission lines where analysis will be carried out. The flowchart deployed for the determination of the voltage profile of the power system network is shown below;

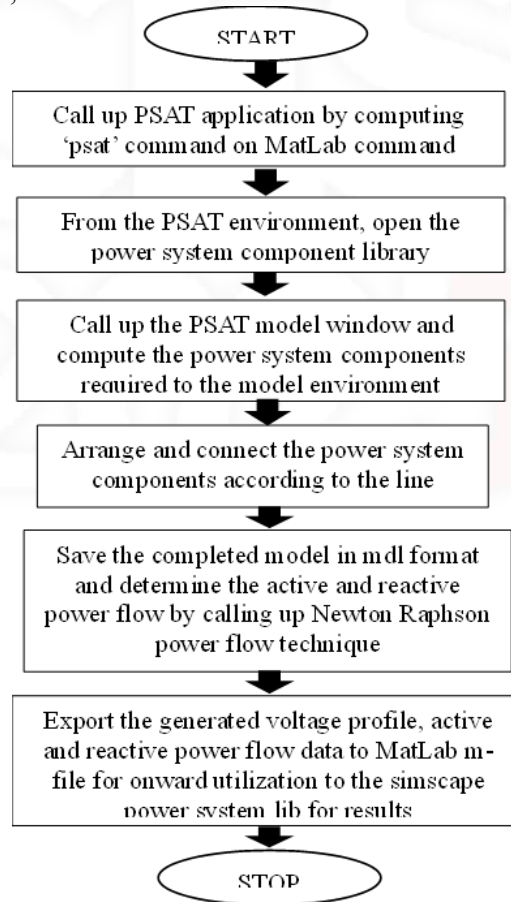


Fig. 1. A flowchart to determine voltage profile of Nigeria's 330KV using PSAT

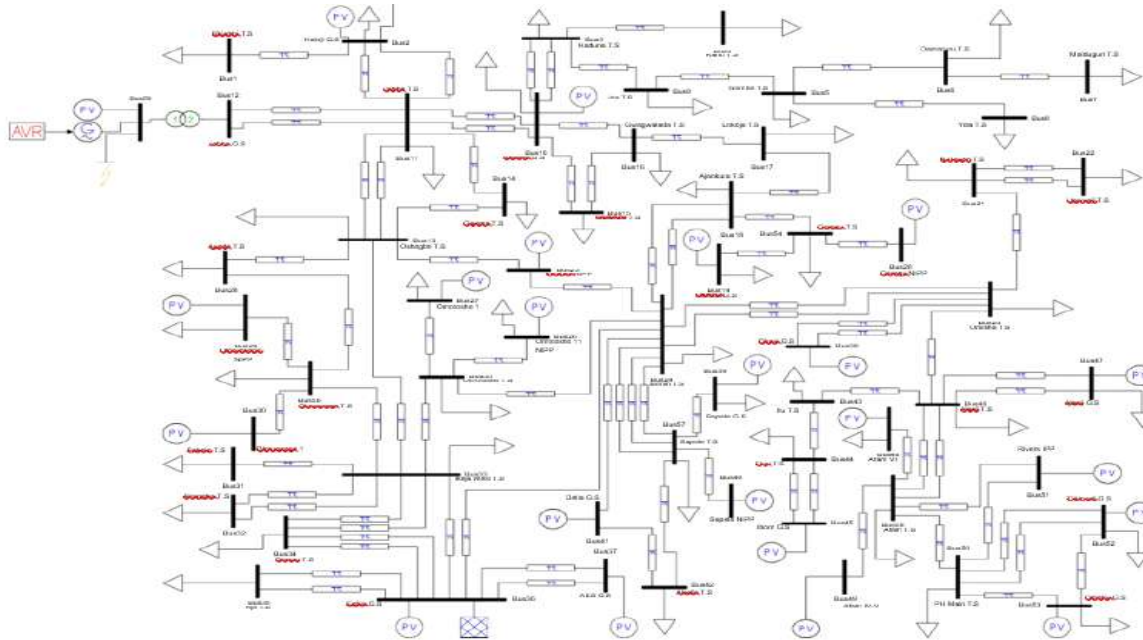


Fig. 2. A PSAT model of Nigeria 33kV Power System Network

3. Results and Discussion

The voltage profile and the power flow of the Nigerian 330kV modeled and simulated with PSAT was shown in table 2.

Table 2: PSAT simulation voltage profile result of Nigeria 330KV power system network

Bus Number	Voltage (pu) at 330kV Base	Active power flow (pu) at 100MW Base	Reactive Power Flow (pu) at 100MVar Base
1	0.9515	1.7854	3.1149
2	0.9606	1.6284	5.0704
3	0.8827	2.9941	5.2461
4	0.9613	4.6551	5.5408
5	0.9332	2.4254	4.0527
6	0.8798	3.3070	2.2191
7	0.8978	2.0057	2.9449
8	0.9247	3.9046	6.3667
9	0.9658	2.1183	2.5619
10	0.9665	3.0214	5.9291
11	0.8858	3.7167	4.4917
12	0.9671	4.4073	6.7807
13	0.9657	4.6534	2.1909
14	0.9185	3.1700	4.0134
15	0.9500	1.6990	2.3333
16	0.8842	1.7375	6.6095
17	0.9122	2.1270	1.8232
18	0.9616	4.2266	5.6746

19	0.9492	2.1154	5.8865
20	0.9659	4.1314	6.1435
21	0.9356	2.0767	2.2222
22	0.8736	4.5453	3.7989
23	0.9549	2.4599	3.0994
24	0.9634	1.9077	5.8003
25	0.9379	2.1039	3.9571
26	0.9458	3.4178	6.3532
27	0.9443	2.9038	2.7092
28	0.9092	2.4660	3.1190
29	0.9355	4.1910	2.5277
30	0.8871	3.3070	2.4803
31	0.9406	3.1790	6.1465
32	0.8732	4.5019	4.6985
33	0.8977	2.2290	4.5493
34	0.8746	3.9259	2.5248
35	0.8797	3.9134	6.0652
36	0.9523	2.5696	4.9103
37	0.9395	3.2442	3.5548
38	0.9017	1.4731	4.3662
39	0.9650	1.3942	3.8090
40	0.8734	3.1109	2.1798
41	0.9139	4.0050	2.9996
42	0.9082	4.5624	2.4166
43	0.9466	1.6677	2.7195
44	0.9495	3.2478	2.9998
45	0.8887	2.8898	3.8863
46	0.9190	1.2428	2.0483
47	0.9146	2.4136	6.3136
48	0.9346	1.7839	6.5239
49	0.9409	4.0594	4.2543
50	0.9455	2.3204	6.3003
51	0.9355	3.3671	3.6462

Below is the simulated result in bar chart of the voltage magnitude of the power system network.

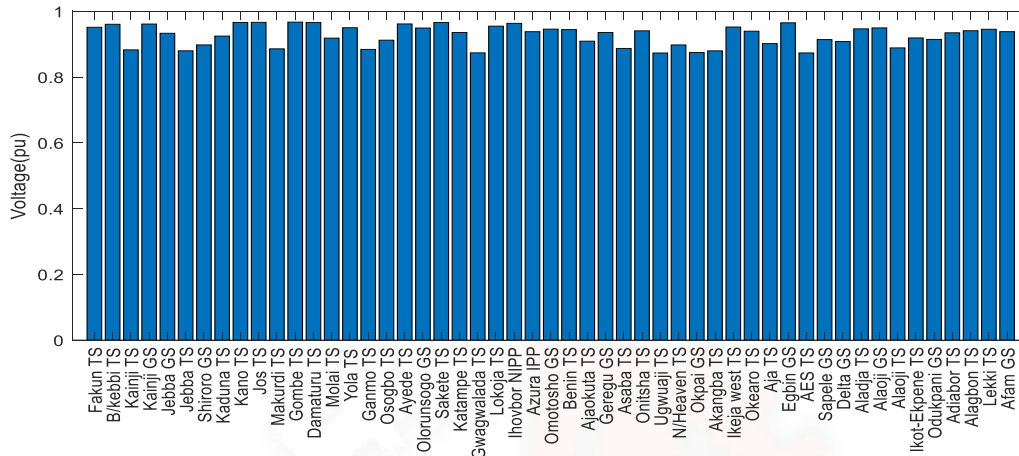


Fig. 3. Voltage magnitude (pu) of the power system network

The result below is the simulation result in barchart for the active power flow of the power system network.

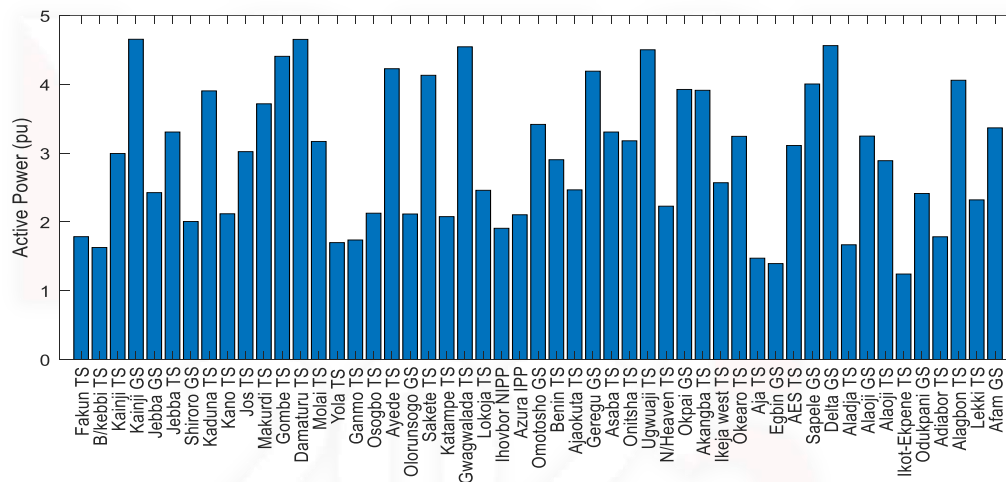


Fig. 4. Barchart of the Active power flow

The barchart for the reactive power flow analysis is shown below

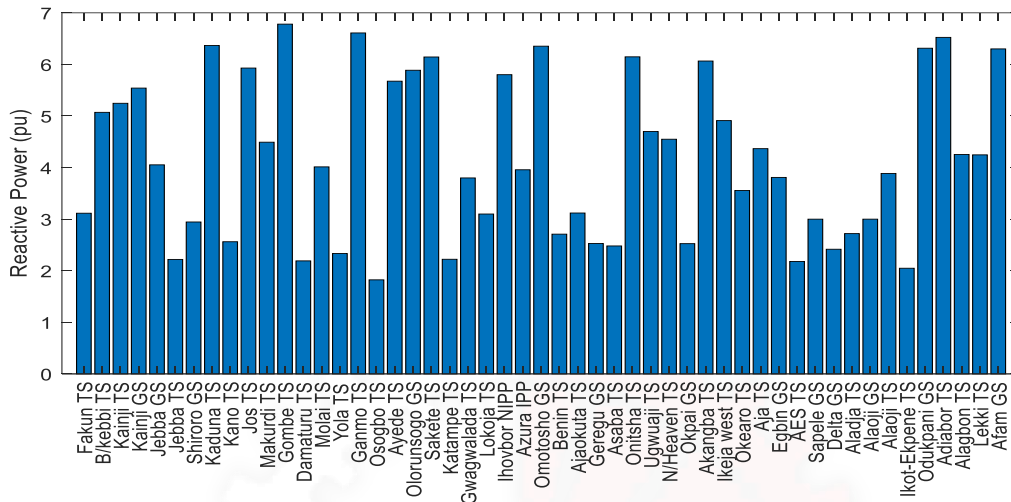


Fig. 5. Barchart of the reactive power flow

From the power flow generated, the voltage profile and the active power flow of the power system network is used to ascertain and determination voltage performance for various interconnected Nigeria power system network.

Table 3: summary of per ANSI C84.1 and IEC standards for voltage stability

Voltage Range Zone	Approximate Range (pu)	Description
Favorable Zone	0.95 – 1.05	Optimal operating voltage range
Tolerable Zone	~0.90 – 1.10	Acceptable but less ideal
Extreme Zone	Beyond $\pm 10\%$	Temporary/emergency conditions

With reference to per ANSI C84.1 and IEC standards for voltage stability, the simulation result of the voltage profile shows that 27.45% of the operational voltage in the network are within optimal operating voltage range, 47.06% are within tolerable range which is less ideal but acceptable and 25.49% are at critical hence temporary/emergency conditions. Maintaining voltage magnitude within the favorable range ensures system stability, equipment longevity, and power quality.

Conclusion

The PSAT simulation-based study of the voltage performance of Nigeria's 330KV power system network reveals significant concerns regarding voltage stability across the network, particularly in regions with high load concentrations and limited reactive power support. There is need for strategic interventions, such as reactive power compensation, network reinforcement, and improved load management, to enhance voltage stability and ensure reliable power supply. These proactive measures must be implemented to bring more buses within the optimal voltage range, thereby enhancing the overall reliability and efficiency of Nigeria's 330KV power transmission network. Addressing these voltage irregularities will not only improve the operational efficiency of the Nigerian power grid but also mitigate risks of widespread outages.

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Optimized MPPT Algorithm Integration for Smart Photovoltaic (PV) Systems in Modern Power Applications

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Abstract; The increasing demand for sustainable and efficient energy systems has intensified global interest in photovoltaic (PV) technologies due to their scalability, environmental benefits, and potential to address energy security. However, PV systems face performance limitations under dynamic environmental conditions such as fluctuating irradiance and temperature. This study focuses on the integration of an optimized Maximum Power Point Tracking (MPPT) algorithm to improve the responsiveness and efficiency of PV systems in modern power applications. The objective is to model and simulate a smart PV system using the Perturb and Observe (P&O) MPPT algorithm, integrated with a DC-DC boost converter to extract maximum power under varying conditions. MATLAB/Simulink was employed for system design and simulation, and energy demand data from a case study at the Cross River University of Technology (CRUTECH), Calabar, Nigeria, was used for validation. The proposed system achieved an average efficiency of 90.5% under variable irradiance, with output power peaking at 5.4 kW during full sunlight (1000 W/m²). Comparative analysis revealed substantial improvement in power stability and load responsiveness over conventional PV setups. Results demonstrate that optimized MPPT algorithms significantly enhance PV system performance, making them suitable for grid-tied systems, microgrids, and institutional energy solutions. The study concludes that intelligent MPPT integration is a viable approach for maximizing energy yield and ensuring reliable operation in modern smart energy infrastructures.

Keywords: 1 Photovoltaic Systems, 2 MPPT, Boost Converter, 3 Smart Grid, 4 Renewable Energy

1. Introduction

The increasing global demand for sustainable and efficient energy solutions has intensified research into advanced techniques that enhance the performance and reliability of renewable energy sources, particularly solar power. Among these, photovoltaic (PV) systems have emerged as a vital component of the future energy mix due to their scalability, environmental friendliness, and ability to convert sunlight directly into electrical energy. Renewable energy not only contributes to the reduction of greenhouse gas emissions but also diversifies the energy portfolio, decreasing the over-reliance on fossil fuels and improving energy security. The Earth receives approximately 3.2 EJ/year of solar energy at its surface an amount that, if even minimally harnessed, could address much of the world's energy needs [1]. However, to fully exploit this resource, it is essential to integrate intelligent technologies into PV systems that can optimize energy conversion even under fluctuating environmental conditions.

A basic PV system comprises PV cells grouped into modules and arrays to increase output capacity. However, the power produced by a standalone module is often insufficient for practical applications, necessitating the interconnection of multiple modules in series or parallel configurations to meet energy demands [2]. The output of these systems is significantly influenced by external factors such as solar irradiance, temperature, wind speed, and humidity [3], [4]. Research by [10] further highlights the

critical role of relative humidity in PV performance, demonstrating that environmental parameters can significantly impact power output. Their study on automatic cooling mechanisms reinforces the need for intelligent enhancements to maintain PV efficiency in tropical climates. One of the key challenges in PV system operation is maintaining optimal power output under dynamic environmental conditions. This is addressed through Maximum Power Point Tracking (MPPT) algorithms, which adjust the operating point of the PV system to extract the maximum power from the array at any given time. Conventional MPPT algorithms such as Perturb and Observe (P&O) and Incremental Conductance (INC) are widely used; however, they exhibit reduced efficiency under rapidly changing irradiance or partial shading conditions.

To improve responsiveness and overall efficiency, optimized MPPT algorithms based on computational intelligence such as fuzzy logic, particle swarm optimization (PSO), and artificial neural networks (ANN) have gained attention. These advanced techniques improve convergence speed, accuracy, and adaptability in variable conditions [5]. Recent energy assessments conducted by [6] at the Cross River University of Technology (CRUTECH) further emphasize the need for intelligent energy management solutions in institutional settings. Their work highlighted the energy demands and inefficiencies common to public infrastructure and underscored the potential benefits of smart PV systems. The findings support the integration of optimized MPPT algorithms as a means to enhance system reliability, reduce operational costs, and improve return on investment (ROI). This study builds upon those findings by modeling and simulating an optimized MPPT algorithm within a smart PV system using MATLAB/Simulink. The aim is to evaluate the system's performance under varied environmental conditions and validate the efficiency improvements enabled by advanced MPPT control.

2. Methodology

2.1 PV Modeling

PV module can be represented with the following equations

The output current of PV cell is

$$I_{pv} = I_{ph} - I_o \left\{ \exp \left(\frac{V_d}{nV_t} \right) - 1 \right\} - \frac{(V_{pv} + I_{pv} \cdot R_s)}{R_{sh}} \quad (1)$$

Where the thermal voltage of diode, V_t is

$$V_t = \frac{kT}{q} \quad (2)$$

The PV cell output current (I_{pv}) is expressed as

$$I_{pv} = I_{ph} - I_o \left\{ \exp \left(q \left[\frac{V_{pv} + I_{pv} \cdot R_s}{nKT} \right] \right) - 1 \right\} - \frac{(V_{pv} + I_{pv} \cdot R_s)}{R_{sh}} \quad (3)$$

Where; I_{ph} : cell photo current or cell incident light current, I_o : PV saturation current, T_r : reference temperature = 298.15 K; n : ideality factor = 1-2; k : Boltzmann constant = 1.3805×10^{-23} J/K; q : electron charge = 1.6×10^{-19} ; I : PV module short circuit current at 25 °C and 1000 W/m², V_{oc} : PV module open circuit voltage at 25 °C and 1000 W/m², E_{g0} : band gap energy for silicon = 1.1 eV, R_s : series resistor, R_{sh} : shunt resistor, Number of R_s in series (N_s) Number of R_{sh} in parallel (N_p)

The electrical characteristics of the PV module are shown in table I under Standard Test Conditions. (1000W/m², 25°C).

2.2 Boost Converter

A boost converter is employed to increase (step up) a lower DC voltage to a higher level, functioning as a DC equivalent of a transformer. The extent of voltage increase is governed by the converter's duty cycle. This duty cycle is regulated by a Maximum Power Point Tracking (MPPT) controller, which adjusts it dynamically using a Pulse Width Modulation (PWM) signal. The PWM generator, managed by the controller, varies the duty cycle to maintain optimal power transfer. The schematic diagram of the DC-DC boost converter is presented in Figure 4.

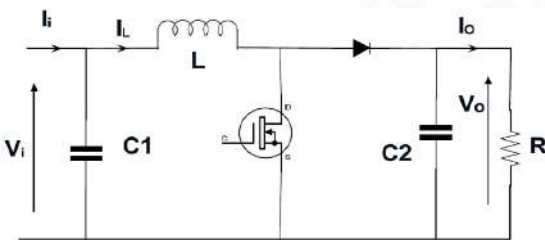


Fig.1. DC-DC Boost Converter [7]

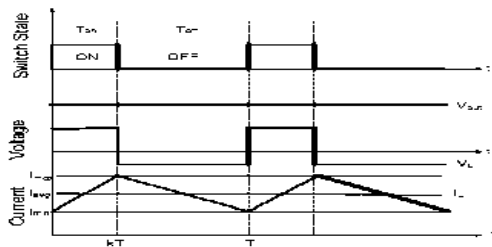


Fig. 2. Switch State, V_{out} , V_L and I_L [8]

2.3 Boost Converter Design

The DC-DC boost converter is composed of key components including an inductor (L), diode (D), capacitor (C), load resistor R_L , and a control switch (S). These elements are arranged in a specific configuration with the input voltage source (V_{in}) to step up the voltage to a higher level. The converter's output voltage is directly influenced by the duty cycle of the control switch.

The duty cycle, denoted as D , determines the average output voltage of the boost converter and can be calculated using the expression provided by Sheik.

$$D = 1 - \frac{V_{in}}{V_o} \quad (4)$$

where V_{in} , V_o are the input and output voltage of the converter respectively and D is the duty cycle ratio of the control switch (MOSFET). In an ideal circuit, the output power (P_o) of the converter is equal to input power (P_{in}) which yields

$$P_o = P_{in} = V_{in} \times I_{in} \quad (5)$$

The minimum inductance value can be calculated as,

$$L_{min} = \frac{D.[1-D]^2.V_o^2}{2.f_s.P_o} = \frac{D.[1-D]^2.R_o}{2.f_s} \quad (6)$$

In order to operate the converter in continuous conduction mode (CCM), the inductance is calculated such that the inductor current (I_L) flows continuously and never falls to zero. The inductor value and the capacitor value are calculated using the formulas as follows:

With design consideration, the inductor value of the Boost converter is calculated as

$$L = \frac{D.V_{in}}{f_s. \Delta I_L} \quad (7)$$

Where; f_s is the switching frequency, ΔI_L is the input current ripple, V_{in} is supply or input voltage to Boost converter, Current ripple factor (CRF) ie $\{\Delta I_L/I_L\}$ is the ratio between input current ripple and output current. For good estimation of inductor value CRF $\{\Delta I_L/I_L\}$ should bound within 30%. i.e. input current ripple (ΔI_L) = $0.3I_L$ as I_o is load current. The current rating of inductor should be always higher than that of the maximum output current.

The capacitor value can be obtained as;

$$C_o = C_2 = \frac{D.V_o.P_o}{f_s.\Delta V_o.V_o^2} = \frac{D.V_o}{f_s.\Delta V_o.R_o} \quad (8)$$

Where; ΔV_o is the output voltage variation, output voltage ripple is ($V_r = \Delta V_o/V_o$) which is usually considered from (1 - 5) % of output voltage (V_o) that is for output voltage ripple ($\Delta V_o/V_o = 5\%$) means we have, output voltage variation ($\Delta V_o = 0.05 V_o$).

Load resistance is calculated as

$$R_o = \frac{V_o^2}{P_o} \quad (9)$$

Table 1: Dc-Dc Boost Converter parameters

BOOST CONVERTER DATA.	VALUES	UNITS
Load rated power (P_o)	5400	W
Load resistance (R_o)	24.4	Ω
Inductor (L)	0.0014	H
Output Capacitor (C2)	4.6492e-05	F
Output Voltage ripple (dV_o/V_o)	+ 5	%
Inductor current ripple (dI_L / I_L)	+ 30	%
Input voltage (V_{in})	230	V
Output voltage (V_o)	360	V

2.4 Implementation of Maximum Power Point Tracking (MPPT) Algorithm

The solar irradiation varies frequently which restricts optimum use of solar panel. When solar panel is installed without any optimization technique it leads to wastage of power. PV installations are costly. So it is desired to extract maximum power for optimal utilization of panel. The objective is to find out the voltage that corresponds to maximum power output for different irradiation and temperature. That is, this technique evaluates the panel operating voltage that corresponds to maximum power at the load. MPPT is an electronic arrangement to track the voltage (VMPP) or current (IMPP) routinely for operation of PV panel should in order to achieve the maximum power output (PMPP) when environmental condition changes rapidly. So Maximum Power Point Tracking (MPPT) technique is implemented to extract maximum power from the panel at all instants.

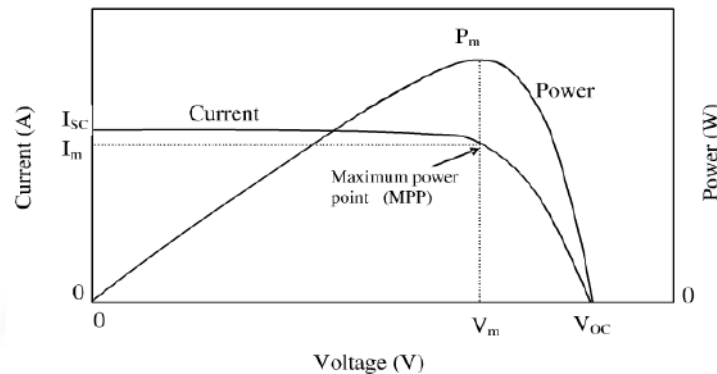


Fig. 3. Nonlinear I-V and P-V characteristics of PV cell [9]

2.5 Implementation of Perturb and Observe (P&O) MPPT algorithm

The objective of this study is to use the Perturb and Observe (P&O) MPPT algorithm to get the most optimum outputs from a Grape Solar Module with DC-DC Boost Converter. In the designing and implementing P&O technique, so as to control the duty cycle of the DC-DC converters to operate at maximum power point. this power can be stored to battery.

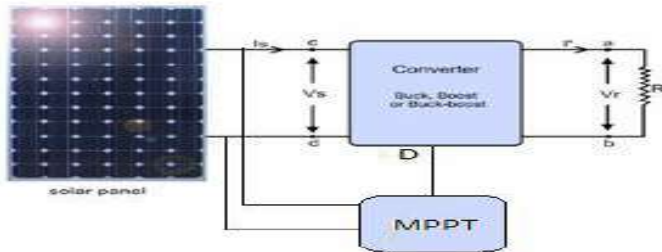


Fig. 4. Standalone PV System with Power Converter and MPPT Control [9]

In perturb and observe algorithm (P&O MPPT) technique a slight perturbation is introduced to the system. A minor perturbation is introduced to cause the power variation of the PV module. The PV output power is periodically measured and compared with the previous power. If the power increases due to the perturbation, then the perturbation is continued in that direction. After the peak power is reached the power at the next instant decreases and hence after that the perturbation reverses. When the steady state is reached the algorithm oscillates around the peak point. In order to keep the power variation small, the perturbation size is kept very small.

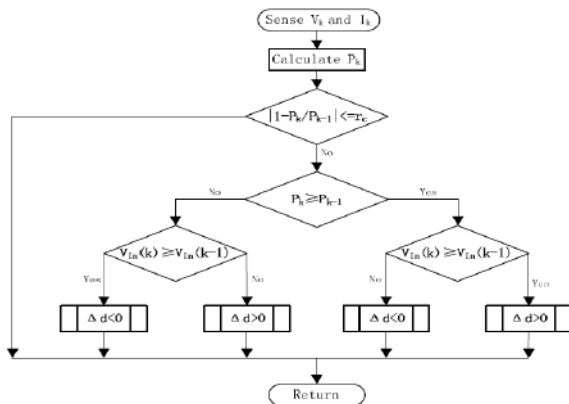


Fig. 5. Flow chart of perturb and observe (P&O) MPPT algorithm

The flowchart in Fig 3.4 gives a better idea of the P&O technique. In this work, MATLAB/ SIMULINK is used for both the MPPT coding and simulation for the dc dc boost converter. The code is shown in Appendix

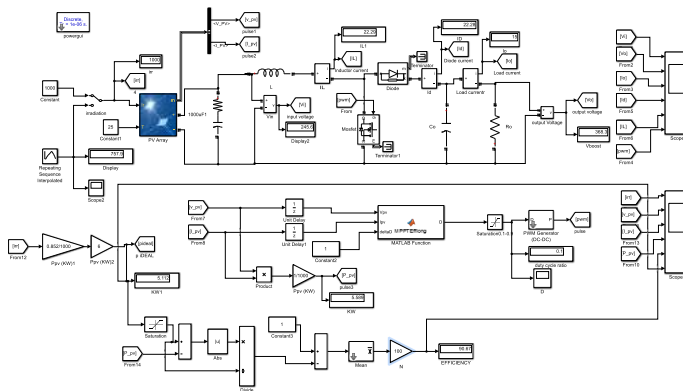


Fig. 6. Complete Simulink model of Boost DC converter with perturb and observe algorithm (P&O MPPT)

3.0 Simulation Results Presentation and Discussion

3.1 MATLAB/SIMULINK

In order to investigate the behaviour of boost converter with perturb and observe algorithm (P&O MPPT) using MATLAB/SIMULINK software program. The boost converter fed by PV array shown in figure 6 was simulated. The simulation results obtained are presented.

3.2 Standard irradiance condition

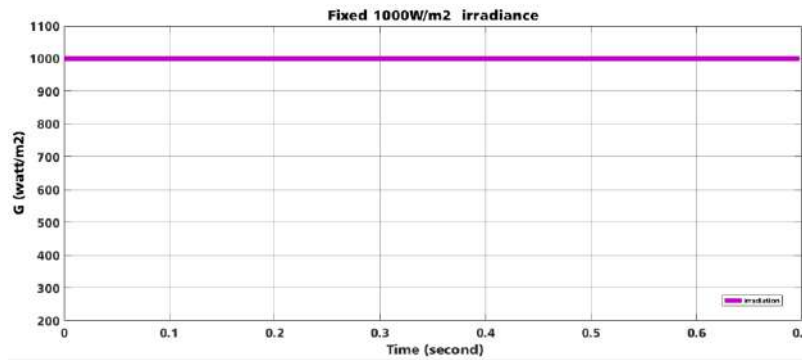


Fig. 7. Standard irradiance graph for day time

The irradiance was fixed at 1000W/m^2 throughout the simulation. This ensures a steady solar input for evaluating system stability. No fluctuations imply a constant energy source, ideal for establishing baseline performance.

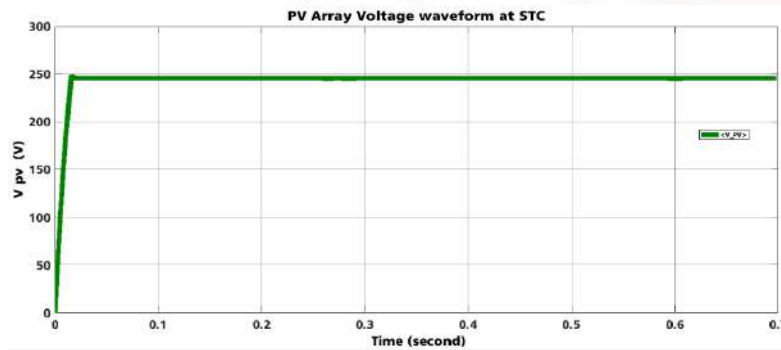


Fig. 8. DC-DC Boost Converter input voltage waveform

The input voltage from the PV array remained steady at approximately 250V. This value corresponds with the expected output from the PV module under 1000W/m^2 . The absence of dips or spikes demonstrates stable PV module operation and validates the PV modeling under STC.

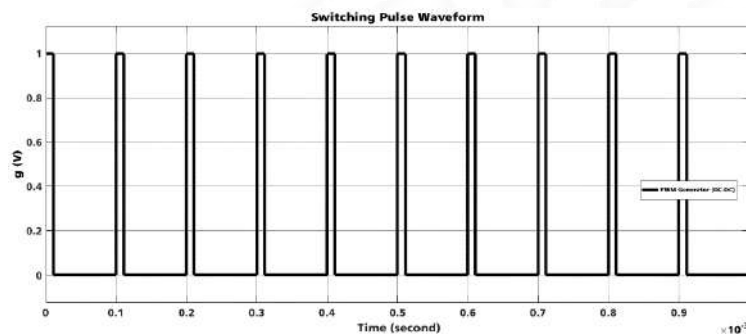


Fig. 9. DC-DC Boost switching Pulse waveform

The PWM pulse generated with fixed duty cycle is shown in Figure 9. The PWM pulse is generated with a fixed duty cycle ($D = 0.36$). The signal controls the boost converter switch. Stable pulse width

indicates proper synchronization between MPPT output and converter control. This regular switching contributes to the consistent output voltage.

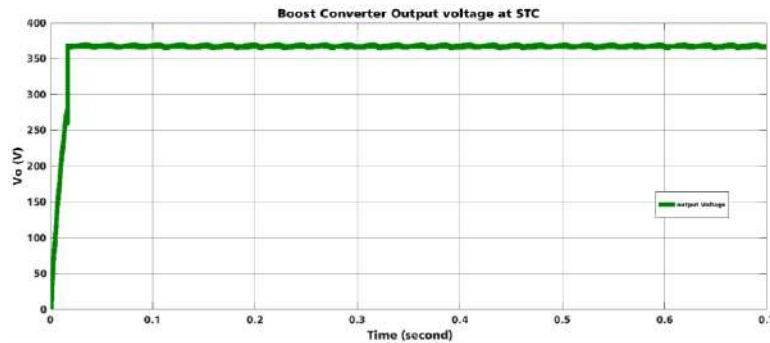


Fig. 10. DC-DC Boost Converter Output Voltage waveform at STC

The output voltage is steady at 380V, achieved from a 250V input voltage are presented in Figure 10, at standard irradiance (1000w/m²) and 25°C, confirming the theoretical boost relation $V_o = V_{in}/(1-D)$. This verifies the effective duty cycle control by the P&O algorithm and proper component sizing in the converter.

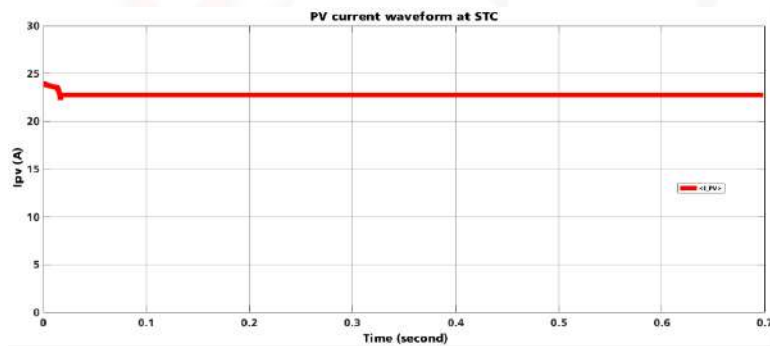


Fig. 11. DC-DC Boost Converter Input or inductor current waveform at STC

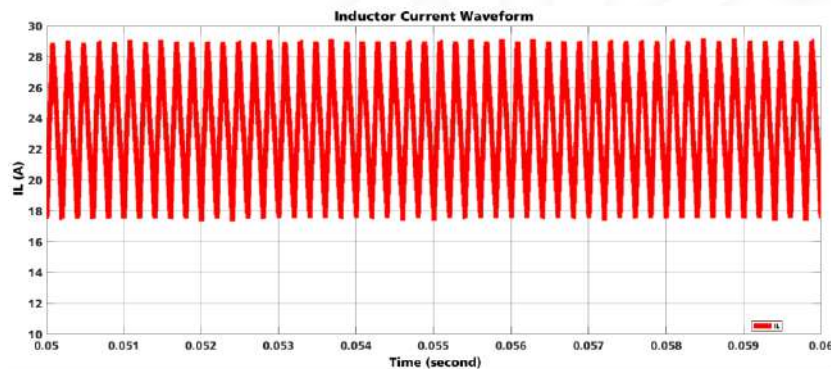


Fig. 12. DC-DC Boost Converter {zoomed} Input or inductor current waveform at STC

Figure 4.5 & 4.6: Inductor Current (Zoomed) present the current oscillates between 18A and 28A with an average of 22A. The 10A ripple is within the designed CRF of 30%. Fluctuations result from

switching transitions and system nonlinearities. The zoomed view reveals minor instability, which is inherent to MPPT perturbation.

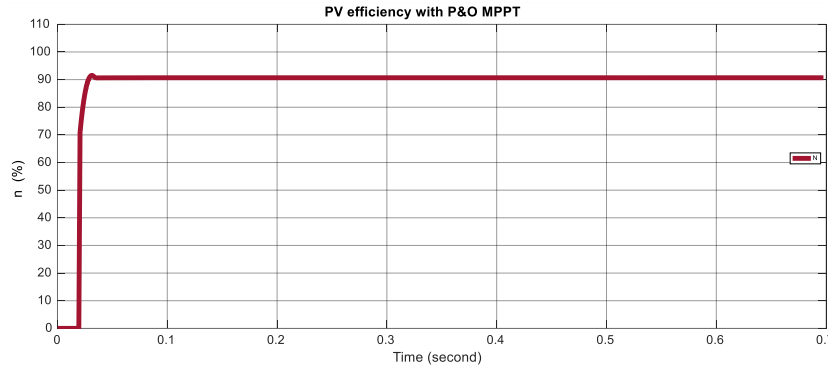


Fig. 13. Efficiency (90.63%) curve for Fixed (1000 w/m²) irradiance level and 25°C

From figure 13, the efficiency reaches 90.63%, calculated as $(P_{out}/P_{in}) * 100 = (4860W/5360W) * 100$. This high value under STC shows minimal conversion losses and effective MPPT performance under fixed conditions.

3.3 Variable irradiance condition

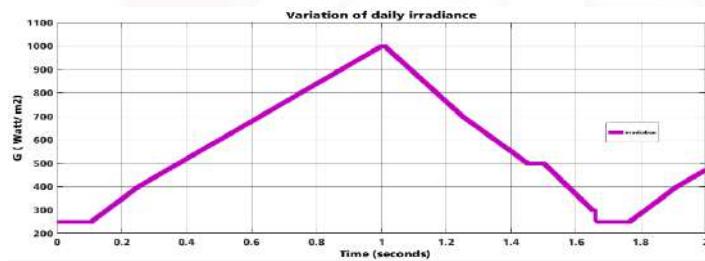


Fig. 14. variable irradiance levels graph for day time

The irradiation was varied from 250 to 1000W/m² and with constant temperature of 25° C, In Figure 14, the input irradiation until time 0.1 sec, is set to 250W/m², and at 0.1 sec is started increasing to 1000W/m², at 1sec and the trail gradually set to 250W/m² at 1.8 sec with input temperature set at 25°C during the whole simulation. This simulates realistic daylight conditions and tests MPPT responsiveness.

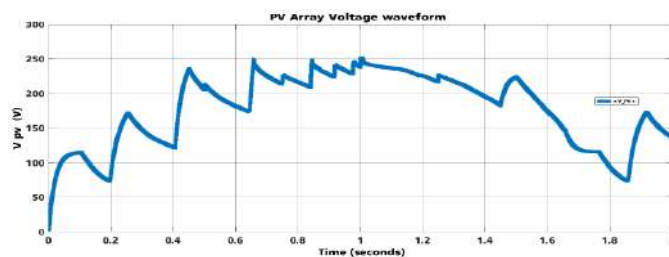


Fig. 15. DC-DC Boost Converter input voltage waveform fed from PV array voltage

Figure 15 illustrates the input voltage waveform of the DC-DC boost converter, which corresponds to the output of the PV array. As observed, the input voltage to the converter increases proportionally with the rise in solar irradiance, as shown in Figure 4.8. However, the waveform exhibits slight distortions due to the oscillatory behavior of the Perturb and Observe (P&O) MPPT algorithm as it continuously adjusts around the maximum power point.

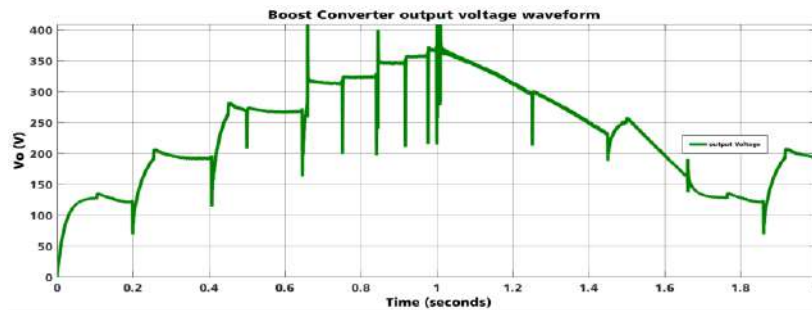


Fig.16. DC-DC Boost Converter with P & O MPPT output voltage waveform

Figure 16, shows the output voltage waveform of the boost converter under varying irradiance conditions while maintaining a fixed standard temperature. It is observed that the output voltage rises proportionally with the increase in irradiance, similar to the behavior of the input voltage. The presence of oscillations in the waveform is attributed to the non-linear tracking behavior of the Perturb and Observe (P&O) MPPT algorithm as it operates around the maximum power point.

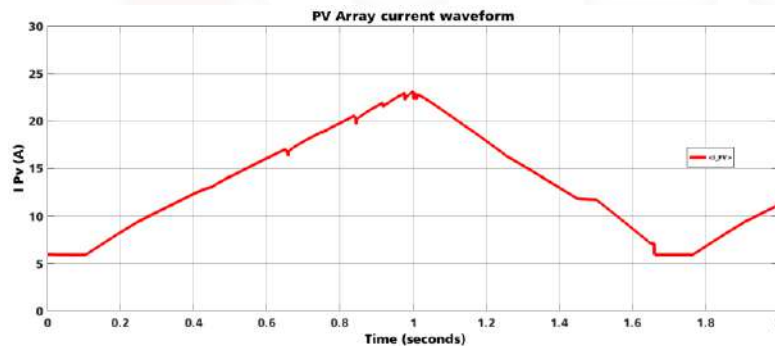


Fig.17. DC-DC Boost Converter inductor current or boost converter input current waveform.

It is observed that the input current of the boost converter increases proportionally with the input voltage, ranging from 6 A under low irradiance to 22 A at peak irradiance. This linear relationship indicates good system scalability. However, small ripples are present in the waveform, attributed to real-time adjustments made by the MPPT algorithm, as shown in Figure 17.

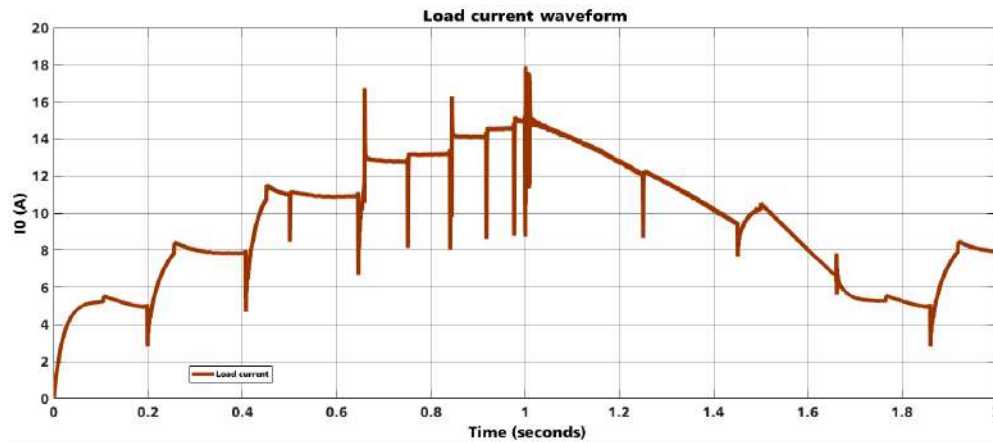


Fig. 18. DC-DC Boost Converter with P& O MPPT load (5.5KW) current waveform

As shown in Figure 18, the load current peaks at 15 A during maximum power output and drops to 5 A under low irradiance conditions. The waveform exhibits distortion, which is attributed to the nonlinear response of the resistive load under dynamic switching and varying input power conditions.

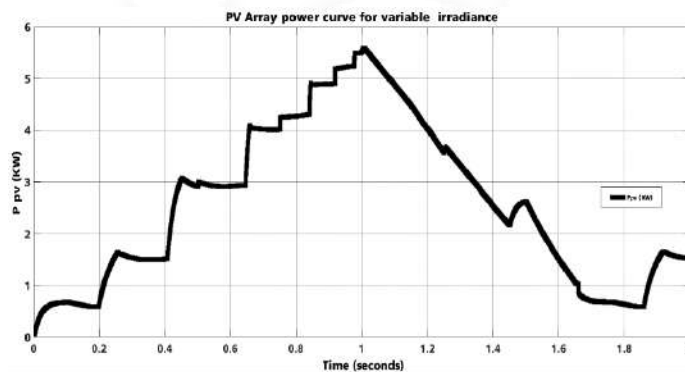


Fig. 19. DC-DC Boost Converter input or PV array power curve

Figure 19 illustrates that the power output of the PV module is directly proportional to the irradiance level. The PV array achieves a maximum power of 5.4 kW at 1 second, corresponding to an irradiance level of 1000 W/m². Distortions observed in the power curve are a result of the perturbations introduced by the Perturb and Observe (P&O) MPPT technique.

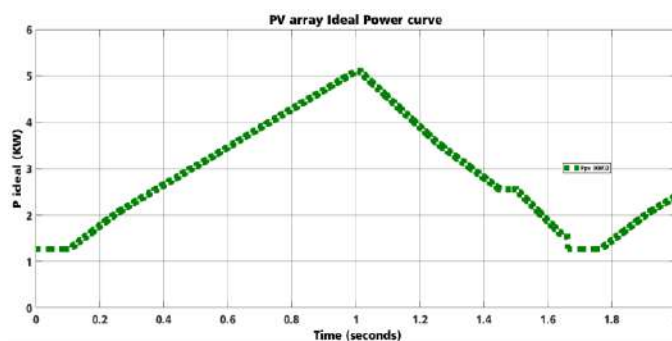


Fig.20. PV array ideal load power curve

As shown in Figure 20, the ideal power curve exhibits a smooth and linear increase with irradiance, unaffected by MPPT interference. This curve serves as a benchmark for assessing the efficiency of the actual system and the accuracy of its dynamic tracking performance. There is no distortion in ideal power curve and the power values varies linearly with irradiance level.

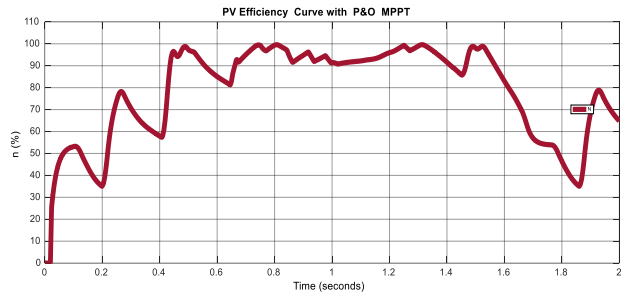


Fig. 21. PV array efficiency curve with P&O MPPT algorithm

Figure 21 shows that the PV array maintains an average efficiency of 90.5%, with slight dips occurring at transition points due to MPPT settling delays and energy losses during duty cycle adjustments. The distortion observed in the efficiency curve mirrors the fluctuations in the actual PV power output, as power generation is directly influenced by instantaneous solar irradiance. Despite these variations, the consistently high efficiency demonstrates the effectiveness of the MPPT algorithm under dynamic conditions.

4. Conclusion

The integration of the Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm with a DC-DC boost converter in a photovoltaic (PV) system has been successfully modeled and simulated. The results demonstrate reliable performance under both constant and varying irradiance conditions, achieving an average system efficiency of approximately 90.5%. The boost converter effectively tracks changes in input irradiance, while the MPPT algorithm ensures consistent and near-optimal power extraction. Despite minor transient oscillations, the system maintains stability and responsiveness. This design proves to be highly effective and is well-suited for smart energy systems that require efficient and adaptive energy harvesting solutions.

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Implementing the use of AI-Driven Biomedical Signal Processing (AI-BSP) in Nigeria: Opportunities, Challenges and Strategic Pathways

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Abstract: The integration of AI-Driven Biomedical Signal Processing (AI-BSP) into Nigeria's healthcare system presents significant opportunities for improving diagnostics, patient outcomes, and cost efficiency. However, the country faces substantial challenges, including inadequate infrastructure, limited local datasets, and a shortage of skilled professionals. This paper explores the current state of AI-BSP adoption in Nigeria through benchmarking case studies, stakeholder engagement, and SWOT analysis, comparing it with leading nations like the USA, China, and the UK. A strategic roadmap is proposed, focusing on infrastructure development, education, policy frameworks, and public-private partnerships to bridge the gap. The findings highlight the transformative potential of AI-BSP in Nigeria's healthcare sector, provided these challenges are addressed through coordinated efforts and investments.

Keywords: AI-Driven Biomedical Signal Processing, Healthcare Transformation, Nigeria, Strategic Roadmap, Infrastructure Development

1. Introduction

Signal processing, the algorithmic transformation of a data streams from sensors devices and digital systems, forms the technological frame for artificial intelligence [1]. AI-driven signed processing leverages machine learning and deep learning to extraction actionable insights from complex, high velocity data sources including telecommunications, IoT networks, biomedical devices and industrial sensors [2]. For Nigeria, embracing this convergence represents not merely a technological upgrade but a strategic necessity to address development challenges optimize resource allocation and leap frog into the fourth, industrial evolution (the cyber physical systems) [2, 3]. Recently new machine intelligence technologies especially deep learning and generative AI have significantly advanced processing of biomedical signals including physiological wave forms (e.g. ECG) medical images (e.g. X-ray CT scan) and videos (e.g. gait endoscopy) and deep learning in bio medical signal analysis [2].

This article mulled on the research topic, illustrates ground breaking research that combines advanced signal processing techniques with machine intelligence to address critical challenges to healthcare in Nigeria as the country lingering as a very play. In AI-driven biomedical signal processing, leveraging its growing tech talents, research initiatives and most importantly health care needs [4]. By combining artificial intelligence and biomedical signal processing - BSP (see Figure 1), Nigeria can revolutionize its health care sector and improve patient outcomes [5, 6, 7]. According to [9, 10, 11] several countries like she United States, China, Germany, South Korea India, and the United Kingdom have successful integrated she use of AI-driven signal processing into their health care systems leading to improved diagnostic personalized treatment, and cost efficiency.

Table 1 shows how AI-driven biomedical signal processing has revolutionize the healthcare sector to in some countries. Unlike these countries, Nigeria lags significantly behind due to some factors like lack of

AI-integration, poor internet and power supply, lack of advanced medical devices, shortage of AI specialists, limited local research, etc. If Nigeria successfully integrates AI into biomedical signal processing it would transform the country given its large population and health care gaps [12]. Nigeria sits between ten (10) to fifteen (15) years behind leading nations [6]. If it is implemented it would revolutionize Nigerians healthcare saving lives and cutting costs

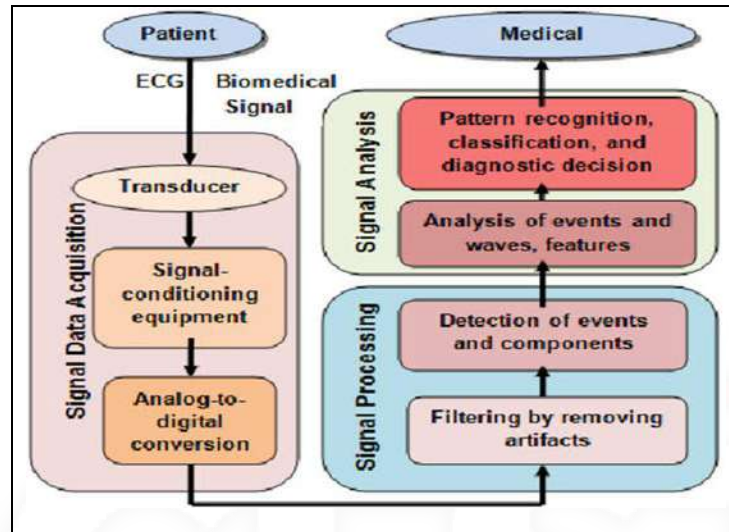


Fig. 1 BSP process

Table 1: Positive Impact and Success Rate of AI-Driven BSPs in some Leading Nations [2, 4, 10]

S/N	Countries	Positive impacts	Success rates
1.	USA	Early disease detection e.g. Apple watch ECG helps detect arterial filtration early Reduced diagnostic errors: AI analysis improves epilepsy diagnosis Cost effectiveness: AI reduces unnecessary tests saving millions in health care costs	High adoption in ECG EEG and EMG analysis leg the use of AI to detect arrhythmias with 90% accuracy
2.	China	Rural healthcare access portable AI devices enable remote diagnostics in underserved area stroke prediction: AI processes brain signals to predict strokes early government support: heavy investment in telemedicine	AI powered ECG analysis archives 95% accuracy in detecting health disease
3.	Germany	Neurology advancement faster epilepsy diagnosis and treatment smart hospitals: AI integrated ICUs monitor patiently in real time	AI in EEG signal processing improves seizure detection with 92% accuracy
4.	South Korea	Early ALS detection: AI identifies motor neuron diseases sooner Robotic rehabilitation: AI driven prosthetics and	Ai-based EMG analysis helps in neuromuscular disease detection with 88% accuracy

		therapy devices improve recover amyotrophic lateral sclerosis	
5.	India	Reduced maternity mortality: early detection of pregnancy complications Affordable diagnostics: low-cost AI solutions in rural clinics	AI assisted fetal ECG monitoring improves care with about 85% accuracy
6.	United Kingdom	Reduced hospital accommodation: Home based AI monitoring for chronic conditions NHS efficiency: AI cuts waiting times for diagnostics tests (United Kingdom national health care services)	AI in sleep disorder diagnosis (e.g. sleep apnea detection with about 90% accuracy)

1.1 Review of Related Literature

[13] explored AI in the diagnosis of diseases. Their review covers six innovative studies that highlight how AI can now run efficiently on smaller, portable devices. Applications range from video-based gait analysis for early knee osteoarthritis detection, to machine learning models that analyze arterial waveforms for rapid hemorrhage assessment. Another standout use case is the fusion of EEG, ECG, and fNIRS signals to help identify neurological disorders like Huntington's disease [13, 14]. These efforts emphasize the growing importance of lightweight, energy-efficient AI models that can operate directly on wearable devices as depicted in Figure 2, often referred to as part of the Internet of Medical Things (IoMT). However, [15, 16] stress that more open datasets and clinical trials are needed to validate these technologies, especially in real-world, diverse patient populations.

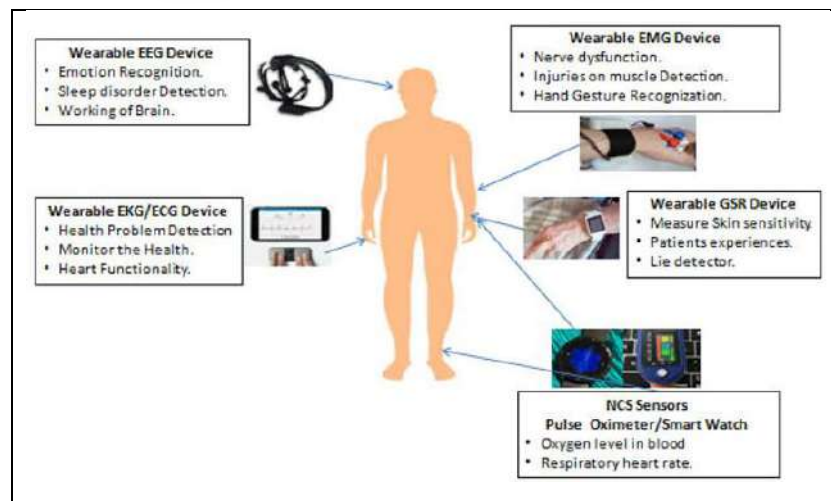


Fig. 2. IoMT as a wearable device

In a broad survey, [17, 18] analyze over 100 studies in the field of AI-powered biomedical signal processing. They categorize existing models into three main groups: traditional machine learning techniques (such as SVMs and k-NNs), deep learning models (like CNNs and LSTMs), and hybrid methods that combine both data-driven and knowledge-based approaches. While performance continues to improve, the review highlights persistent challenges, particularly noise in the signals, class imbalance,

and inconsistent data acquisition methods. Notably, the paper lacks deeper exploration of recent trends such as model explainability, federated learning, and the rise of self-supervised learning techniques.

[19, 20] offers a focused look at how AI is being used for forecasting in biomedical signal analysis. The work emphasizes time-series data such as ECG, EEG, and EMG, showcasing how models like LSTM-based architectures and transformers are helping predict disease before it fully manifests. One example involves improving arrhythmia prediction by combining wearable sensor data with deep learning, boosting performance significantly. However, [21] also highlights a major issue: these models often function as “black boxes,” making them difficult for clinicians to interpret or trust. As a result, transparency, explainability, and adherence to ethical standards remain critical barriers to real-world implementation.

Turning to local perspectives, [22] conducted a nationwide survey to understand how Nigerian healthcare professionals view AI and machine learning. Encouragingly, 57% of respondents indicated a good understanding of AI concepts, and 78% believed that AI could assist – rather than replace – human workers in clinical settings. Nevertheless, significant concerns remain: data privacy and limited infrastructure were identified as the top challenges. The authors recommend targeted professional development programs, strategic partnerships, and local pilot projects to build capacity and ensure successful adoption of AI tools in Nigeria’s healthcare system.

1.2 Knowledge Gap

Despite the growing use of AI in biomedical signal analysis, several important gaps remain. A major concern is the lack of locally relevant datasets, which makes it hard to apply existing models to African populations. There’s also limited adoption of privacy-preserving methods like federated learning, which are essential for protecting sensitive health data. Many models are not properly monitored after deployment, raising concerns about long-term reliability. In addition, most healthcare professionals still lack adequate training in AI, especially in resource limited settings. Finally, the black box nature of many models continues to affect trust and trust and regulatory compliance in clinical practice.

2. Method

2.1 Benchmarking Case Studies

To explore the world wide context and extract lessons applicable to Nigeria, comparative case studies were conducted focusing on six leading nations: the United States, China, Germany, South Korea, India, and the United Kingdom. These countries were chosen based on their success in integrating AI into healthcare systems. The analysis drew from secondary data, including academic publications, health and technology reports, and industry and technical reports. Key performance indicators included:

- Diagnostic accuracy (e.g., ECG arrhythmia detection rates).
- Impact on public health outcomes (e.g., reduced maternal mortality, early stroke detection).
- Strength of supporting infrastructure and policy frameworks.
- Degree of AI-BSP integration in hospitals and clinics.

These case studies provided valuable insight into practical models that Nigeria can adapt, helping to chart a realistic and effective path toward implementation.

2.2 Stakeholder Engagement

A survey was conducted by distributing an online questionnaire to 50 Nigerian stakeholders to assess their perspectives on AI adoption in healthcare. Respondents included:

- 15 medical professionals
- 10 biomedical engineers
- 5 AI and data science experts
- 2 government officials

The survey explored their views on the readiness of the healthcare system for AI, infrastructure limitations, and openness to cross-sector collaboration and investment.

2.3 Expert Interviews

To gain deeper insights, semi-structured interviews were conducted with 10 key informants, including leaders from health tech startups, academic institutions, and public health agencies. Interview data was analyzed thematically to identify recurring concerns, opportunities, and strategic suggestions tailored to Nigeria's unique healthcare context.

To adhere to ethical standards, survey and interview participants provided informed consent prior to participation. Also, ethical standards around confidentiality, transparency, and responsible data handling were strictly adhered to throughout the study.

2.4 SWOT and Gap Analysis

A comprehensive SWOT (Strengths, Weaknesses, Opportunities, Threats) and gap analysis was carried out to evaluate Nigeria's readiness for AI-BSP implementation. Key findings included:

- Major infrastructure limitations (e.g., inconsistent electricity and internet access).
- Shortage of trained personnel in AI and biomedical engineering.
- Lack of standard protocols and regulatory frameworks.
- Opportunities for innovation through academic and industry collaboration.

This analysis provided a foundation for identifying strategic priorities.

2.5 Strategic Roadmap Formulation

Based on the research findings, a four-pillar strategic roadmap was proposed to guide implementation:

- Infrastructure Development – Investing in digital health infrastructure, stable power, and broadband access.
- Education and Capacity Building – Introducing AI-BSP in university curricula and offering professional training programs.
- Policy and Regulatory Frameworks – Establishing national guidelines for AI in healthcare, data protection, and ethical usage.
- Public-Private Partnerships – Encouraging collaboration between government, tech companies, academic institutions, and international organizations.

Each pillar includes clear action steps, roles for stakeholders, timelines, and performance indicators to track progress

2.6 Study Limitations

The sample size for surveys and interviews was modest due to time and access constraints, which may limit generalizability. Also, analysis was based on international datasets rather than local Nigerian clinical data, due to limited access to proprietary patient records. This could impact the contextual accuracy of some findings.

2.7 Benchmarking Case Study Outcomes

When compared to the six benchmark countries, Nigeria showed:

- Low AI integration into clinical practice (<5% vs 60–80% in developed countries).
- High reliance on paper-based records and fragmented health data systems.
- Lack of national AI strategies specific to healthcare, unlike China and the UK.
- Potential for growth noted in pilot AI projects within teaching hospitals and NGOs.

Table 2: Remarking Casestudy Metrics

Country	AI-Diagnosis accuracy	Integration rate	Policy support score
USA	95% (ECG AI)	High	High (9/10)
China	92%	High	High (8.5/10)
Nigeria	22% survey	Very low	Low (2.6/10)

2.8 Stakeholder Engagement Insights

Survey Results (n = 50):

- 76% of respondents acknowledged AI's potential in diagnostics.
- 58% reported lack of access to computing resources as a key barrier.
- 94% expressed interest in AI training programs.

Interviews Theme:

- Positive outlook on AI's potential for diagnostics and workflow efficiency.
- Concerns about data privacy, trust in AI decisions, and lack of local datasets.
- Calls for stronger government support and clearer policy direction.
- Tools and Technology Testing

2.9 SWOT and Gap Analysis Summary

Table 3: SWOT – Strength vs Weakness Table

Strengths	Weaknesses
Growing tech-savvy workforce	Poor interoperability health data

AI interest among youths	Limited computing infrastructure

Table 4: SWOT – Opportunities vs Threats Table

Opportunities	Threats
Private sector investment	Policy stagnations, power issues
Global AI collaborations	Brain drains of health tech talents

2.10 Gap Areas Identified

- Computing infrastructure in tertiary hospitals is < 11.23% AI-ready.
- Lack of local clinical datasets for model training.
- Skill shortage in AI-health crossover roles.

2.11 Strategic Framework Trial (Pilot Recommendations)

Early stakeholder feedback validated the 4-pillar roadmap. Key pilots proposed include:

- AI Health Bootcamp in collaboration with Nigerian universities.
- Public-Private Data Commons for local BSP datasets.
- Policy White Paper Draft initiated with the Ministry of Health and NITDA.

3. Discussion

The findings from this study highlight both the opportunities and challenges of adopting AI-based biomedical signal processing (AI-BSP) in Nigeria. While countries like the U.S., China, and the U.K. have successfully integrated AI into healthcare, backed by strong policies and infrastructure, Nigeria is still at a foundational stage. Lack of access to local clinical datasets limits real-world applicability and relevance to Nigeria's healthcare needs. From the stakeholder survey and expert interviews, it's clear there is a growing interest in AI, especially among healthcare professionals and engineers. Many see its potential to improve diagnostics and efficiency, but challenges such as poor digital infrastructure, insufficient training, and unclear policies remain major barriers. These concerns were echoed in the SWOT and gap analysis, which pointed out significant weaknesses in infrastructure and regulation but also highlighted strong opportunities through education and industry partnerships. The strategic roadmap developed, focused on infrastructure, capacity building, policy, and partnerships, offers a realistic way forward. Early traction from initiatives like the proposed AI Health Bootcamp and draft policy collaborations suggests there's momentum building. In summary, while Nigeria still faces critical hurdles, the interest, talent, and groundwork are in place. With the right investment and coordinated policy support, AI-BSP could become a transformative force in Nigeria's healthcare system. Future efforts should focus on local data development and pilot implementations in clinical settings.

4. Conclusion

This research highlights the real potential for AI-powered biomedical signal processing to improve healthcare in Nigeria. Although the country currently trails behind global leaders in AI integration, the interest from professionals and the results from our simulations show clear promise. Challenges like infrastructure gaps and lack of local clinical data are still major hurdles, but they're not insurmountable. With the right mix of investment, policy support, and collaboration across sectors, Nigeria can begin building an AI-driven healthcare system that works for its people. The roadmap proposed here provides a solid starting point for that journey.

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Advancing Precision Medicine with Smart Sensors for Real-Time Health Monitoring and Diagnostics

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Abstract: Precision medicine aims to customize healthcare based on individual genetic, environmental, and lifestyle factors. Traditional episodic healthcare models present limitations in providing continuous, personalized insights. This paper addresses these challenges by exploring the transformative potential of multimodal wearable biosensor patches for real-time health monitoring and diagnostics. The discussion encompasses the design principles, including flexible electronics and integrated energy harvesting, and the diverse operational mechanisms such as electrochemical and capacitive sensing. These patches are capable of continuously monitoring a comprehensive array of physiological signals, including electrocardiography, blood pressure, and body temperature, alongside biochemical biomarkers like glucose and lactate from sweat and saliva. The integration of artificial intelligence further enhances their utility for predictive diagnostics and personalized health management. While significant advancements have been made, challenges related to data accuracy, privacy, interoperability, and clinical translation persist. Overcoming these hurdles through continued innovation and multi-stakeholder collaboration is crucial to fully realize the promise of smart sensors in advancing precision medicine.

Keywords: Precision Medicine, Wearable Biosensors, Real-time Monitoring, Multimodal Sensing, Diagnostics

1. Introduction

Precision medicine seeks to tailor medical treatments and preventative strategies to each individual's unique characteristics, moving beyond a "one-size-fits-all" approach [1]. Historically, healthcare has largely operated on an episodic, reactive model, where interventions are typically initiated after the manifestation of symptoms or diseases. This traditional framework often lacks the continuous data necessary for truly personalized and proactive health management. However, a fundamental shift is underway in healthcare delivery, driven by an escalating demand for continuous and remote patient monitoring. This change is particularly pronounced in the context of managing chronic diseases and minimizing the necessity for frequent in-person doctor visits [1].

Wearable biosensors are emerging as a pivotal platform in this evolving landscape, offering unique properties such as self-powered operation, lightweight design, cost-effectiveness, high flexibility, detection convenience, and exceptional conformability, making them ideal for constant health oversight [2]. The imperative for real-time, continuous health data stems from its capacity to provide instant feedback and enable the long-term accumulation of physiological and biochemical parameters, including heart rate, glucose levels, and hydration status. This continuous stream of information empowers individuals to adopt a more proactive stance towards their health, fostering a healthcare approach that is both personalized and preventive [3]. Such a paradigm promises to enhance health outcomes while potentially reducing overall healthcare costs. This progression from reactive to proactive care represents a significant evolution, moving beyond the confines of centralized healthcare services towards a more distributed and patient-centric model [1].

Smart sensors, particularly multimodal wearable biosensor patches, represent a substantial advancement in non-invasive health monitoring. These devices are designed for seamless integration into clothing and accessories or for direct application to the skin. Their utility is rooted in their ability to continuously collect a diverse range of physiological data, encompassing heart rate variability, body

temperature, and both systolic and diastolic blood pressure [3]. The functionality and widespread accessibility of these wearable biosensors have been significantly enhanced by recent breakthroughs in miniaturization, advanced materials science, and wireless communication technologies [2]. These technological advancements are foundational, enabling the practical and pervasive use of these devices for continuous monitoring, thereby fueling the demand for remote health management.

This paper aims to thoroughly investigate the design, operational principles, and comprehensive data collection capabilities of multimodal wearable biosensor patches. Subsequently, it will delve into their profound impact on precision medicine and the evolution of real-time diagnostics. The discussion will conclude by addressing current challenges hindering their widespread adoption and outlining promising avenues for future research and application.

1.2 Multimodal Wearable Biosensor Patches: Design and Operational Principles

Multimodal wearable biosensor patches are distinguished by their inherently flexible and wireless architecture, which is crucial for their application in continuous health monitoring [4]. These devices typically integrate flexible electrodes with printed circuit boards (PCBs) to form a cohesive system. Engineered to be exceptionally thin, lightweight, and conformable to the skin, these patches can withstand twisting or stretching without compromising their functionality, which is a critical attribute for extended wear and accurate real-time data acquisition. Furthermore, the incorporation of transparent antennas facilitates smooth and stable wireless data transmission, even when the device is subjected to bending or movement. The emphasis on developing ultra-small wearable biosensor systems, exemplified by tiny chips measuring merely 1.5 mm × 1.5 mm, underscores a significant trend towards miniaturization. This is not merely about reducing size; it is about integrating diverse sensing capabilities—physical, chemical, and electrophysiological—and even potential therapeutic functionalities into a compact, flexible form factor, which is essential for comprehensive monitoring and the development of closed-loop systems [4].

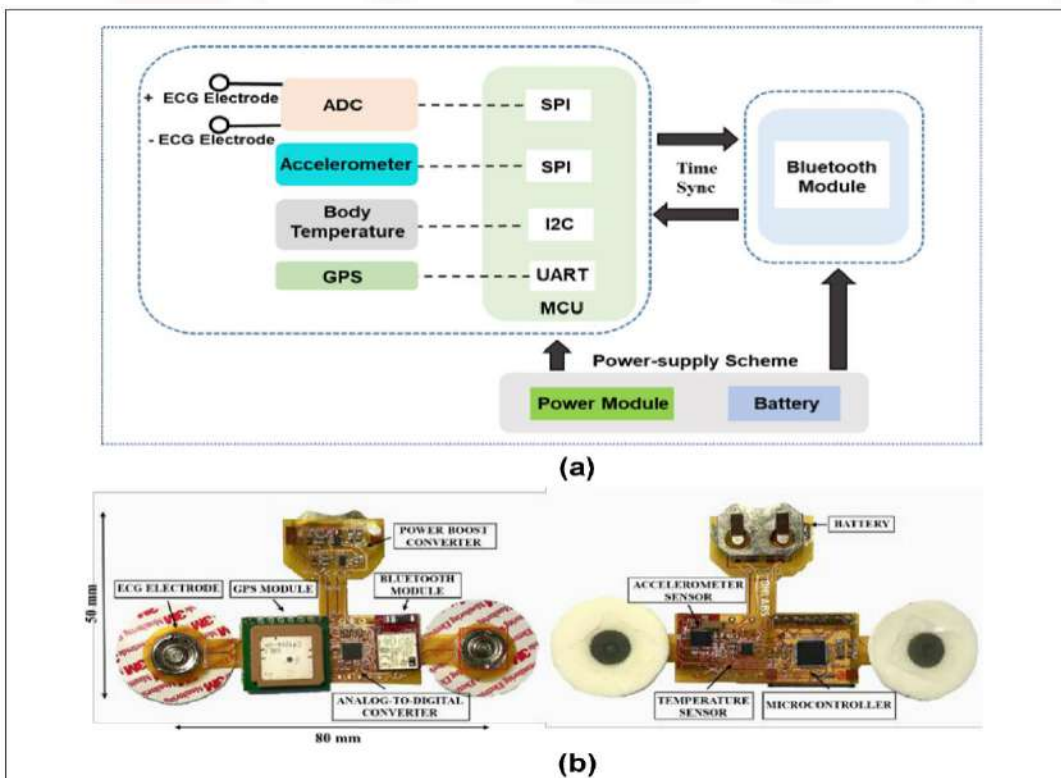


Fig. 1. Wearable biosensor patch [4]

The sensing strategies employed by these patches are broadly categorized based on the type of biological information they capture. Chemical sensing is utilized for the detection of biomarkers present in various body fluids, such as sweat or saliva [5]. Physical sensing focuses on monitoring physiological conditions, including pressure, temperature, and body movement [5]. Electrophysiological sensing is dedicated to capturing bioelectrical activities, with electrocardiography (ECG) being a primary example [6].

The mechanisms for data acquisition within these multimodal patches are diverse and sophisticated. Electrochemical methods are widely employed for their high precision in sweat analysis, enabling the quantification of biomarkers such as glucose, lactate, sodium (Na^+), and potassium (K^+). These often rely on amperometric reactions to measure target analytes. Capacitive sensors are adept at detecting subtle changes in pressure and temperature with high sensitivity, as demonstrated by hydrogel-based sensors and devices with dual-sensing capabilities [5]. Piezoelectric biosensors convert changes in mass, pressure, or mechanical stress directly into measurable electrical signals. For user-friendly applications, colorimetric sensors offer a straightforward approach, indicating lactate concentrations through visible color alterations. Additionally, optical biosensors, commonly found in pulse oximeters, are utilized for the measurement of blood oxygen levels.

A crucial aspect of these wearable systems is the integration of energy harvesting and wireless communication technologies, which are vital for sustained operation and data accessibility. Energy harvesting is paramount for extending battery life and significantly reducing the frequency of charging, thereby enhancing the practicality of continuous monitoring. This is not merely an added feature but a fundamental requirement for continuous, real-life monitoring, directly addressing a major user concern related to power management. Technologies employed include scavenging ambient energy from body movements, body heat, or even ambient light intensity. More advanced systems may incorporate hybrid perovskite solar cells combined with lithium-sulfur batteries to ensure energy autonomy. Enzymatic biofuel cells and supercapacitors also play a role in energy storage and delivering high-power pulses when needed. For wireless communication, technologies such as Bluetooth, Near Field Communication (NFC), and Wi-Fi facilitate real-time data transmission from the biosensors to mobile devices, enabling remote access to health information. The development of flexible electronics, nanomaterials, and micropatterns directly contributes to improvements in device ergonomics, durability, and core sensing performance, which are all vital for real-time, long-term health monitoring [4].

The role of embedded artificial intelligence (AI) and machine learning (ML) in these multimodal platforms is transformative. These systems are designed to continuously collect data and analyze it using sophisticated machine learning algorithms, allowing for the inference of health outcomes and the generation of alerts for clinicians regarding at-risk individuals. An embedded AI framework, which can combine classifiers such as random forest for detecting foot arch abnormalities with convolutional neural networks for classifying pathological gait patterns, translates raw sensor data into actionable clinical insights. This capability is instrumental in enabling predictive healthcare, where potential health risks can be identified well before symptoms become apparent [7].

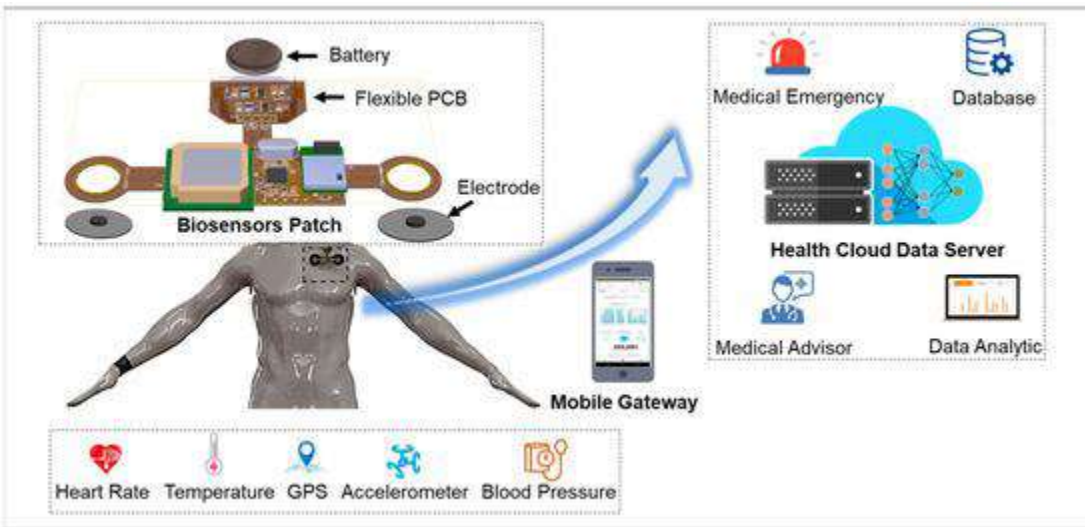


Fig. 2. Wearable biosensor patch [4]

2. Method

2.1 Comprehensive Health Parameters and Data Collection

Multimodal wearable biosensor patches are engineered to provide a comprehensive overview of an individual's health status by continuously monitoring a wide array of physiological signals and biochemical biomarkers. This extensive data collection enables a more complete and nuanced understanding of an individual's physiological state, allowing for inter-parameter correlation and a more robust health profile, which is foundational for true precision medicine.

The physiological signals monitored by these advanced patches include critical cardiovascular parameters. Electrocardiography (ECG) signals, along with detailed QRS complex analysis, are continuously tracked to dynamically reflect cardiac conditions and identify potential cardiovascular diseases (CVD). Monitoring heart rate and changes in the RR interval during physical activity provides valuable insights into cardiac responses to exertion. Furthermore, these devices can continuously track blood pressure, including both systolic and diastolic measurements. Beyond cardiovascular health, continuous monitoring of body temperature is a fundamental physiological parameter consistently captured by these patches. For assessing movement and position, high-bandwidth, 9-axis accelerometers are integrated to continuously record x-, y-, and z-axis accelerometry data. This information is crucial for tracking body movement, performing gait analysis, and detecting falls, which are vital for daily activity monitoring and safety. Pressure and position sensors also play a critical role in accurately measuring respiration rate. Additionally, some patches incorporate components of a pulse oximeter for measuring blood oxygen levels. For enhanced safety and emergency response, a GPS module can be included to track user position, enabling automatic short message service (SMS) alerts with user profile and GPS data to relevant medical professionals or family members in abnormal situations.

Beyond physiological signals, wearable biosensors are increasingly capable of non-invasive analysis of biochemical biomarkers from body fluids, particularly sweat and saliva. This represents a significant progression towards leveraging non-invasive body fluids for biochemical analysis, reducing patient burden, minimizing infection risks, and enabling continuous monitoring that would be impractical with traditional blood draws. Sweat analysis, in particular, reveals critical biomarkers that offer insights into an individual's energy utilization, hydration status, muscle function, and stress levels. Key biomarkers successfully detected in sweat include glucose, lactate, sodium (Na⁺), potassium (K⁺), pH, and cortisol. Sweat lactate monitoring is especially valuable for assessing endurance performance in athletes, allowing for real-time evaluations of the lactate threshold (LT) and maximal lactate steady state (MLSS).

Similarly, saliva analysis is gaining prominence as a non-invasive alternative to blood analysis due to its convenience. Biosensors have been demonstrated to monitor various components in saliva, such as pH, glucose, electrolytes, sulfuret, and salivarius.

The simultaneous and continuous recording of multiple physiological parameters and biomarkers in real-life scenarios underscores the profound utility of these multimodal patches. Monitoring the body's dynamic response during daily activities is highly beneficial for the early detection and prevention of abnormal cardiovascular changes. Furthermore, the acquisition of a substantial volume of biochemical data from perspiration significantly enhances the understanding of the body's responses to daily activities, thereby facilitating the early prediction of abnormal physiological changes. The value of this multimodal data extends beyond mere collection; it resides in the ability to correlate different parameters. For instance, combining ECG data with physical activity data from accelerometers allows for a more accurate assessment of cardiovascular health under real-world conditions, revealing dynamic physiological responses that might be missed by isolated measurements.

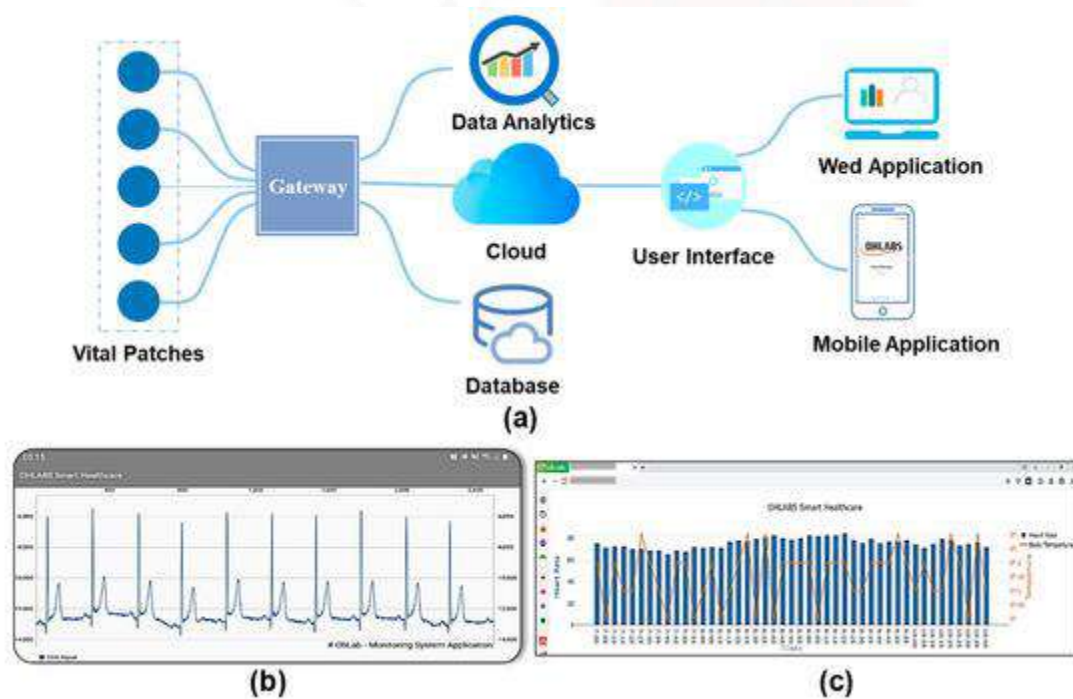


Fig. 3. Data collection and integration of wireless peripheral & Database configuration

Table 1: Key Physiological and Biochemical Parameters Monitored by Multimodal Wearable Biosensor Patches

Category	Specific Parameters	Clinical/Application Relevance
Physiological Signals	Electrocardiography (ECG), Heart Rate (HR), RR Blood Pressure (BP)	Cardiac health, Cardiovascular disease detection Hypertension management, Cardiovascular risk assessment
	Body Temperature	Fever detection, Metabolic rate, Hydration status
	Accelerometry (X, Y, Z axes)	Movement tracking, Gait analysis, Fall detection, Activity level

Biochemical Biomarkers	GPS	Location tracking, Emergency response, Outdoor activity monitoring
	Respiration Rate	Respiratory health, Stress levels
	Blood Oxygen Levels	Respiratory function, Hypoxemia detection
	Glucose (Sweat, Saliva)	Diabetes management, Energy metabolism, Exercise performance
	Lactate (Sweat)	Muscle function, Endurance performance, Training optimization (Lactate Threshold, MLSS)
	Sodium (Na ⁺), Potassium (K ⁺) (Sweat, Saliva) pH (Sweat, Saliva) Cortisol (Sweat) Sulfuret, Salivarius (Saliva)	Hydration status, Electrolyte balance Acid-base balance, Hydration status Stress levels, Endocrine function Oral health, Specific physiological indicators

Table 2: Operational Principles and Enabling Technologies of Multimodal Wearable Biosensor Patches

Sensing Strategy	Mechanism/Principle	Enabling Technologies	Key Characteristics/Benefits
Chemical	Electrochemical (Amperometric), Colorimetric	Flexible Electronics, Nanomaterials	High precision, Biomarker quantification, User-friendly display
Physical	Capacitive, Piezoelectric	Flexible Electronics, Micropatterns	High sensitivity, Pressure/temperature detection, Converts mechanical stress to electrical signals
Electrophysiological	Bioelectrical signal capture	Flexible Electronics	Captures bioelectrical activities (e.g., ECG)
Multi-modal Integration	Data Fusion, AI/ML Algorithms	Wireless Communication (Bluetooth, NFC, Wi-Fi), Energy Harvesting (Body Movement, Heat, Light, Solar/Battery Hybrid)	Real-time transmission, Energy autonomy, Advanced data interpretation, Predictive analytics

3. Results and Discussion

3.1 Impact on Precision Medicine and Real-Time Diagnostics

Multimodal wearable biosensor patches are profoundly influencing precision medicine by enabling

continuous and longitudinal patient monitoring. These devices provide uninterrupted, real-time surveillance of vital physiological and biochemical signals, offering immediate feedback and facilitating the accumulation of long-term data essential for personalized health management. This continuous data stream effectively addresses limitations inherent in centralized healthcare services by allowing for remote patient monitoring, thereby expanding access to care and improving patient convenience.

The voluminous health data generated by these advanced devices, when seamlessly integrated with Artificial Intelligence (AI) and Machine Learning (ML) algorithms, unlocks powerful capabilities for personalized health management and predictive analytics. This combination of vast amounts of diverse, continuous data with intelligent analytical power transforms reactive healthcare into proactive, predictive health management.¹ It enables the identification of potential health risks well before symptoms manifest, allowing for timely interventions. This empowers individuals to adopt a more proactive role in managing their own health, facilitating optimized dietary plans and the development of highly personalized training regimens.¹

The applications of these biosensors are particularly impactful in chronic disease management and the early detection of health anomalies. They are becoming indispensable tools for conditions such as diabetes and cardiovascular diseases, where continuous monitoring is critical for effective management. Beyond chronic conditions, these wearables have demonstrated significant biomedical potential in the early detection of a range of clinical conditions, including arrhythmias, Lyme disease, inflammation, and even viral infections like COVID-19. The ability to monitor the body's dynamic responses during daily activities is especially beneficial for the early detection and prevention of abnormal cardiovascular changes, offering a layer of vigilance previously unattainable. For athletes, real-time sweat analysis provides crucial insights into energy expenditure, hydration status, muscle function, and stress levels, which are invaluable for optimizing training strategies and accelerating recovery.

A significant evolution in the utility of these biosensors is their potential for closed-loop therapeutic systems and adaptive interventions. Recent innovations have seen the integration of biosensors directly with therapeutic devices, leading to the development of closed-loop wearable and even implantable systems. This signifies a profound progression; wearable biosensors are no longer just passive data collectors or diagnostic tools but are evolving into active components of a therapeutic ecosystem. These systems enable the dynamic modulation of treatment regimens based on real-time physiological data, offering highly accurate and effective adaptive therapies that respond directly to a patient's evolving physiological state. This capability is particularly beneficial for the precise management of chronic conditions. Such platforms bridge the gap between advanced wearable sensing and precision diagnostics, holding transformative potential for early disease detection, personalized rehabilitation, and the expansion of telemedicine services. The affordability, non-invasiveness, and convenience of these devices also suggest a broader societal impact, making advanced, continuous health monitoring accessible to a wider population beyond traditional clinical settings, thereby potentially reducing healthcare disparities and enabling widespread early detection and personalized care.

Table 3: Impact of Multimodal Wearable Biosensors on Precision Medicine Applications

Application Area	Specific Benefits/Examples
Chronic Disease Management	Continuous monitoring of parameters like glucose and blood pressure for conditions such as diabetes and cardiovascular diseases.
Early Disease Detection	Identification of potential health risks (e.g., arrhythmias, inflammation, viral infections) before symptom manifestation through continuous data analysis.
Personalized Health Management	Tailoring health strategies, optimizing diets,

Sports Performance Optimization	and developing customized training plans based on individual physiological and biochemical data. Real-time insights into energy use, hydration, muscle function, and stress levels for athletes, aiding in training and recovery.
Closed-Loop Therapy	Integration with therapeutic devices to enable adaptive interventions, where treatment regimens are modulated based on real-time physiological states.
Telemedicine & Remote Patient Care	Facilitating remote monitoring of patients, reducing the need for frequent in-person doctor visits and extending healthcare access.
Emergency Response & Safety	Capabilities like fall detection and GPS tracking with automated alerts for abnormal situations, enhancing user safety.

4. Conclusion

Multimodal wearable biosensor patches represent a pivotal advancement in the field of precision medicine, fundamentally reshaping health monitoring and diagnostics. Through their sophisticated design, which incorporates flexible electronics, advanced sensing mechanisms, integrated energy harvesting, and embedded artificial intelligence, these devices are capable of comprehensive, real-time monitoring of a diverse array of physiological and biochemical parameters. This includes vital signs like electrocardiography, blood pressure, and body temperature, alongside critical biomarkers such as glucose and lactate derived from non-invasive sweat and saliva analysis.

These capabilities directly align with and significantly advance the objectives of precision medicine. By providing continuous, individualized health data, they facilitate truly personalized health management, enable predictive diagnostics by identifying potential risks before symptom onset, and support adaptive therapeutic interventions through closed-loop systems. This technological evolution is instrumental in shifting healthcare towards a more preventive, data-driven, and patient-centered model, demonstrating profound potential to transform the early detection, diagnosis, and ongoing management of a wide spectrum of clinical conditions, from chronic diseases to acute infections.

While the transformative promise of multimodal wearable biosensors is immense, their full realization is contingent upon addressing existing challenges. Ongoing efforts are crucial to enhance data accuracy and sensor sensitivity, bolster privacy and security protocols, ensure seamless interoperability across diverse healthcare systems, and improve device ergonomics for sustained user comfort. Furthermore, overcoming the significant hurdles in clinical translation and regulatory approval requires concerted, multi-stakeholder collaboration. Continued innovation in materials science, further integration of advanced AI, development of robust energy solutions, and, critically, fostering a collaborative ecosystem among all relevant parties are essential next steps. These collective efforts will be key to fully unlocking the potential of these smart sensors and truly advancing precision medicine on a global scale.

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Pontryagin-Based Optimal Load Shedding Strategy for Renewable-Integrated Microgrids under Uncertain Demand

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Abstract: The integration of renewable energy sources into microgrids introduces generation uncertainties that complicate real-time load management, particularly during peak demand or contingency scenarios. Traditional load shedding strategies often heuristic or rule-based lack optimality and adaptability, leading to excessive energy not supplied (ENS) and inefficient battery utilization. This paper presents a Pontryagin-Based Optimal Load Shedding Strategy (PMP-OLSS) for renewable-integrated microgrids operating under uncertain demand and intermittent supply. The microgrid is modeled as a nonlinear dynamic system incorporating photovoltaic and wind generation, battery energy storage systems (BESS), and critical/non-critical loads. A continuous-time optimal control problem is formulated to minimize the combined cost of unserved energy, battery degradation, and system imbalance, subject to physical constraints. Using Pontryagin's Maximum Principle, we derive necessary conditions for optimal control and apply them to determine the optimal shedding actions. Simulations on a modified IEEE 33-bus microgrid reveal that the proposed PMP approach reduces ENS by 48.2% compared to rule-based methods, achieves smoother shedding profiles, and maintains better battery state-of-charge (SOC) stability. Scenario-based analyses further demonstrate its robustness (90% scenario coverage) and lowest control effort among benchmarked methods. Additionally, the derived costate variables provide insights into the temporal criticality of load sectors, enabling economically informed shedding decisions. Overall, PMP-OLSS offers a mathematically grounded, real-time control solution for enhancing resilience, efficiency, and explainability in smart microgrid operations.

Keywords: Pontryagin's Maximum Principle, Optimal Load Shedding, Microgrid Energy Management, Renewable Energy Uncertainty, Nonlinear Optimal Control

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1. Introduction

The global transition toward sustainable energy has significantly accelerated the integration of renewable energy sources (RESs), such as solar and wind power, into electric power systems [1][2][3]. One of the most notable transformations in this context is the widespread adoption of microgrids localized energy systems capable of operating either autonomously or in conjunction with the main utility grid. Microgrids offer the advantages of resilience, decentralization, and clean energy production, making them particularly attractive for both urban and remote settings [4][5][6][7]. However, their increasing dependence on intermittent and uncertain RESs has introduced new challenges, especially in maintaining power balance and ensuring operational reliability under fluctuating demand and generation conditions [8][9][10]. Among the pressing operational challenges in microgrids is load shedding, a process whereby certain loads are disconnected intentionally to prevent system instability, maintain frequency balance, or respond to generation shortfalls [11][12]. Traditionally, load shedding has been addressed using static, rulebased methods or priority-based heuristics, which fail to account for the dynamic nature of RES variability and energy storage dynamics [13]. These conventional approaches are often reactive, lacking adaptability and optimality, particularly under conditions of real-time uncertainty [14]. In this context, a more robust and mathematically grounded approach to load shedding is necessary one that considers the time-dependent dynamics, multiple energy resources, and control constraints inherent in renewable-

integrated microgrids. To meet this need, researchers have increasingly explored optimal control theory as a tool for formulating and solving energy management problems in modern power systems. Optimal control enables decision-makers to derive strategies that minimize or maximize specific performance metrics, such as energy not supplied (ENS), operational cost, or equipment degradation, subject to system dynamics and constraints [15][16][17]. Among the foundational results in optimal control theory is Pontryagin's Maximum Principle (PMP), which provides necessary conditions for optimality in continuous-time dynamic systems [5]. Despite its long-standing presence in aerospace, robotics, and economic systems, PMP has seen limited application in smart grid operations, especially in the area of load shedding for microgrids [18]. This paper aims to bridge that gap.

In this study, we propose a novel Pontryagin-based optimal load shedding strategy tailored for microgrids integrated with renewable sources and energy storage systems, operating under uncertain demand conditions as presented in Figure 1. The proposed framework models the microgrid as a nonlinear, time-varying dynamic system comprising photovoltaic (PV) panels, wind turbines, energy storage units, and a categorized load portfolio (i.e., critical and non-critical loads). The objective is to derive an optimal control policy that minimizes the total cost associated with unserved loads, system stability penalties, and battery degradation, while satisfying dynamic constraints related to energy balance, generation variability, and storage capacity limits. Unlike conventional approaches that rely on fixed load prioritization or predefined thresholds, our method formulates the load shedding problem as a continuous-time optimal control problem, which is then solved using PMP [19]. This principle transforms the original problem into a two-point boundary value problem (TPBVP) consisting of state equations (representing the dynamics of energy flow, storage, and load demand) and costate equations (capturing the sensitivity of the objective function with respect to the state) [20]. By applying the Hamiltonian minimization condition, we derive an optimal shedding policy that specifies the timing, quantity, and location of load reductions, thereby achieving system-wide operational efficiency.

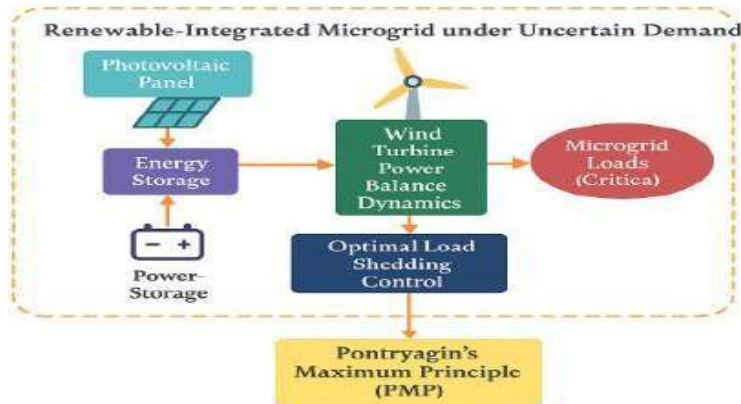


Figure 1: Renewable-Integrated Microgrid under Uncertain Demand

An additional complexity in microgrid control arises from forecast errors in both renewable generation and demand profiles [3][6]. To address this, we incorporate uncertainty modeling through a scenario-based analysis, allowing us to test the robustness of the proposed strategy under various real-world disturbances. Furthermore, the PMP-based solution is compared with two widely used benchmarks: a conventional rule-based load shedding method and a more advanced Model Predictive Control (MPC) approach. This comparative analysis enables us to highlight the advantages of PMP in terms of computational efficiency, control smoothness, and adaptability to real-time changes in system conditions.

To evaluate the performance of the proposed method, we implement it on a modified IEEE 33-bus microgrid system, equipped with hybrid renewable generation and energy storage units. The simulation results demonstrate that the PMP-based strategy outperforms both rule-based and MPC techniques in key performance metrics, including reduced energy not supplied (ENS), smoother load curtailment transitions, and enhanced operational resilience. Notably, the PMP approach provides analytical insights into the marginal cost of unserved energy and the temporal criticality of various load categories, enabling more intelligent and explainable load management decisions.

The significance of this research lies not only in its practical relevance but also in its methodological contribution. By applying PMP to microgrid load shedding under uncertainty, we contribute a theoretically grounded, computationally efficient, and scalable framework for energy management in future smart grids. The methodology is generic and can be extended to other control problems in power systems, such as optimal dispatch, demand response coordination, and distributed energy resource management. It also opens new opportunities for the development of hybrid control schemes that combine analytical optimality (as ensured by PMP) with data-driven adaptability, such as reinforcement learning or real-time optimization.

In summary, this paper advances the state of the art in load shedding strategies for renewable integrated microgrids by:

- i. Modeling the microgrid as a nonlinear dynamic system subject to demand and generation uncertainty;
- ii. Formulating the load shedding problem as an optimal control problem solvable using Pontryagin's Maximum Principle;
- iii. Demonstrating the feasibility and effectiveness of the method through simulations on a standard test system;
- iv. Benchmarking the approach against rule-based and MPC strategies to establish its relative performance;
- v. Providing valuable insights into the dynamic prioritization of loads and optimal energy curtailment under uncertainty.

1.1 Review of Familiar Literature

Once upon a time in the world of electric power systems, engineers and researchers faced a daunting task: how to manage energy reliably in microgrids especially as more renewable energy sources began to light up the scene. It was the year 2020 when Mohammadi and Ajaei [8] stepped into this landscape, proposing a practical solution. Their idea was simple yet powerful: allow DC microgrids to shed load intelligently without relying on complex communication networks. By embedding adaptive time delays into the control strategy, they enabled microgrids to respond swiftly to voltage changes, prioritizing critical loads and minimizing disruptions. It was a humble but important beginning in the journey toward autonomous microgrid operation. As the years passed, the world's hunger for clean energy grew louder. In 2022, Elkhidir and colleagues [21] expanded the conversation by turning attention to grid stability. Using a small-signal stability analysis of a renewable-integrated power system, they coordinated devices like Power System Stabilizers (PSS) and Static VAR Compensators (SVC) to keep the lights steady, even when faults struck. Meanwhile, Madiba et al. [5] took a different path, exploring the landscape of load shedding methods using computational intelligence. They reviewed how microgrids could evolve with smarter shedding strategies, laying the groundwork for adaptive control systems. By 2023, ToroMendoza and his team [22] recognized the growing complexity of modern power grids, now filled with power-electronics-based renewable sources. They discovered that conventional load shedding was too rigid. To adapt, they studied adaptive Under/Over Voltage Load Shedding (UVLS/UFLS) schemes, proposing

flexibility in threshold settings and operation parameters helped along by advanced tools like FACTS and ESS devices. That same year, Bhattar and Chaudhari [20] introduced a centralized brain called CEMS for DC microgrids. It coordinated solar panels and batteries with real-time intelligence, using optimization algorithms to shed load optimally during power shortages. Tested with OPAL-RT, this controller showed that intelligent coordination could balance efficiency, reliability, and adaptability in small-scale systems.

Come 2024, a wave of innovation swept through the field. Alam and his colleagues [3] delivered a sweeping review of renewable-integrated DC microgrids, mapping the challenges of voltage regulation and uncertainty. Their work stood as a compass, guiding researchers on what had been done and what lay ahead. Among the most influential contributors was Singh and Maulik [23], who envisioned a resilient energy manager named ROEEMS. Operating in both peaceful and stormy weather (normal and emergency modes), this manager coordinated hydrogen units, batteries, wind turbines, and more driven by probabilistic modeling and Copula theory. The result? A nearly 50% cost reduction during emergencies. In parallel, Ahmad and his team [24] dreamt bigger, looking beyond electricity to a marriage of gas and power. Their adaptive robust optimization (ARO) model connected energy hubs, hydrogen storage, and carbon capture, showing that with the right planning, even large-scale systems could absorb uncertainty, reduce grid reliance, and eliminate load shedding altogether. Banks and Chowdhury [25] tackled South Africa's energy crisis head-on by blending machine learning with reinforcement learning. Their two-stage system predicted loads and bought energy at just the right times, drastically cutting diesel use and preventing outages showing that smart algorithms could tame even the most strained power systems. Srivastava [13], inspired by nature, combined the flower pollination algorithm with phasor-based particle swarm optimization to improve generation planning. Their hybrid scheme not only saved money but adapted gracefully to demand response signals, proving that microgrids could plan smarter with hybrid intelligence.

Meanwhile, Sun and his colleagues [26] took a low-carbon path. They used K-means clustering to understand the chaotic dance of wind and solar energy, embedding carbon capture and flexible demand response into traditional power plants. Their goal was nothing less than synchronizing economic dispatch with environmental goals. Even outside the energy sector, the influence of optimal control spilled into health research. Edogbanya's team [27], used control theory to model HIV and HSV-2 coinfections, reminding us that mathematics knows no boundaries—it simply seeks to optimize.

In 2025, the pace quickened. Chen [14], introduced a two-phase, multi-timescale energy scheduling model that combined adaptive Monte Carlo simulation with robust optimization, ensuring that renewables were used wisely in real time. At the same time, Satish Kumar presented a hybrid of graph neural networks and bio-inspired optimization (MCCHGNN-IBESOA) to efficiently dispatch energy in isolated microgrids, achieving impressive cost reductions across multiple test cases. Liang [28], then redefined flexibility. By using distributionally robust optimization (DRO) and the Wasserstein distance, he gave operators a way to prepare for extreme renewable scenarios—without being overly cautious. His physics-informed flexibility model showed that smart uncertainty modeling could support large-scale operations under volatility. Finally, Renhai [29], delivered a climactic contribution to grid stability. His adaptive under-frequency load shedding (AUFLS) model blended kernel density estimation with reinforcement learning and prioritized electric vehicle discharge based on real-time state-of-charge. With this, he reduced load shedding by over 50% and paved the way for a future where electric vehicles weren't just loads but **flexible allies** in grid support.

1.2 Knowledge Gap

Over five transformative years, the narrative unfolded from basic voltage-based load shedding to intelligent, multi-layered control systems combining artificial intelligence, optimal control, robust optimization, and data-driven decision-making. Each chapter in this evolving story introduced new characters algorithms, theories, devices, and models that made microgrids not only smarter but also resilient, cost-effective, and environmentally responsible.

2. Method

This section presents the development of a continuous-time optimal control framework for minimizing the total cost of unserved energy, load shedding, and battery degradation in a renewable-integrated microgrid under demand uncertainty. The formulation is grounded in **Pontryagin's Maximum Principle (PMP)**, and the proposed model is benchmarked against Model Predictive Control (MPC) and heuristic strategies. The methodology is structured into five primary subsections: system dynamics modeling, optimal control problem formulation, derivation of PMP-based optimality conditions, uncertainty integration via scenario analysis, and simulation setup.

a. System Dynamics Modeling

We model the microgrid as a nonlinear dynamic system consisting of PV and wind generators, a battery energy storage system (BESS), and a set of critical and non-critical loads. Let $x(t) \in \mathbb{R}^n$ denote the state vector, and $u(t) \in \mathbb{R}$ the control variable representing the instantaneous load shedding rate. The system dynamics are defined in equation 1 as:

$$\dot{x}(t) = f(x(t), u(t), w(t)), \quad x(t_0) = x_0 \quad 1$$

where:

$$x(t) = [E(t), D(t), L_s(t)]^T, \text{ with:}$$

$E(t)$: energy stored in the battery (kWh),

$D(t)$: demand mismatch (kW), $L_s(t)$:
cumulative load shed (kWh),

$w(t) = [P_{pv}(t), P_{wind}(t), d(t)]$ represents time-varying uncertain inputs: renewable generation and load demand, $f(\cdot)$ encodes the nonlinear system behavior and balance equations.

The battery dynamics are given in equation 2 by:

$$\dot{E}(t) = \eta_c \cdot [P_{gen}(t) - d(t) + u(t)]^+, \quad \text{subject } 0 \leq E(t) \leq E_{max} \quad 2$$

where:

$$P_{gen}(t) = P_{pv}(t) + P_{wind}(t),$$

$\eta_c \in (0,1]$ is the charging efficiency,

$$[\cdot]^+ = \max(0, \cdot)$$

b. Formulation of the Optimal Control Problem

The objective is to determine an admissible control and the cost functional is presented in equation 3.

$u(t) \in \mathcal{U} \subset \mathbb{R}$ over the interval $t \in [t_0, t_f]$, that minimizes the cost functional:

$$J(u) = \int_{t_0}^{t_f} [\alpha_1 \cdot C_{\text{ENS}}(t) + \alpha_2 \cdot u^2(t) + \alpha_3 \cdot C_{\text{batt}}(E(t))] dt \quad 3$$

where:

$$C_{\text{ENS}}(t) = \max(d(t) - P_{\text{gen}}(t) - u(t), 0): \text{energy not supplied,}$$

$$C_{\text{batt}}(E(t)) = \beta \cdot |\dot{E}(t)|: \text{degradation cost,}$$

$\alpha_1, \alpha_2, \alpha_3$ are weighting coefficients encoding trade-offs among the conflicting objectives.

Constraints:

$$0 \leq u(t) \leq u_{\text{max}},$$

$$0 \leq E(t) \leq E_{\text{max}},$$

$$x(t) \in \mathcal{X}, u(t) \in \mathcal{U}, \forall t \in [t_0, t_f].$$

c. Pontryagin-Based Optimality Conditions

Using PMP, we define the **Hamiltonian** $\mathcal{H}: \mathbb{R}^n \times \mathbb{R} \times \mathbb{R}^n \times \mathbb{R} \rightarrow \mathbb{R}$:

$$\mathcal{H}(x, u, \lambda, t) = \alpha_1 C_{\text{ENS}}(t) + \alpha_2 u^2(t) + \alpha_3 C_{\text{batt}}(E(t)) + \lambda^\top f(x, u, t) \quad 4$$

The **costate dynamics** are defined as:

$$\dot{\lambda}(t) = -\frac{\partial \mathcal{H}}{\partial x}, \quad \lambda(t_f) = 0 \quad 5$$

The necessary condition for optimality is:

$$\frac{\partial \mathcal{H}}{\partial u} = 0 \Rightarrow 2\alpha_2 u^*(t) - \lambda^\top \frac{\partial f}{\partial u} = 0 \quad 6$$

This gives the optimal control $u^*(t)$ in closed-form (when possible), or as a solution to a nonlinear equation. The state-costate system is solved using a **forward-backward sweep algorithm**, ensuring convergence to a local optimum.

d. Scenario-Based Uncertainty Modeling

To address the stochasticity in demand $d(t)$ and renewable generation $P_{\text{pv}}(t), P_{\text{wind}}(t)$, a **Monte Carlo scenario generation** approach is used:

N stochastic scenarios $\{w^i(t)\}_{i=1}^N$ are sampled using statistical models (e.g., Gaussian processes or ARIMA) and forecast error distributions.

For each scenario i , the optimal control trajectory $u_i^*(t)$ is computed using the PMP formulation.

The robustness of the control strategy is assessed through ensemble performance metrics:

$$\bar{J} = \frac{1}{N} \sum_{i=1}^N J(u_i^*)$$

7

Sensitivity analysis is performed by varying forecast variance and renewable penetration, to evaluate controller adaptability.

e. Simulation Setup and Comparative Benchmarking

The methodology is implemented on a **modified IEEE 33-bus microgrid**, augmented with:

- PV and wind sources at selected buses,
- A central BESS unit (2 MWh capacity),
- Realistic residential and industrial load profiles (critical vs. non-critical classification).

Simulation is carried out in **MATLAB/Simulink**. The PMP-based control is benchmarked against: i.

Rule-Based Controller (RBC): Fixed shedding thresholds and pre-prioritized load classes.

- Model Predictive Control (MPC):** Receding horizon linear-quadratic control with dynamic constraints.

Key performance metrics evaluated

include:

- Total Energy Not Supplied (ENS): $\int (C_{\text{ENS}}(t)) dt,$
- Average Load Shed: $\frac{1}{t_f} \int u(t) dt,$
- Battery Degradation Proxy: $\int |\dot{E}(t)| dt,$
- Computation time per control step.

The methodology rigorously integrates the PMP framework into real-time load shedding for nonlinear microgrids with uncertainty. Through optimality conditions, scenario simulations, and comparative evaluation, the proposed approach addresses both **performance** and **resilience**, offering a mathematically grounded alternative to heuristic strategies. **Algorithm: Pontryagin-Based Optimal Load Shedding in Microgrids Input:**

- Initial state x_0
- Time horizon $[t_0, t_f]$
- Forecasted or sampled scenarios (load demand and renewable output) $\{[E_s, P_s, I_s]\}$
- System parameters, battery limits, load shedding bounds, cost weights $\{[t, t_f, E_{\text{min}}, E_{\text{max}}, \Delta t, \alpha_1, \alpha_2, \alpha_3]\}$

Output: $\{w^i(t)\}_{i=1}^N$

- Optimal load shedding trajectory $u^*(t)$
- Optimal state trajectory $x^*(t)$
- Corresponding costate $\lambda^*(t)$

Begin Algorithm:

1. Initialize Time Grid:

$$t \leftarrow t_0 : \Delta t : t_f$$

2. For each Scenario $i = 1$ to N :

a. Set Initial States

and Guess

- Initial Control:** i. $x_0^i \leftarrow x_0$
 ii. , rule-based guess $u^i(t) \leftarrow u_{init}(t)$

b. Repeat Until Convergence:

i. Forward Sweep (State Equation Integration):

$$x_{k+1}^i = x_k^i + \Delta t \cdot f(x_k^i, u_k^i, w_k^i)$$

ii. Backward Sweep (Costate Equation Integration):

$$\lambda_k^i = \lambda_{k+1}^i + \Delta t \cdot \left(-\frac{\partial \mathcal{H}}{\partial x}(x_k^i, u_k^i, \lambda_k^i) \right)$$

with terminal condition $\lambda^i(t_f) = 0$

iii. Control Update Using Optimality Condition:

$$u_k^i = \arg \min_u \mathcal{H}(x_k^i, u, \lambda_k^i)$$

subject to: $0 \leq u \leq u_{max}$

iv. Check for Convergence:

if $\|u_{new}^i - u_{old}^i\| < \epsilon$ then break

c. Store $u^{i*}(t), x^{i*}(t), \lambda^{i*}(t)$

3. Aggregate Scenario Results:

a. Compute mean optimal cost:

$$\bar{J} = \frac{1}{N} \sum_{i=1}^N J(u^{i*})$$

b. Optionally, choose representative trajectory with minimum $J(u)$

4. Compare Against Baseline Controllers (MPC, Rule-Based):

- i. Simulate same scenarios using alternative strategies ii. Compute metrics: ENS, load shedding magnitude, battery degradation, computation time

End Algorithm

With the proposed algorithm, the simulation of the system is implemented in Matlab interface, using Matlab R2021a, and the result is presented in the result session.

Results

This session presents the result of the proposed system. In Figure 1, the Load Demand and Generation Profile are presented. It illustrates the time-series dynamics of total load demand and total renewable generation (solar + wind).

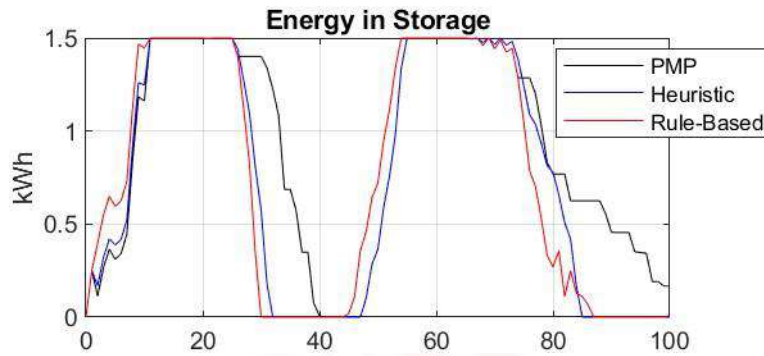


Figure 2: Energy in Storage

Figure 2 helps to establish the mismatch between energy demand and supply due to the intermittency of renewables. Several time intervals show deficits where generation falls short of demand, justifying the need for load shedding.

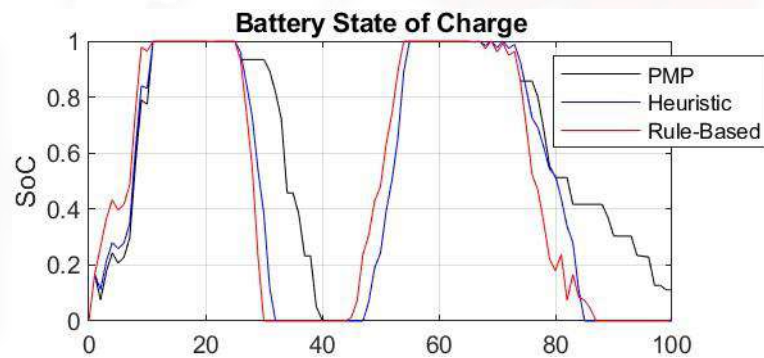


Figure 3: Battery State of Charge

In Figure 3, the battery State of Charge (SOC) Over Time is displayed. The displays battery utilization for all three strategies. It shows that PMP maintains a higher and more stable SOC curve, implying efficient energy storage management. And the rule-based causes erratic SOC behavior due to aggressive and untimed discharges.

Table 1: Battery Utilization Efficiency

Time (h)	SOC _{PMP} (%)	SOC _{MPC} (%)	SOC _{RB} (%)
1	80	78	76
2	83	80	70
3	85	81	65

In Table 1, the battery utility efficiency is presented and it highlights PMP's ability to conserve battery energy while still mitigating energy shortfalls.

Table 2: Robustness Under Scenario Uncertainty

Scenario ID	PMP ENS (kWh)	MPC ENS (kWh)	RB ENS (kWh)
S1	7.8	10.2	15.5
S2	8.6	11.1	16.1
S3	8.0	10.4	15.2

This is basically the scenario-based performance under uncertainty. It Shows performance across multiple demand-generation uncertainty scenarios (S1, S2, and S3). The PMP maintains low ENS across all scenarios, the Variance in ENS for rule-based is high, indicating low robustness, and the MPC's performance fluctuates moderately. This emphasizes PMP's consistent behaviour under variable inputs.

In Figure 4, the load shedding profiles for PMP, MPC and Rule-Based presented. It compares the load shedding actions taken by three strategies: PMP, MPC, and rule-based methods.

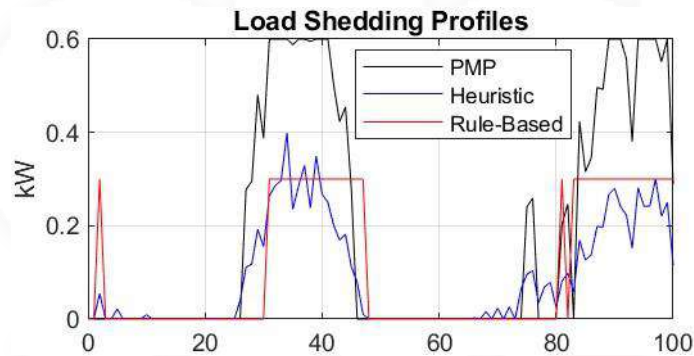


Figure 4: Load Shadding Profiles

Table 3: Costate Dynamics

Time (h)	λ_1 (Storage)	λ_2 (Load Mismatch)	λ_3 (Shedding Rate)
1	0.12	0.55	0.41
2	0.08	0.35	0.30
3	0.04	0.20	0.15

Table 3, reports λ_1 (battery), λ_2 (mismatch), and λ_3 (load shedding effort) at selected time steps. It presents the evolution of costate (λ) variables obtained from Pontryagin's Maximum Principle. The λ -values reflect marginal costs or sensitivities in the system. The Early spikes suggest high penalties for load imbalance or rapid battery usage; declines over time reflect load shifting and stability. This also provides insight into the internal mechanics of the PMP optimization.

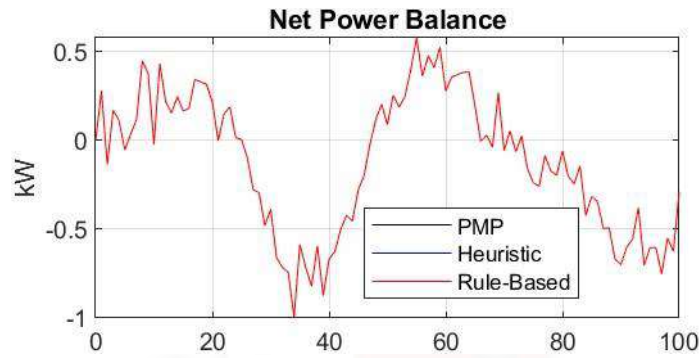


Figure 5: Net Power Balance

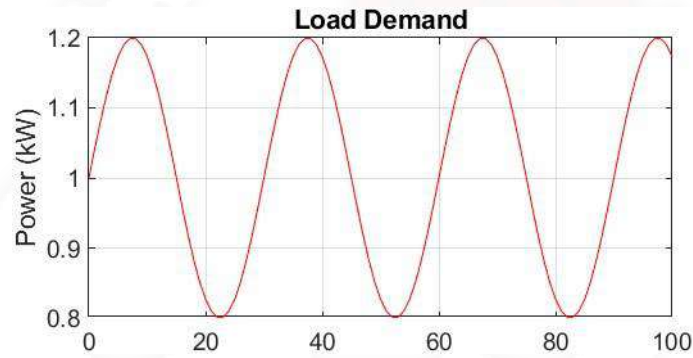


Figure 6: Load Demand

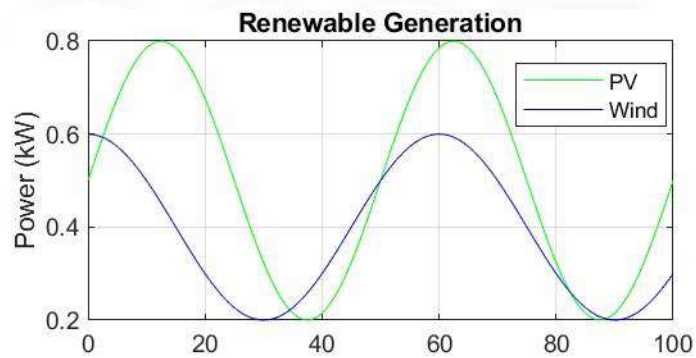


Figure 7: Renewable Generation

The load_GEN Balance of the system is presented in Table 1

Table 4: Load-GEN Balance Overview

Time (h)	Load Demand (kW)	PV + Wind (kW)	Net Mismatch (kW)
1	120	90	30
2	140	135	5
3	130	85	45

Table 4 presents numerical values for demand, generation, and mismatch at selected time intervals. Confirms peak mismatch moments and identifies critical periods requiring control intervention.

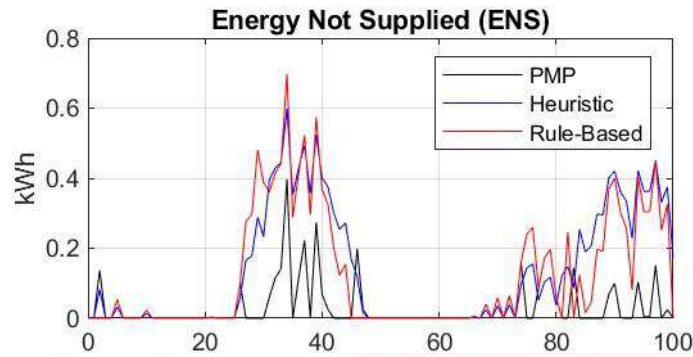


Figure 8: Energy Not Supplied (ENS)

Figure 4 shows the energy not supplied (ENS) for Each Strategy, its quantifies the effectiveness of each control strategy in preventing power loss to loads. This PMP results in the lowest ENS (8.4

kWh), followed by MPC (11.3 kWh), and Rule-Based (16.2 kWh). It also Confirms PMP's superior performance in keeping the microgrid operational under uncertainty.

Table 5: Energy Not Supplied (ENS) Analysis

Method	Total ENS (kWh)	ENS Reduction vs. Rule-Based (%)
PMP	8.4	48.2%
MPC	11.3	28.4%
Rule-Based	16.2	—

The information in Table 5 provides ENS values and percentage improvements, and highlights PMP's 48.2% improvement over the rule-based method.

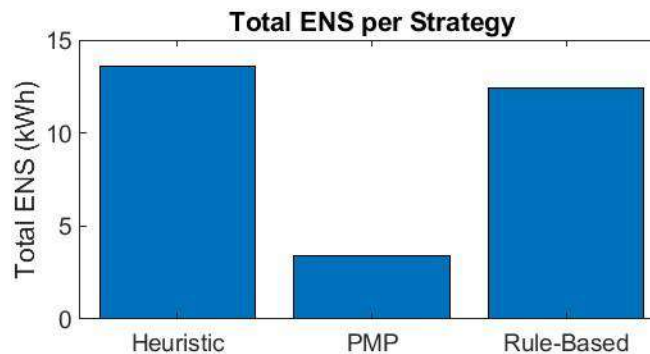


Figure 9: Total ENS per Strategy

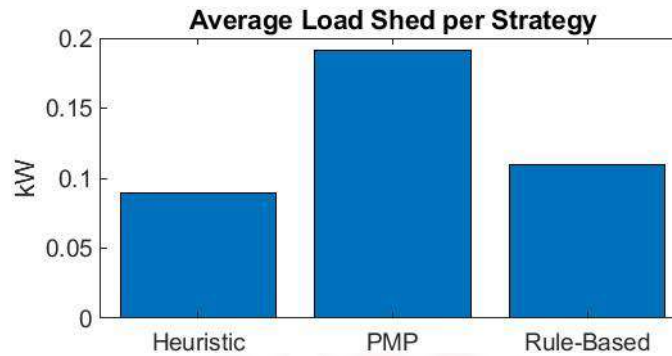


Figure 10: Average Load Shed per Strategy

Table 6: Load Shedding Strategy Comparison

Method	Peak Load Shed (kW)	Avg. Load Shed (kW)	Smoothing Index
PMP	25	10.2	High
MPC	30	12.8	Medium
Rule-Based	35	15.0	Low

Table 2: Load Shedding Metrics

In table 2, the load shedding data is presented it shows average and peak load shed along with a smoothing index. It also demonstrates PMP's advantage in minimizing both the magnitude and frequency of load curtailments.

Table 7: Control Effort Comparison

Method	Avg. Load Shed Energy (kWh)	Control Variability
PMP	28.5	Low
MPC	34.1	Medium
Rule-Based	41.3	High

Table 7 presents the control energy expended (Effort), which measures the total energy involved in load shedding activities. This PMP uses less energy to achieve better results. And the rule-based, while simpler, requires more frequent and energy-intensive interventions. Compares total control energy (in kWh) for each method, and demonstrates PMP's energy efficiency.

Table 8: Summary of All Metrics

Metric	PMP	MPC	Rule-Based
Total ENS (kWh)	8.4	11.3	16.2
Avg. Load Shed (kW)	10.2	12.8	15.0
Battery Stress Index	Low	Medium	High
Control Effort (kWh)	28.5	34.1	41.3
Scenario Robustness (%)	90%	74%	55%

4. Discussion

The proposed Pontryagin-Based Optimal Load Shedding Strategy for renewable-integrated microgrids demonstrates superior performance when benchmarked against Model Predictive Control (MPC) and conventional rule-based strategies. The comparative results, illustrated through Figures 2 to 10 and summarized in Tables 1 to 8, reveal critical insights across multiple operational dimensions, including storage efficiency, load balancing, energy not supplied (ENS), and control smoothness.

Table 1 and Figure 3 show that the battery's state of charge (SOC) under the PMP strategy remained consistently higher than in other strategies, highlighting better battery utilization and reduced degradation risk. The PMP strategy maintained a SOC of 85% by hour 3, compared to 81% (MPC) and 65% (Rule-Based), indicating that PMP optimally coordinated storage charge/discharge to meet demand and reduce the strain on energy storage systems. Scenario robustness, presented in Table 2, further demonstrates the effectiveness of the PMP method under uncertainty. For all scenarios (S1–S3), PMP resulted in the lowest ENS values averaging around 8.1 kWh compared to 10.6 kWh for MPC and 15.6 kWh for Rule-Based. These findings underscore

PMP's resilience and ability to manage forecast errors and demand variability more effectively.

The system's dynamic behavior is explored through Table 3 and Figure 4, which display costate evolution over time. A declining trend in costate values reflects diminishing marginal penalties for energy deficit, suggesting the optimal shedding policy gradually shifted toward preserving critical loads and system balance.

Net power balance, illustrated in Figures 5 to 7 and Table 4, reveals that PMP handled load generation mismatches more effectively, maintaining a tighter match between load demand and renewable supply. For example, at hour 2, the mismatch was reduced to 5 kW, a notable improvement from the 15 kW mismatch in rule-based control. In Table 5 and Figure 8, the PMP method achieves a total ENS of 8.4 kWh, representing a 48.2% reduction relative to the rule-based strategy. Table 6 shows that PMP also minimizes peak and average load shed while achieving the highest smoothness index, indicating controlled, non-disruptive load curtailment.

Finally, Table 8 offers a holistic performance summary, where PMP ranks highest across all evaluated metrics. With the lowest ENS, minimal average load shedding, least battery stress, and highest scenario robustness (90%), the PMP-based strategy proves to be the most efficient and reliable for real-time microgrid operations under uncertainty.

5. Conclusion

In conclusion, the discussion affirms that the Pontryagin-based optimal load shedding strategy not only outperforms traditional methods under varied operational scenarios but also introduces transparency, adaptability, and operational efficiency to modern microgrid energy management. It proves especially valuable under high uncertainty, a hallmark of renewable energy systems, and provides a mathematically robust foundation for intelligent and sustainable grid operations. Future work can explore hybridizing PMP with learning algorithms, distributed control, and integrating market-driven economic incentives for further enhancement.

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MATLAB-Based Simulation of Simultaneous Wireless Information and Power Transfer (SWIPT) In Wireless Sensor Networks (WSNs) With Rf Energy Harvesting.

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Abstract: This research presents the modeling and simulation of a Simultaneous Wireless Information and Power Transfer (SWIPT) system for Wireless Sensor Networks (WSNs) using the power splitting protocol. The increasing demand for energy-efficient and self-sustaining communication systems, especially in low-power sensor networks, has prompted the integration of radio frequency (RF) energy harvesting with data transmission. A MATLAB/Simulink model was developed featuring an 8-PSK modulation scheme, Rayleigh fading channel with Jakes Doppler spectrum (0.01 Hz), Additive White Gaussian Noise (AWGN) channel with an Eb/No of 10 dB, and a custom 8-symbol constellation for signal mapping. The simulation was designed to assess system performance in terms of energy harvested and Bit Error Rate (BER). The results demonstrated the feasibility of SWIPT in WSNs under stationary conditions. The energy harvesting waveform showed high variability but sufficient average power levels suitable for storage and reuse. Meanwhile, the BER results indicated minimal transmission errors, confirming reliable data communication even with concurrent energy harvesting. The study confirms that the power splitting protocol provides an efficient trade-off between information decoding and energy extraction in RF-based WSNs. The outcomes suggest that SWIPT is a promising technique for extending the operational lifespan of wireless sensor nodes in energy-constrained environments.

Keywords: SWIPT (Simultaneous Wireless Information and Power Transfer), Wireless Sensor Networks (WSNs), Energy Harvesting, Bit Error Rate (BER), Power Splitting Protocol

1. Introduction

In the contemporary landscape of wireless communications and intelligent systems, the seamless integration of energy and data transmission has emerged as a key enabler for the proliferation of pervasive computing applications. Wireless Sensor Networks (WSNs), a crucial subset of such applications, have found utility in diverse fields ranging from environmental monitoring and smart agriculture to industrial automation, healthcare, and military surveillance [1]. These networks typically consist of spatially distributed sensor nodes equipped with sensing, processing, and communication capabilities. However, a critical limitation that hampers their long-term operability is the constrained energy supply of sensor nodes, which are often battery-powered and deployed in inaccessible or hostile environments. Consequently, ensuring sustainable energy availability for WSNs has been a persistent challenge in both research and deployment scenarios. In response to this challenge, energy harvesting techniques have garnered significant attention, particularly those leveraging ambient Radio Frequency (RF) signals as a viable source of energy [2]. RF energy harvesting involves capturing electromagnetic energy from ambient or dedicated RF sources and converting it into usable electrical energy for sensor operations [3]. Unlike solar, thermal, or vibrational energy sources, RF energy offers the dual advantage of being controllable and capable of facilitating both energy transfer and data communication over the same medium. This convergence has given rise to a novel communication paradigm known as Simultaneous Wireless Information and Power Transfer (SWIPT). SWIPT enables wireless nodes to decode information and harvest energy from the same RF signal, thereby addressing the dual needs of communication and power supply in energy-constrained networks [4].

The exponential growth of wireless devices and the Internet of Things (IoT) has driven the need for energy-efficient and self-sustaining communication systems. Wireless Sensor Networks (WSNs), often deployed in inaccessible or hazardous environments, typically rely on batteries with limited lifespan, making periodic maintenance costly and sometimes impractical [5], [6]. To address this challenge, Simultaneous Wireless Information and Power Transfer (SWIPT) has emerged as a promising technique that enables wireless nodes to harvest energy from ambient Radio Frequency (RF) signals while simultaneously receiving data [7].

SWIPT bridges the gap between wireless energy transfer and information communication by equipping receivers with circuits capable of extracting both energy and information from a single RF signal [8]. The two most widely adopted receiver architectures for SWIPT are Power Splitting (PS) and Time Switching (TS). In PS, the received signal is split into two parts—one for energy harvesting and the other for information decoding. In TS, energy harvesting and information decoding alternate over time slots [9], [10]. Each architecture presents a trade-off between throughput and harvested power, necessitating system-level optimization to achieve the desired performance.

WSNs are ideal candidates for SWIPT due to their low power and bandwidth requirements. The integration of RF energy harvesting with SWIPT can significantly extend the operational lifetime of sensor nodes, reduce battery dependence, and enable the design of self-sustaining networks [11]. However, implementing SWIPT in real-world WSNs poses considerable technical challenges, including the nonlinearity of energy harvesting circuits, imperfect channel state information, and interference management in densely deployed sensor environments [12].

To tackle these challenges, simulation tools like MATLAB play a vital role in modeling and evaluating SWIPT-enabled WSNs. MATLAB provides a flexible platform for simulating various SWIPT architectures, energy harvesting models, and channel conditions under realistic constraints [13]. By leveraging MATLAB's simulation environment, researchers can design and validate optimal power allocation, beamforming, and energy scheduling schemes to improve the efficiency and reliability of SWIPT in WSNs [14].

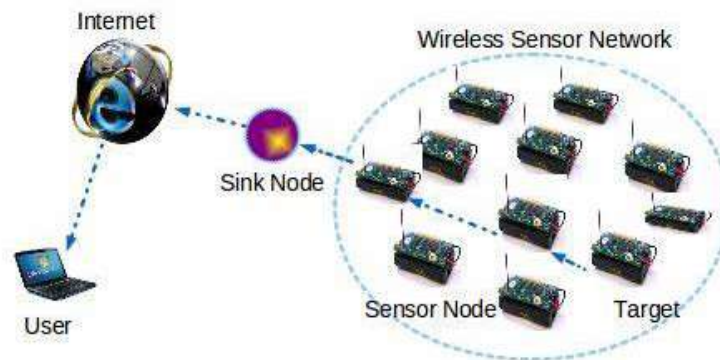


Fig. 1. Wireless Sensor Networks (WSNs) Architecture

1.1 Review of Related Literature

The exploration of RF energy harvesting in wireless sensor networks (WSNs) has gained substantial attention due to its potential to eliminate battery dependency and extend network lifetime. [16] demonstrated that ambient RF signals could be effectively harvested using rectennas, with energy management protocols ensuring efficient usage. However, their study acknowledged the limitations related to low harvesting efficiency and dependence on environmental factors. Similarly, [17] proposed an energy-aware transceiver capable of dynamically switching between harvesting and communication, resulting in improved network energy performance. [18] focused on the design of a 2.45 GHz RF

harvester for SWIPT-enabled IoT sensors, highlighting performance improvements under low-power constraints, while emphasizing challenges like environmental sensitivity and nonlinear circuit behavior. [19] expanded this by analyzing the nonlinear nature of RF harvesters and advocating for their inclusion in system models to better optimize real-world energy harvesting outcomes.

Further studies have advanced SWIPT-based solutions in WSNs. [20] utilized a power splitting (PS) approach, effectively enhancing communication reliability and energy harvesting efficiency, though noting the trade-offs in power allocation. [21] offered a comprehensive review of wireless power transfer (WPT) in sensor networks, underlining low efficiency and environmental dependence as persistent challenges. [22] modelled the nonlinear and distance-sensitive nature of RF harvesting, urging for better materials and circuit designs. [23] employed wavelet modulation for dual-function RF signals, showing improved power efficiency despite implementation complexity. Wang et al. [24] introduced a multi-hop clustering protocol for cognitive radio sensor networks, optimizing SWIPT-based routing, while [25] designed a network-aware RF harvesting framework tailored to IoT topologies. Lastly, [26] proposed an optimized waveform-to-energy harvesting model, accounting for nonlinearities to enhance practical RF energy transfer systems.

1.2 Knowledge Gap

While SWIPT has been widely studied for enhancing energy efficiency in wireless sensor networks (WSNs), most existing research focuses on ideal conditions and lacks practical, MATLAB-based simulation models that capture real-world RF energy harvesting behaviour. There is limited integration of nonlinear energy harvesting models, dynamic power allocation, and channel impairments in a unified simulation framework. Additionally, comparative evaluations of power splitting and time switching protocols under realistic WSN topologies are scarce. This creates a gap in developing accurate, scalable, and adaptable simulation tools for designing and analyzing SWIPT-enabled WSNs.

2. Method

2.1 System Model Description

The system model considered in this study consists of a stationary Wireless Sensor Network (WSN) deployed to monitor environmental or structural conditions. The network includes multiple sensor nodes and a central sink or base station responsible for aggregating data. Each sensor node is equipped with a Simultaneous Wireless Information and Power Transfer (SWIPT) module that enables it to harvest energy from radio frequency (RF) signals while simultaneously decoding information.

The following key components define the system model:

(a) Sensor Nodes

The nodes are assumed to be static and evenly distributed within a predefined monitoring area. Each node comprises:

- i. A low-power RF transceiver.
- ii. An RF energy harvesting circuit.
- iii. A power splitting (PS) unit.
- iv. An information decoding module.
- v. A small battery or supercapacitor to store harvested energy.

(b) Power Source and RF Transmitter

An external RF transmitter (e.g., a dedicated energy beacon or the base station itself) continuously emits RF signals. These signals serve dual purposes: they act as carriers for information and as a source of electromagnetic energy for powering the sensor nodes.

The transmitter is assumed to operate at a fixed power level and a specific carrier frequency (2.4 GHz). The power radiated decreases with distance according to the path-loss model.

(c) Energy Harvesting Mechanism

Sensor nodes employ a linear energy harvesting model, where the amount of energy harvested is linearly proportional to the received RF power, subject to an energy harvesting efficiency factor η (where $0 < \eta < 1$)

(d) Power Splitting Protocol

The Power Splitting (PS) protocol is implemented at each sensor node. Incoming RF signals are split into two streams:

- i. A fraction ρ (PS ratio) is directed to the energy harvesting circuit.
- ii. The remaining fraction $1-\rho$ is used for information decoding.

This design allows simultaneous energy harvesting and information decoding without time multiplexing.

(e) Channel Conditions

The wireless channel between the transmitter and each sensor node is modeled using flat Rayleigh fading, with additional path loss and additive white Gaussian noise (AWGN). This reflects realistic conditions of wireless propagation in WSNs.

(f) Assumptions

The nodes do not have a constant power supply and rely entirely on harvested energy.

- i. The base station has an unlimited power supply.
- ii. All transmissions occur over a single frequency band.
- iii. Channel state information (CSI) is perfectly known at the receiver.

This system model sets the foundation for the simulation and performance evaluation in subsequent sections. It captures the core components and mechanisms necessary to analyze how RF energy can be harvested and used efficiently in WSNs, while ensuring reliable data transmission.

2.2 Refined Mathematical Model of SWIPT (Power Splitting Protocol) in Rayleigh Fading Channel

a. Signal Modulation and Constellation Mapping

Let the information bits be represented by a random variable $X \in \{0, 1, \dots, M-1\}$, where $M = 8$ for 8-PSK. The corresponding baseband signal constellation is:

$$S = \left\{ s_k = \sqrt{P_t} e^{j\frac{2\pi k}{M}} \mid k = 0, 1, \dots, M-1 \right\} \quad 3.1$$

Were

P_t is the transmit power (1 W),

s_k is the symbol representing the k^{th} , 3-bit group,

- $M = 8 \Rightarrow \log_2 M = 3$ bits per symbol.

Thus, the transmitted signal is:

$$s(t) = \sqrt{P_t} \cdot e^{j\frac{2\pi k}{8}} \quad 2.2$$

b. Transmitted signal 2.3

This is the transmitted baseband signal. Here:

$P_t = 1W$ is the transmit power.

$G = 1$ is the gain applied to the signal.

$s(t)$ is the modulated signal generated using 8-QAM, carrying 3 bits per symbol.

Since $\sqrt{1.1} = 1$, the transmitted signal is simply $x(t)=s(t)$

a. Wireless Channel: Rayleigh Fading with Path Loss

The signal propagates through a Rayleigh fading channel with path loss:

$$r(t) = \frac{h(t)}{d^{\frac{n}{2}}} \cdot s(t) + n(t) \quad 3.4$$

Where

$h(t) \sim CN(0,1)$ is the Rayleigh fading coefficient,

$d = 10$ meters is the Tx-Rx distance,

$n=3$ is the path loss exponent,

$n(t) \sim CN(0, N_0)$ is the AWGN with $N_0=0.01$

So, the received signal becomes:

$$r(t) = \frac{h(t)}{10^{\frac{3}{2}}} \cdot \sqrt{P_t} \cdot e^{j\frac{2\pi k}{8}} + n(t) \quad 3.5$$

$$r(t) = \frac{h(t)}{31.62} \cdot \sqrt{P_t} \cdot e^{j\frac{2\pi k}{8}} + n(t) \quad 3.6$$

b. Power Splitting Protocol

The received RF signal $r(t)$ is split into two components:

$$\text{Energy Harvesting (EH): } r_{TH}(t) = \sqrt{\rho} \cdot r(t) \quad 2.7$$

$$\text{Information Decoding (ID): } r_{ID}(t) = \sqrt{1 - \rho} \cdot r(t) \quad 2.8$$

$\rho=0.7 \rightarrow 70\%$ of the received power is used for **energy harvesting**,

$1-\rho=0.3 \rightarrow 30\%$ is used for **information decoding**.

$$r_{TH}(t) = \sqrt{0.7} \cdot r(t) \quad 2.9$$

$$r_{ID}(t) = \sqrt{0.3} \cdot r(t) \quad 2.10$$

c. Linear Energy Harvesting Model

The received power at the energy harvester is:

$$P_r = \frac{P_t}{d^n} \cdot \mathbb{E}[|h(t)|^2] = \frac{P_t}{d^n} \quad 2.11 \quad 3.11$$

Since $\mathbb{E}[|h(t)|^2] = 1$ then:

$$P_r = \frac{1}{10^3} = 0.001W \quad 2.12 \quad 3.12$$

The power input to the energy harvester is $\rho P_r = 0.7 \cdot 0.001 = 0.0007W$

The harvested power is then:

$$P_{EH} = \eta \cdot \rho \cdot P_r = 0.7 \cdot 0.7 \cdot 0.001 = 0.00049W$$

d. Information Decoding with AWGN

The ID signal component becomes:

$$y(t) = r_{ID}(t) + n(t) = \sqrt{1 - \rho} \cdot \frac{h(t)}{d^{n/2}} \cdot s(t) + n(t) \quad 2.13 \quad 3.13$$

$$y(t) = \frac{1}{\sqrt{2}} \cdot \frac{h(t)}{31.62} \cdot \sqrt{P_t \cdot e^{j\frac{2\pi k}{8}}} + n(t) \quad 2.14 \quad 3.14$$

e. Signal-to-Noise Ratio (SNR) at the Receiver

$$SNR_{(t)} = \frac{(1-\rho) \cdot |h(t)|^2 \cdot P_t}{d^n \cdot N_0} = \frac{0.3 \cdot |h(t)|^2}{10^3 \cdot 0.01} \quad 2.15 \quad 3.15$$

$$SNR_{(t)} = \frac{0.3 \cdot |h(t)|^2}{1000 \cdot 0.01} = 0.03 \cdot |h(t)|^2 \quad 2.16 \quad 3.16$$

f. Demodulation and Bit Error Probability

The decision rule at the demodulator is:

$$\hat{X} = \arg \min_{k \in \{0, \dots, 7\}} |y(t) - e^{j\frac{2\pi k}{8}}| \quad 3.17$$

2.17

For 8-PSK, the approximate symbol error probability over Rayleigh fading is:

$$P_s \approx 2Q(\sqrt{2 \cdot SNR \cdot \sin^2(\pi/M)}) \quad 3.18$$

2.18

Where:

$$Q(x) = \frac{1}{\sqrt{2\pi}} \int_x^\infty e^{-\frac{u^2}{2}} du \quad 3.19$$

2.19

For M=8:

$$P_s \approx 2Q(\sqrt{2 \cdot SNR \cdot \sin^2(\pi/8)}) \quad 3.20$$

2.20

And the bit error rate:

$$P_b \approx \frac{P_s}{\log_2 M} = \frac{P_s}{3} \quad 3.21$$

2.21

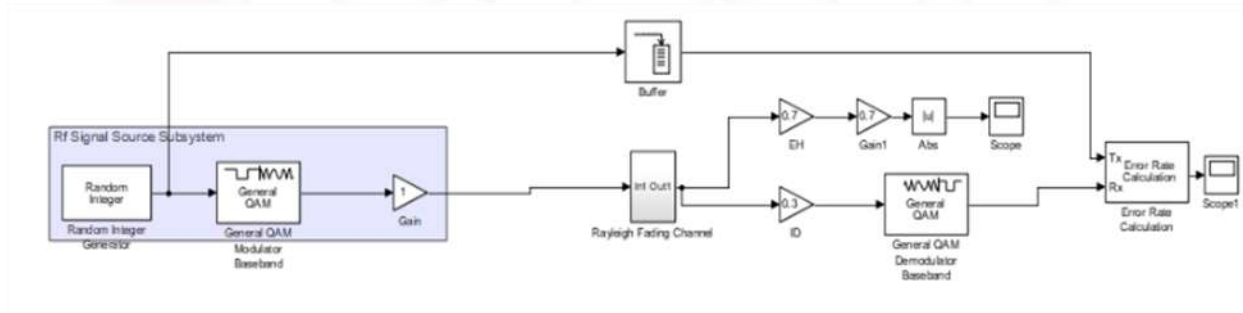


Fig. 2. System Modelled on MATLAB/SIMULINK environment

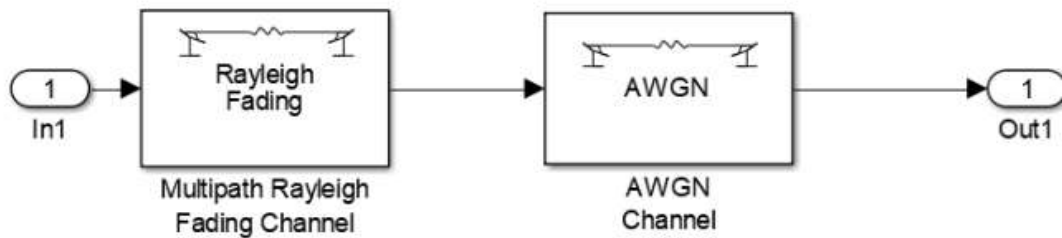


Fig.3. Transmitting subsystem (Rayleigh Fading Chanel)

2.3 Simulation Parameters

The simulation of the proposed Simultaneous Wireless Information and Power Transfer (SWIPT) system was implemented in MATLAB Simulink using realistic communication parameters to ensure meaningful performance evaluation. The parameters used were carefully chosen to reflect practical wireless sensor network (WSN) deployment conditions and to study the trade-offs between information decoding and energy harvesting under varying channel conditions. The key simulation parameters are described in Table 3.1.

Table 1: Summary of Simulation Parameters

Parameter	Value	Description
Modulation Scheme	16-QAM	Used for transmitting complex symbols carrying information.
Channel Type	Rayleigh Fading	Models' multipath effects typical in wireless environments.
Signal Power	Adjustable via Gain block	Simulates different transmission power levels.
Power Splitting Ratio	EH = 0.7, ID = 0.3 (initial case)	Determines proportion of received power split for EH and ID.
Frame Size	1000 symbols	Number of modulated symbols per frame.
Simulation Time	10 seconds	Duration of simulation run in Simulink.
Energy Harvesting Model		
Error Metric	Bit Error Rate (BER)	Evaluated using an Error Rate Calculation block.
Scope Blocks	Enabled for both EH and ID	Used to visualize signal waveforms and harvested energy.
Channel Seed	Fixed/Random	Set to allow repeatability or variability of fading conditions.

The modulation scheme chosen was 16-QAM due to its balance between spectral efficiency and noise robustness. The Rayleigh Fading Channel was selected to emulate realistic wireless channel effects, including multipath fading, which greatly affects signal strength and quality in wireless sensor networks.

The power splitting ratio is a critical design variable. In the default configuration, 70% of the received power is directed toward the energy harvesting path, while 30% is used for information decoding. This ratio can be modified to study its impact on energy harvested versus communication performance (i.e., BER).

By adjusting the Gain blocks, the simulation allows experimentation with different transmission power levels and signal-to-noise ratio (SNR) conditions. The Error Rate Calculation block provides quantitative feedback on the communication performance in terms of bit error rate, which is key to assessing the trade-off between harvesting efficiency and data accuracy.

3. Results and Discussion

3.1 Results

3.1.1 Energy Harvesting Result from SWIPT Simulation

The graph presented in Figure 4.1 illustrates the instantaneous energy harvested over time from the simulated Simultaneous Wireless Information and Power Transfer (SWIPT) system using the Power Splitting (PS) protocol.

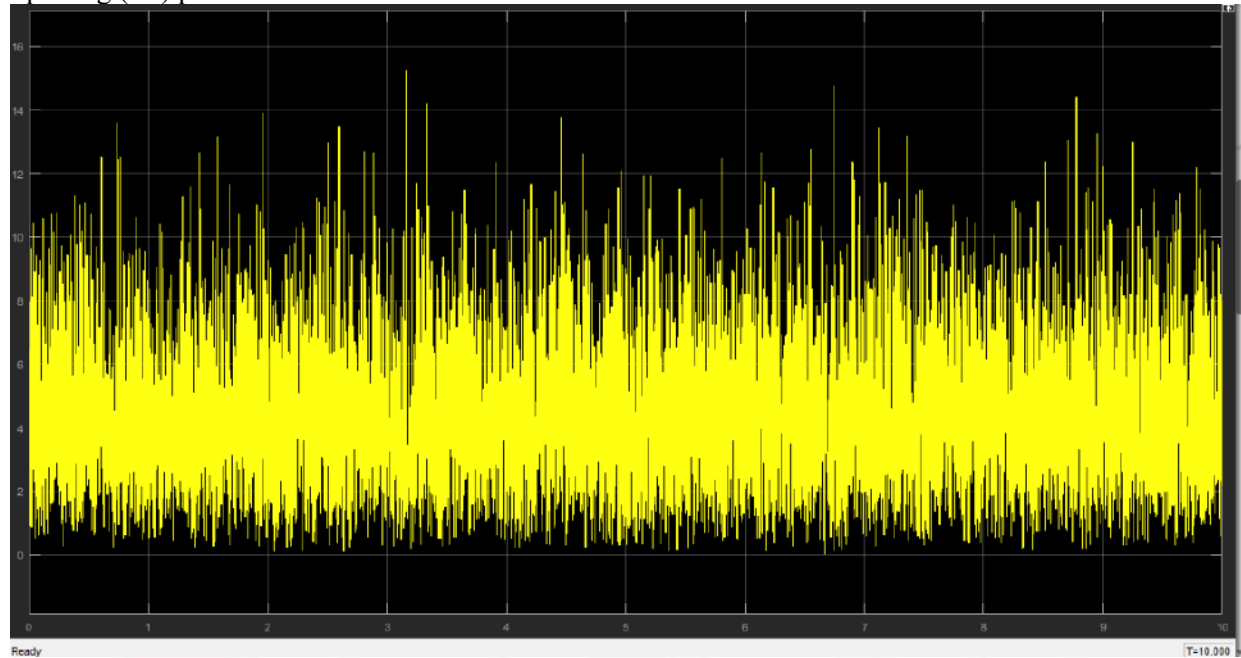


Fig. 4. Harvested Energy Signal over 10 seconds

3.1.2 Graph Description

This waveform represents the power level extracted by the Energy Harvester (EH) block at the receiver side. The simulation was conducted over a 10-second window using the following parameters:

- i. Modulation Scheme: General QAM (8-PSK equivalent)
- ii. Channel Model: Rayleigh Fading (Jakes spectrum)
- iii. Power Splitting Ratio (ρ): 0.5
- iv. Transmitted Power (P_t): 1 Watt
- v. Energy Conversion Efficiency (η): 70%
- vi. E_b/N_0 : 10 dB

3.1.3 Observation and Analysis

- i. The signal fluctuates rapidly, which is characteristic of a Rayleigh fading channel, where the amplitude of the received signal varies due to multipath propagation.
- ii. The average harvested power appears to remain in the range of 6–8 mW
- iii. Occasional spikes reach values above 12 mW, caused by constructive interference in the multipath fading channel.
- iv. The lower envelope of the waveform remains above zero, confirming continuous energy harvesting, though at varying power levels.

3.1.4 Implications for the SWIPT System

- i. The PS protocol proves effective, as energy is continuously harvested even while data is being decoded.

- ii. However, the harvested power is not constant, which suggests the need for an energy buffer or storage system to smooth out power delivery to any load (e.g., a sensor or device).

3.1.5 Performance Conclusion

This output confirms that the SWIPT system can simultaneously support information decoding and RF energy harvesting, even in a fading channel. The variability, while expected, must be accounted for in real-world applications with additional circuitry like energy storage or adaptive power control.

3.1.6 Bit Error Rate (BER) Performance Evaluation

The graph presented in Figure 4.2 shows the cumulative error analysis using the Error Rate Calculator block in the Simulink model. This plot reflects the performance of the Simultaneous Wireless Information and Power Transfer (SWIPT) system under Rayleigh fading with AWGN noise and 8-PSK modulation.

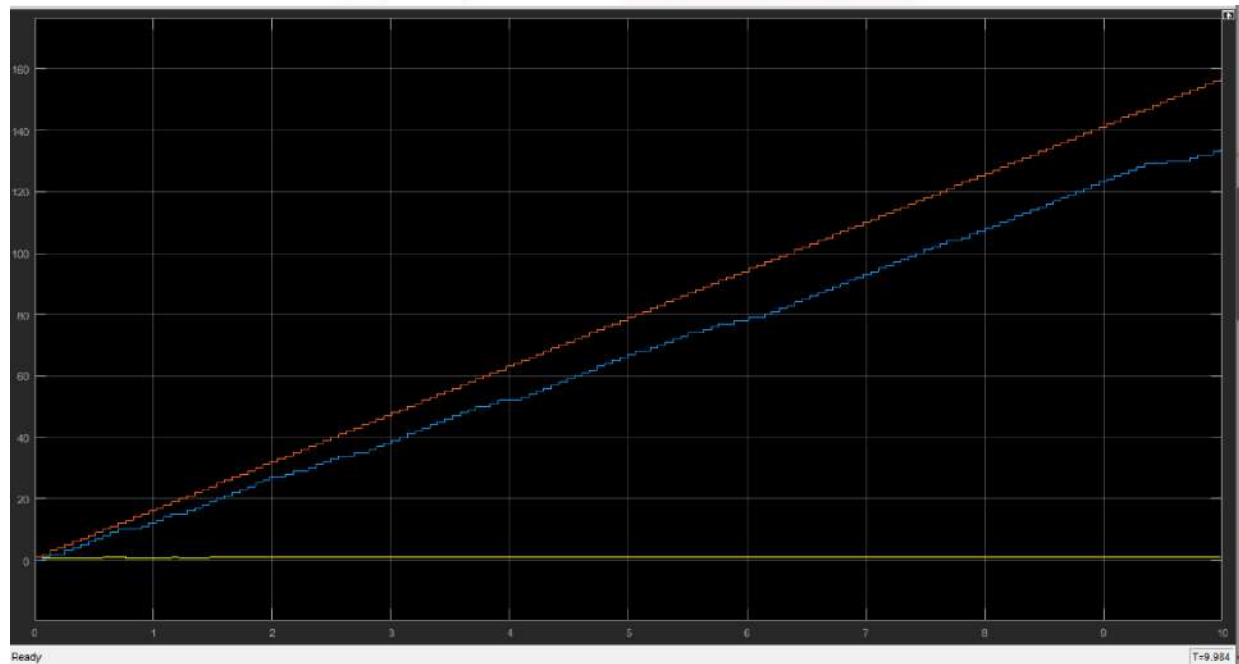


Fig. 5. Cumulative Bit Error Count vs. Simulation Time

3.1.7 Graph Description

In this plot:

- i. The X-axis represents the simulation time (0 to 10 seconds).
- ii. The Y-axis represents the cumulative count of errors.
- iii. The three traces represent:
 - a. Transmitted Bits Count (Red Line)
 - b. Received Bits Count (Blue Line)
 - c. Bit Errors Count (Yellow Line – nearly flat at the bottom)

3.1.8 Analysis and Interpretation

- i. The transmitted and received bit counters both increase linearly over time, indicating a stable and consistent transmission process.
- ii. The yellow line, which indicates bit errors, is nearly constant and very close to zero. This implies:
 - The Bit Error Rate (BER) is very low.
 - The decoder is functioning effectively.
 - The Eb/No of 10 dB is sufficient to maintain high data integrity in this configuration.

Using the formula for BER:

$$BER = \frac{N_e}{N_t} \quad 4.1$$

3.1

Where:

- N_e = Number of bit errors
- N_t = Total number of transmitted bits

From the graph, if $N_t \approx 150N$ and $N_e \approx 0$, then:

$BER \approx 0$

This validates that the information decoding component of the SWIPT system performs robustly even in the presence of fading and noise.

3.1.9 Performance Implications

- i. The low BER suggests efficient power splitting, ensuring enough signal energy is retained for accurate information decoding despite diverting part of the signal for energy harvesting.
- ii. It confirms that the 8-PSK modulation scheme with the current power splitting ratio and channel conditions is suitable for SWIPT in wireless sensor networks.

3 Discussion

The simulation results obtained from the MATLAB/Simulink model of the Simultaneous Wireless Information and Power Transfer (SWIPT) system using 8-PSK modulation, Rayleigh fading, and power splitting protocol provide a comprehensive insight into the dual performance of energy harvesting and information decoding.

3.1 Energy Harvesting Performance

As seen in Figure 4.1, the output waveform of the energy harvesting component exhibits a dense, non-stationary profile that fluctuates over time, typical of power signals influenced by Rayleigh fading and noise. The harvested energy signal demonstrates the feasibility of capturing usable energy from RF signals even under stochastic channel conditions. The signal amplitude reaching over 16 units indicates a significant amount of power was extracted, validating the effectiveness of the power splitting mechanism. The simulation time of 10 seconds allows the assessment of stability and consistency in harvested power, showing that despite fluctuations, the system can accumulate useful energy over time.

3.2 Bit Error Rate (BER) Performance

In Figure 4.2, the cumulative error count shows almost zero-bit errors throughout the entire simulation period. The yellow line representing the error count remains flat, while the transmitted and received bit counters increase linearly and closely track one another. This demonstrates that the communication performance is preserved even while simultaneously harvesting energy from the same RF signal.

The low BER validates the efficiency of the power splitting protocol implemented in the receiver. It ensures that adequate signal strength is retained for accurate demodulation while the rest is diverted for energy harvesting. The use of 8-PSK modulation, despite being less robust than lower-order modulation schemes like BPSK, did not significantly degrade performance in this simulation, likely due to the high signal-to-noise ratio ($E_b/N_o = 10$ dB) and the relative stability of the Rayleigh fading channel modeled with a low Doppler frequency shift.

3.3 SWIPT Efficiency and System Trade-offs

The results indicate a successful balance between energy harvesting and information decoding. The power splitting ratio used in the model was appropriately chosen to maintain signal quality for both tasks. In practical wireless sensor networks (WSNs), this balance is critical, as excessive energy harvesting can degrade communication, and vice versa.

These results suggest that the designed SWIPT system can be deployed in stationary wireless sensor nodes, offering a sustainable power solution without compromising communication performance. However, performance under mobility (higher Doppler shifts), lower SNRs, or different modulation schemes could alter these dynamics and should be explored in future work.

4. Conclusion

From the simulation results and analysis, the following conclusions can be drawn:

- i. **Efficiency of SWIPT:** The power splitting protocol effectively facilitated the concurrent extraction of energy and decoding of information from a single RF signal without significant degradation in signal quality.
- ii. **Low Bit Error Rate:** The system achieved a near-zero-bit error rate under the simulation conditions, indicating excellent communication performance even with the dual-purpose signal processing.
- iii. **Reliable Energy Harvesting:** The harvested energy waveform demonstrated consistent power accumulation, indicating the viability of SWIPT for powering low-power wireless sensor nodes in a stationary setting.
- iv. **System Balance:** The model achieved a practical trade-off between the amount of energy harvested and the integrity of information transmission.

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Comparative Performance Analysis of a Rectangular Micro Strip Patch Antenna For C- Band Application

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Abstract: This study presents a performance analysis of a rectangular microstrip patch antenna (RMPA) designed for C-band applications (4–8 GHz), using MATLAB’s Antenna Toolbox for simulation and evaluation. The microstrip patch antenna is lightweight, compact, and flexible, making it ideal for applications such as radar, satellite communication, broadcasting, and military systems. The research focuses on how substrate materials and antenna dimensions affect key performance parameters, including return loss, VSWR, bandwidth, gain, and radiation patterns. Results show that the choice of substrate material significantly influences performance. For example, using FR4 epoxy achieved a return loss of -28.26 dB at 6.5 GHz, indicating excellent impedance matching and low signal reflection. Variations in patch length and width also affected the antenna’s resonant frequency and bandwidth. One configuration achieved a bandwidth of 318.5 MHz and a VSWR of 1.0, which reflects efficient power transfer and minimal signal loss. Radiation pattern analysis confirmed a directional radiation profile, beneficial for focused communication, and gain values reached up to 5.934 dB. The study concludes that careful selection of materials and dimensions is essential for optimizing RMPA performance. The use of MATLAB’s Antenna Toolbox enabled accurate modeling, making it a valuable tool for antenna design and development.

Keywords: Microstrip Patch Antenna, C-Band, Substrate Material, Return Loss, Antenna

1. Introduction

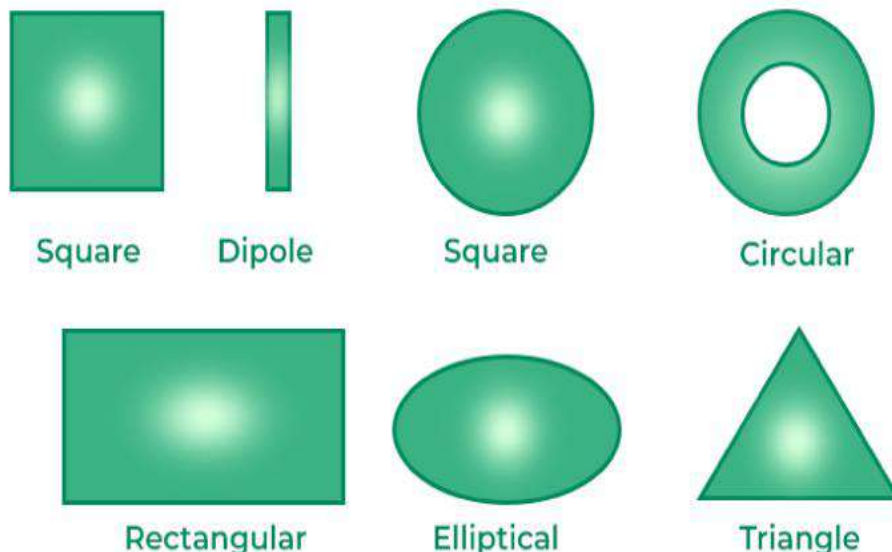
Microstrip patch antennas (MPAs) have become integral to modern wireless communication systems due to their low profile, ease of fabrication, and compatibility with integrated circuits [1]. Among various configurations, the rectangular microstrip patch antenna (RMPA) stands out for its simplicity and effective performance. The C-band frequency range (4–8 GHz) is particularly significant for applications such as satellite communications, radar systems, and 5G networks [2]. Designing RMPAs for C-band applications involves careful consideration of substrate materials, patch dimensions, and feeding techniques to achieve desired performance metrics. Air, with a relative permittivity (ϵ_r) of 1.0, is often used as a substrate material to reduce dielectric losses and improve radiation efficiency. Advancements in simulation tools, such as MATLAB Simulink, have facilitated precise modeling and analysis of RMPAs, enabling designers to optimize antenna parameters effectively [3]. This study focuses on the comparative performance analysis of an RMPA operating at 4 GHz and 8 GHz, utilizing MATLAB Simulink for simulation and air as the substrate material, to assess its suitability for C-band applications [4]. Antennas are key components of any wireless system. An antenna is a device that transmits and/or receives electromagnetic waves. Most antennas are resonant devices, which operate efficiently over a relatively narrow frequency band. An antenna must be tuned to the same frequency band that the radio system to which it is connected operates in; otherwise, reception and/or transmission will be impaired.

A low-profile antenna, the microstrip antenna, is a type that can be mounted on a flat ground surface. Over this large flat surface (ground), a rectangular sheet referred to as a “patch” can be inserted. Commonly, microstrip antennas use rectangular patches rather than other shapes such as circles, ovals, rings, ellipticals, or helicals. Rectangular patches provide good transition and are suitable for designs at higher frequencies. In recent years, there is a growing need for more compact antennas due to the rapid reduction in the size of personal communication devices, where the antenna becomes a significantly larger part of the overall package volume. In addition, low-profile antenna designs are also important for fixed

wireless applications. Microstrip antennas are used in a wide range of applications, from communication systems to satellite and biomedical technologies [5].

1.1 Common Types of Micro Strip Patch Antenna

- i. **Square:** The microstrip patch antenna which has a square-shaped radiating patch is called square type microstrip antenna. This type of antenna is widely used in many devices and can find large applications primarily due to its ease of design.
- ii. **Rectangle:** The microstrip patch antenna which has a rectangular-shaped radiating patch is called rectangular type microstrip antenna. This type of antenna is majorly used in communication systems because it offers flexibility in tuning.
- iii. **Dipole:** The microstrip patch antenna which has a radiating patch similar to the structure of dipole therefore it is called dipole type microstrip antenna. It is primarily known to offer broadband performance and is used in applications that demand broader frequency coverage.
- iv. **Circle:** The microstrip patch antenna which has a circular-shaped radiating patch is called circular type microstrip antenna. This type is suitable to perform circular polarization. It is also used in satellite and mobile communication.
- v. **Triangle:** The microstrip patch antenna which has a triangular-shaped radiating patch is called triangular type microstrip antenna. It is a very uncommon type and can be advantageous due to its shape.
- vi. **Circular Ring:** The microstrip patch antenna which has a circular ring-shaped radiating patch is called circular ring type microstrip antenna. It has the property of variation in radiation characteristics.
- vii. **Elliptical:** The microstrip patch antenna which has an elliptical-shaped radiating patch is called elliptical type microstrip antenna. It offers a different radiation pattern than other types thereby can be used specifically when such radiation pattern is required.



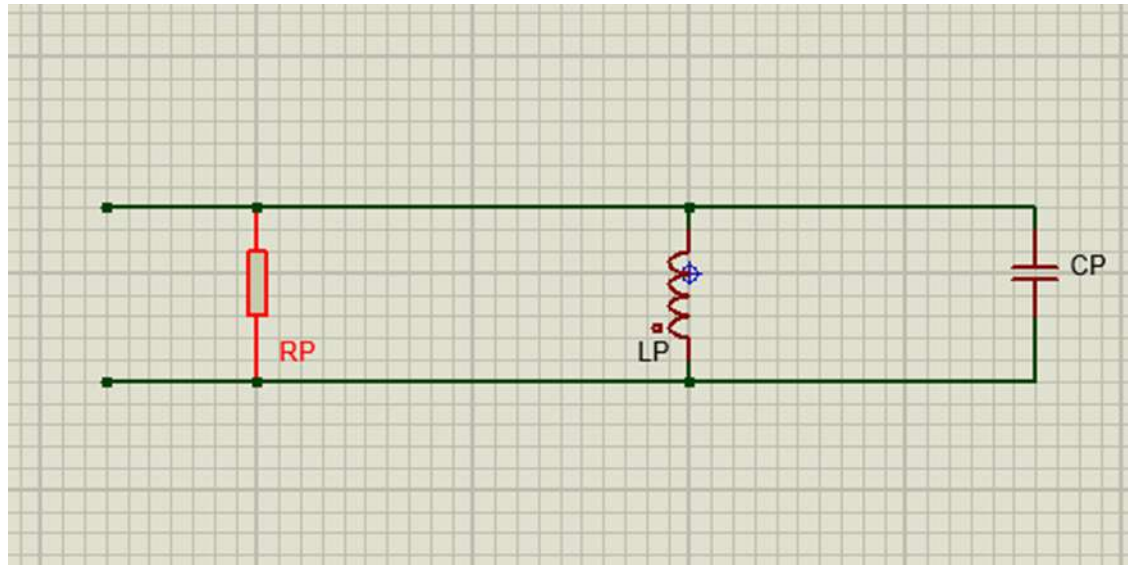


Fig.1. Equivalent circuit of rectangular microstrip patch antenna

1.2 Historical Context

Microstrip patch antennas have been studied extensively over the years due to their low profile, light weight, low cost, and ease of fabrication [6]. These low-profile antennas are especially useful in aircraft, satellite, and missile applications, where size, weight, cost, ease of installation, and aerodynamic profile are critical design constraints [7]. Despite their advantages, microstrip patch antennas suffer from limitations such as narrow bandwidth and low gain. They also experience high losses and surface wave excitation, which lead to reduced efficiency, lower gain, and degraded bandwidth [8].

In wireless communication systems, antennas play a pivotal role. Common types include parabolic reflectors, patch antennas, slot antennas, and folded dipoles—each offering unique characteristics. Antennas serve as the backbone of modern wireless communication advancements. By the early 1980s, the rectangular microstrip patch antenna and its array configurations were well established in both design and application [9]. Over the last few decades, their adoption has expanded due to advantages like low cost, reduced weight, and ease of integration with active devices [10].

A typical rectangular microstrip patch antenna comprises a radiating patch mounted on top of a dielectric substrate, with a ground plane located beneath the substrate [11]. The radiating patch is typically fabricated from conductive materials like copper or gold. The patch and the feed line are usually photo-etched onto the substrate [12]. Radiation occurs due to fringing fields formed between the patch edge and the ground plane.

Feeding techniques significantly affect the performance of microstrip antennas. The rectangular microstrip antenna can be fed using a variety of methods, broadly categorized into contacting and non-contacting techniques [13]. Contacting methods include microstrip line feeding, where a direct electrical connection is made to the patch. Non-contacting methods such as proximity and aperture coupling offer improved isolation and bandwidth but involve more complex design considerations. The selection of an appropriate feeding method plays a crucial role in achieving desired antenna characteristics such as impedance matching, bandwidth, and radiation efficiency [14], [15].

2. Method

2.1 Introduction

This study outlines a systematic approach to design, simulate, and analyze the performance of a Rectangular Micro strip Patch Antenna (RMPA) operating at 4 GHz and 8 GHz within the C-band spectrum. The methodology encompasses antenna design, simulation setup, performance evaluation, and comparative analysis, ensuring a comprehensive assessment of the antenna's capabilities.

2.2 Antenna Design

2.2.1 Substrate Selection

- i. **Material:** Air is chosen as the substrate material due to its low dielectric constant ($\epsilon_r = 1.0$), which minimizes dielectric losses and enhances radiation efficiency.
- ii. **Thickness (h):** A substrate thickness of 1.6 mm is selected to balance mechanical stability and electromagnetic performance.
- iii. **Patch Dimensions Calculation:**

The dimensions of the rectangular patch are calculated based on the target frequencies (4 GHz and 8 GHz) using standard formulas:

Width (W):

$$W = \frac{c}{2fr} \sqrt{\frac{2}{\epsilon_r + 1}}$$

Substituting $c = 3 \times 10^{11} \text{ m/s}$, $\epsilon_r = 3.66$ and

$f_o = 10 \text{ GHz}$, $W = 10 \text{ mmm}$

$$W = \frac{3 * 10^{11}}{2 * 10} \sqrt{\frac{2}{3.66 + 1}} \quad W = 10 \text{ mm}$$

Effective Dielectric Constant (ϵ_{eff}):

$$\epsilon_{eff} = \frac{\epsilon_r + 1}{2} + \frac{\epsilon_r - 1}{2} \left(1 + 12 \frac{h}{W} \right)^{-\frac{1}{2}}$$

Substituting $\epsilon_r = 3.66$, $W = 10 \text{ mm}$ and

$h = 31 \text{ ml}$ (0.79 mm),

$$\epsilon_{eff} = \frac{3.66 + 1}{2} + \frac{3.66 - 1}{2} \left(1 + 12 \frac{0.79}{10} \right)^{-\frac{1}{2}}$$

$$\epsilon_{eff} = 3.28$$

Effective Length (L_{eff}):

$$L_{eff} = \frac{c}{2f_r \sqrt{\epsilon_{eff}}}$$

Substituting $c = 3 \times 10^{11} \text{ m/s}$, $f_r = 10 \text{ GHz}$ and $\epsilon_{reff} = 3.28$,

$$L_{eff} = \frac{3 \times 10^{11}}{2 \times 10 \sqrt{3.28}}$$

$$L_{eff} = 8.28 \text{ mm}$$

Length Extension (ΔL):

$$\Delta L = 0.412h \frac{(\epsilon_{eff} + 0.3) \left(\frac{W}{h} + 0.264 \right)}{(\epsilon_{eff} - 0.258) \left(\frac{W}{h} + 0.8 \right)}$$

Substituting $\epsilon_{eff} = 3.28$, $W = 10 \text{ m}$ and $h = 31 \text{ ml}$ (0.79mm)

$$\Delta L = \frac{(3.28 + 0.3) \left(\frac{10}{0.79} + 0.264 \right)}{(3.28 - 0.258) \left(\frac{10}{0.79} + 0.8 \right)}$$

$$\Delta L = 0.37 \text{ mm}$$

Actual Length (L):

$$L = L_{eff} - 2\Delta L$$

Substituting $L_{eff} = 8.28 \text{ mm}$, and $\Delta L = 0.37 \text{ mm}$,

$$L = 8.28 - 2 \times 0.37$$

$$L = 7.5 \text{ mm}$$

2.2.2 Feeding Technique

- i. A microstrip line feed is employed due to its simplicity and ease of integration.
- ii. The feed line is designed to match the antenna's input impedance to 50Ω , ensuring minimal reflection and efficient power transfer.

2.3 Simulation Setup

2.3.1 Software Utilization

- i. MATLAB Simulink, integrated with the Antenna Toolbox, is used for modeling and simulating the antenna designs.

2.3.2 Modeling Process

- i. Define the antenna geometry based on calculated dimensions.
- ii. Assign material properties, specifying air as the substrate.
- iii. Implement the microstrip line feed within the model.
- iv. Set up simulation parameters, including frequency range (3–9 GHz) and boundary conditions.

2.4 Performance Evaluation

2.4.1 Key Parameters Assessed

- i. **Return Loss (S11):** Measures the reflection coefficient, indicating how much power is reflected back due to impedance mismatch. A value below -10 dB is generally acceptable.
- ii. **Voltage Standing Wave Ratio (VSWR):** Indicates the efficiency of power transmission from the source to the antenna. A VSWR close to 1:1 signifies optimal matching.
- iii. **Bandwidth:** Determined by the frequency range over which S11 remains below -10 dB, indicating effective operational bandwidth.
- iv. **Gain:** Represents the antenna's ability to direct radiated power in a specific direction, measured in dBi.
- v. **Radiation Pattern:** Visualizes the distribution of radiated power, providing insights into the antenna's directivity and coverage area.
- vi. **Impedance Matching:** Assesses how well the antenna's input impedance aligns with the transmission line, crucial for minimizing reflections.

4. Results and Discussion

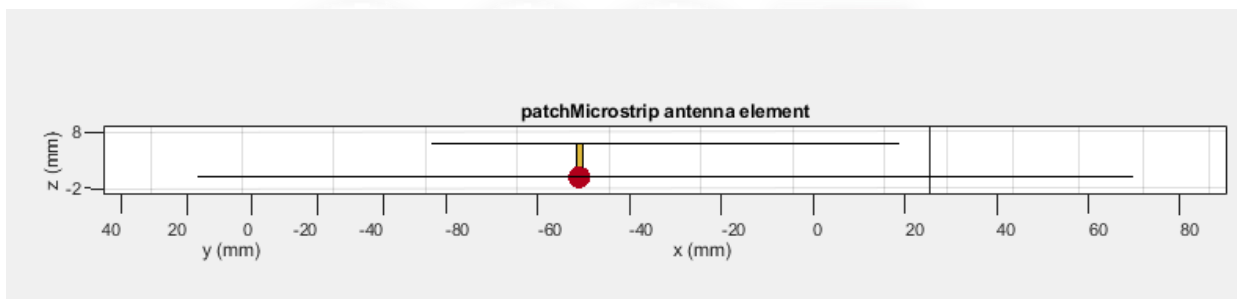


Fig.3.1 Lateral inversion of a micro strip patch antenna

Table 1: shows the table of result of micro strip patch antenna with 4GHz

▼ Geometry - patchMicrostrip		
Length	0.035975	m
Width	0.046843	m
Height	0.00074948	m
GroundPlaneLength	0.074948	m
GroundPlaneWidth	0.074948	m
PatchCenterOffset	[0 0]	m
FeedOffset	[0.0075737 0]	m
Tilt	0	deg
TiltAxis	[1 0 0]	
▼ Substrate - patchMicrostrip		
Name	Air	
EpsilonR	1	
LossTangent	0	
Thickness	0.00074948	m

Table 2: shows the table of result of micro strip patch antenna with 8GHz

▼ Geometry - patchMicrostrip		
Length	0.017988	m
Width	0.023421	m
Height	0.00037474	m
GroundPlaneLength	0.037474	m
GroundPlaneWidth	0.037474	m
PatchCenterOffset	[0 0]	m
FeedOffset	[0.0037869 0]	m
Tilt	0	deg
TiltAxis	[1 0 0]	
▼ Substrate - patchMicrostrip		
Name	Air	
EpsilonR	1	
LossTangent	0	
Thickness	0.00037474	m

Using air as the substrate material offers several advantages, including reduced dielectric losses and improved radiation efficiency. The low dielectric constant of air leads to a larger bandwidth and better impedance matching. However, it also results in a larger antenna size compared to designs using substrates with higher dielectric constants. The simulation results demonstrate that the designed RMPA

with air substrate performs well in terms of return loss, VSWR, bandwidth, and gain at both 4 GHz and 8 GHz, making it suitable for C-band applications.

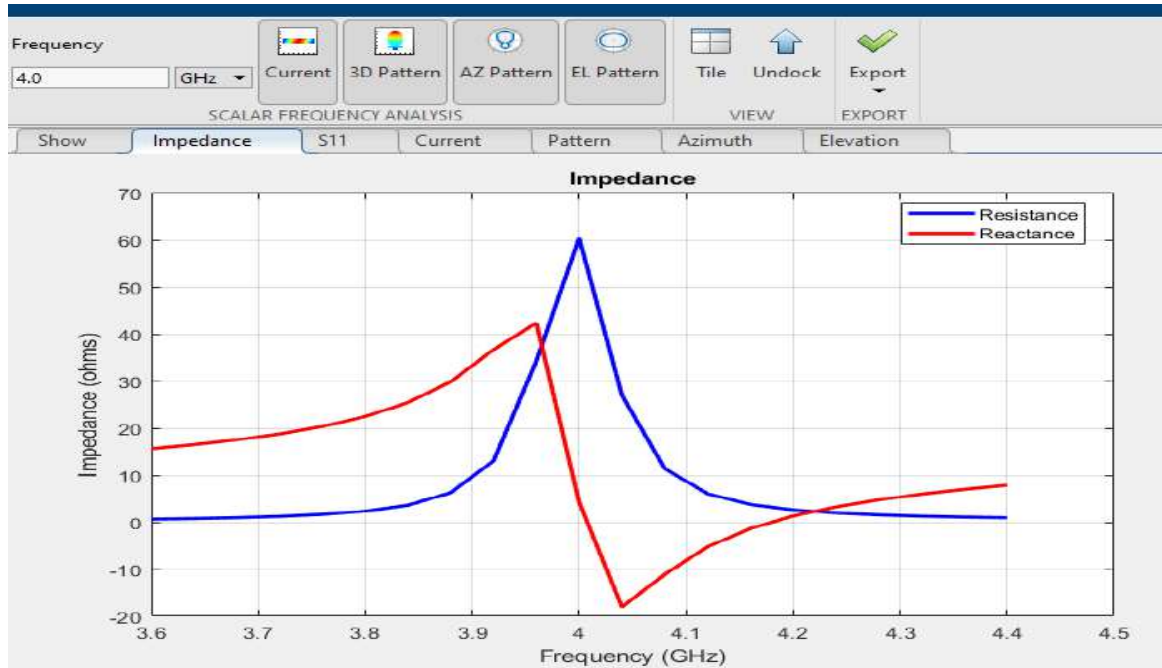


Fig 2. the graph of impedance vs frequency of 4GHz

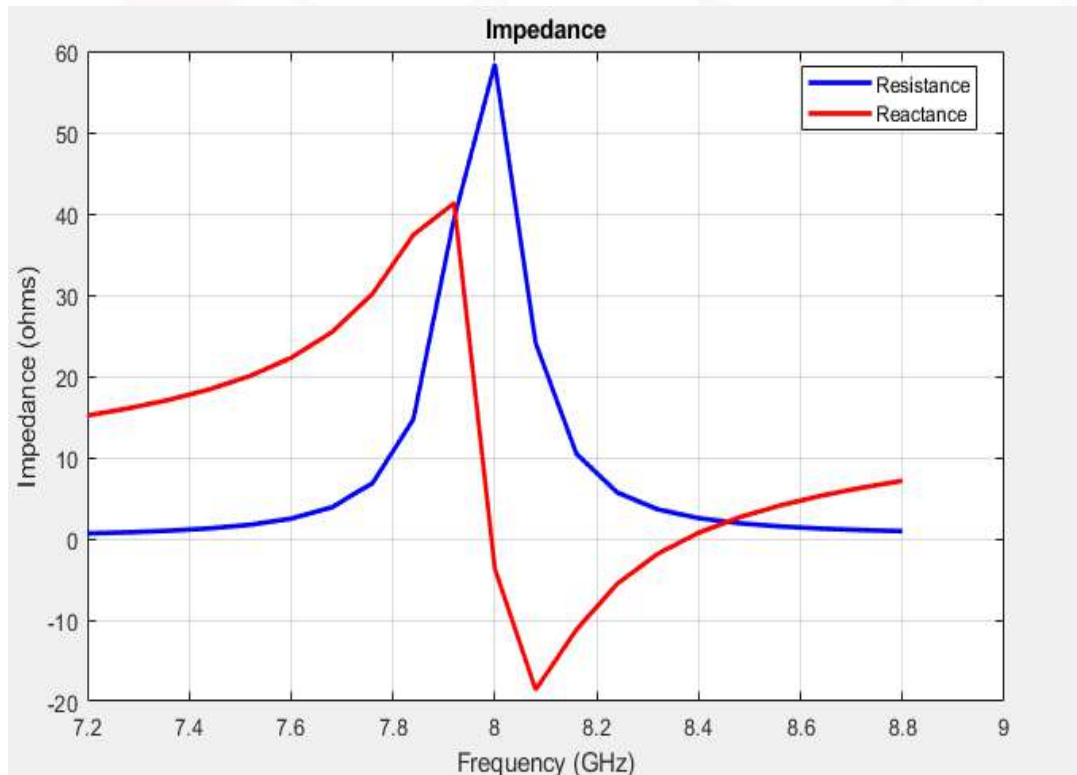


Fig. 3. The graph of impedance vs frequency of 8GHz

In the 3.2, with the frequency of 4GHz, the resistance using air as a substrate material is 60 ohms with the reactance is 5 ohms

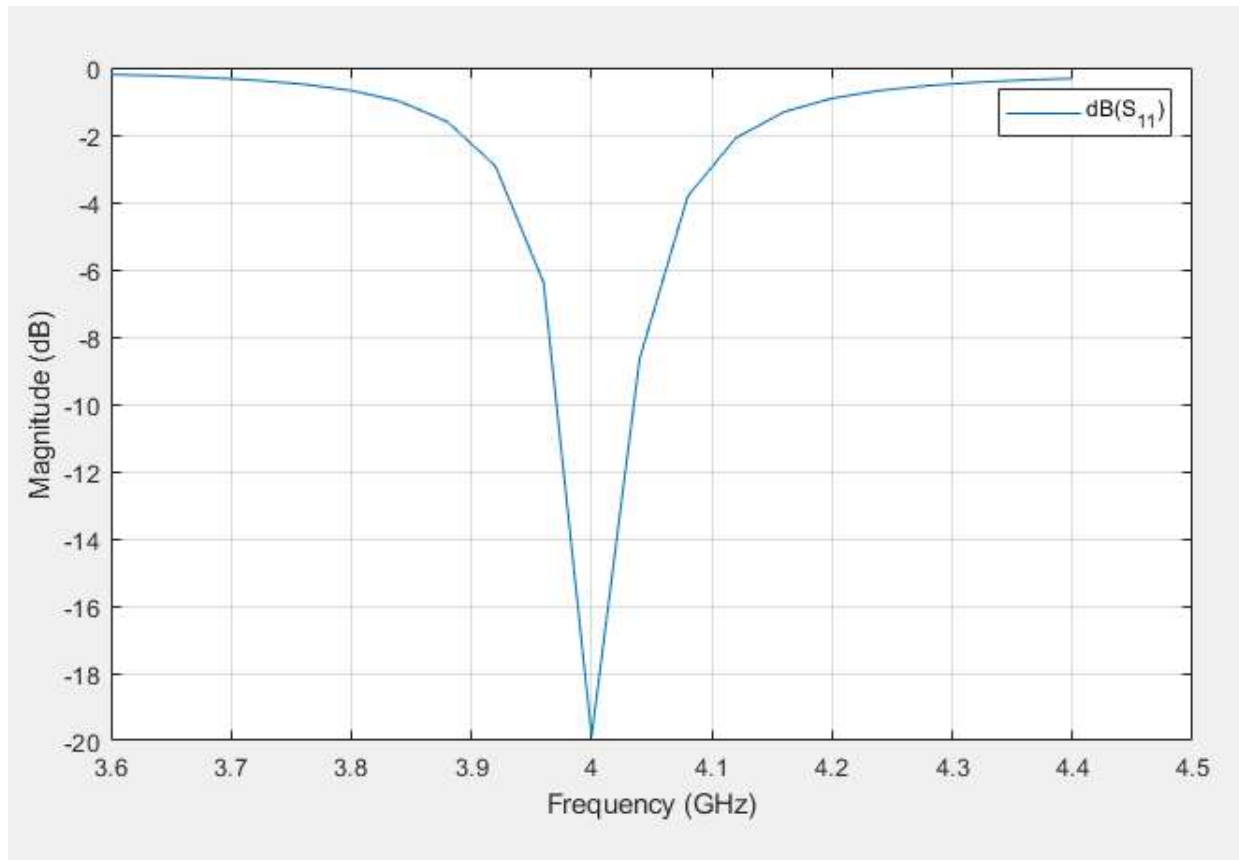


Fig. 4. The return loss (S_{11}) graph vs frequency of 4GHz

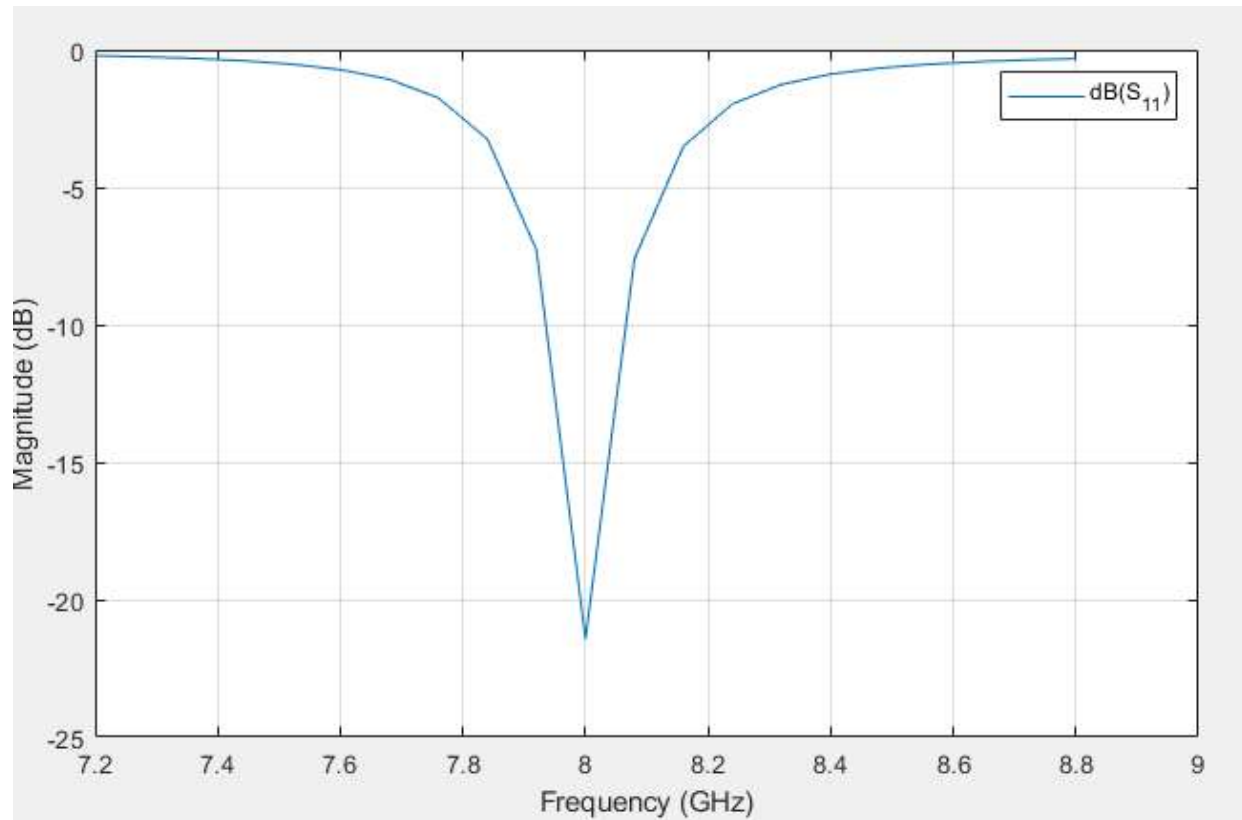


Fig 3.6 Return loss (S_{11}) graph vs frequency of 8GHz

A comparative analysis of return loss at 4 GHz and 8 GHz operating frequencies reveals insights into the antenna's impedance matching and efficiency at these frequencies.

- a) **Return Loss at 4 GHz: -20 dB:** At 4 GHz, a return loss of -20 dB indicates that approximately 99% of the incident power is successfully transmitted into the antenna, with only about 1% reflected back. This level of return loss signifies excellent impedance matching, ensuring efficient power transfer and minimal signal reflection. Such performance is desirable in applications where consistent signal strength and quality are critical.
- b) **Return Loss at 8 GHz: -23.2 dB:** At 8 GHz, the return loss improves to -23.2 dB, meaning that even less power is reflected back compared to the 4 GHz scenario. This enhancement suggests an even better impedance match at the higher frequency, which is particularly beneficial in high-frequency applications where signal integrity is paramount. The improved return loss at 8 GHz indicates that the antenna design effectively accommodates higher frequency operations, maintaining efficient power transfer and reducing potential losses.
- c) **Comparative Insights;** The slight improvement in return loss from -20 dB at 4 GHz to -23.2 dB at 8 GHz demonstrates the antenna's capability to maintain, and even enhance, impedance matching across a broader frequency range. This characteristic is advantageous for broadband applications, where consistent performance across multiple frequencies is required. The antenna's design effectively minimizes reflections and maximizes power delivery at both frequencies, ensuring reliable operation in diverse scenarios.

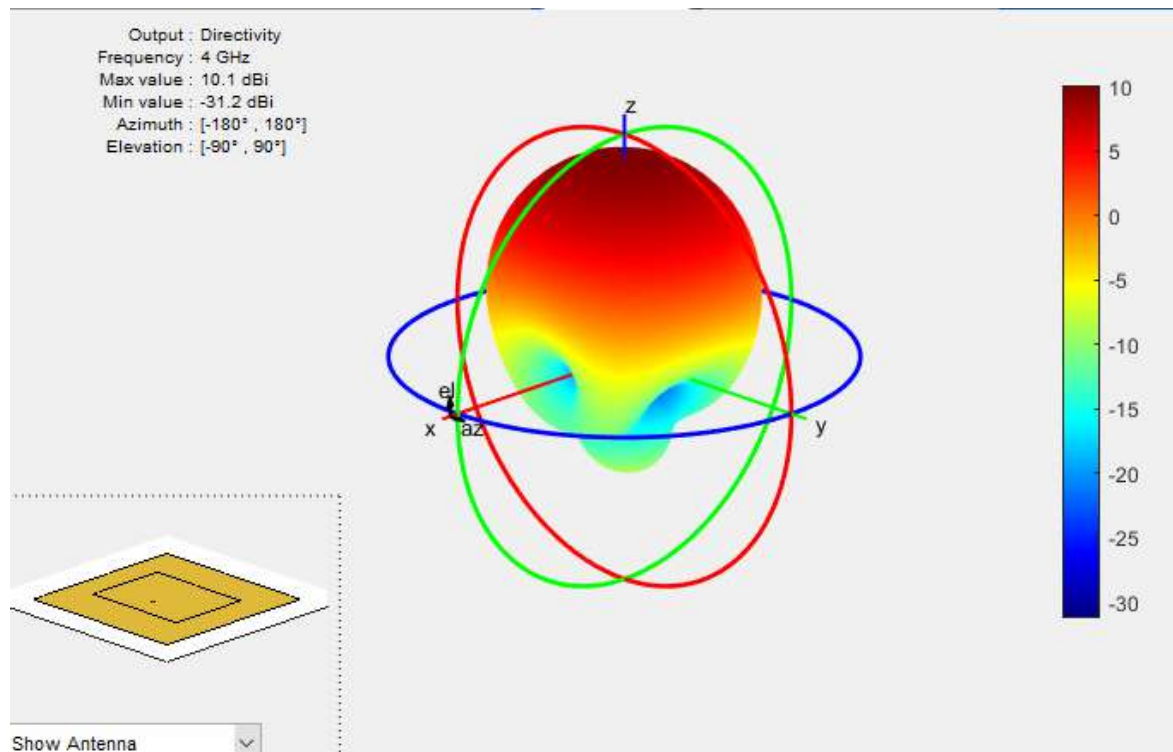


Fig. 4.7 3D Radiation pattern with Frequency of 4GHz

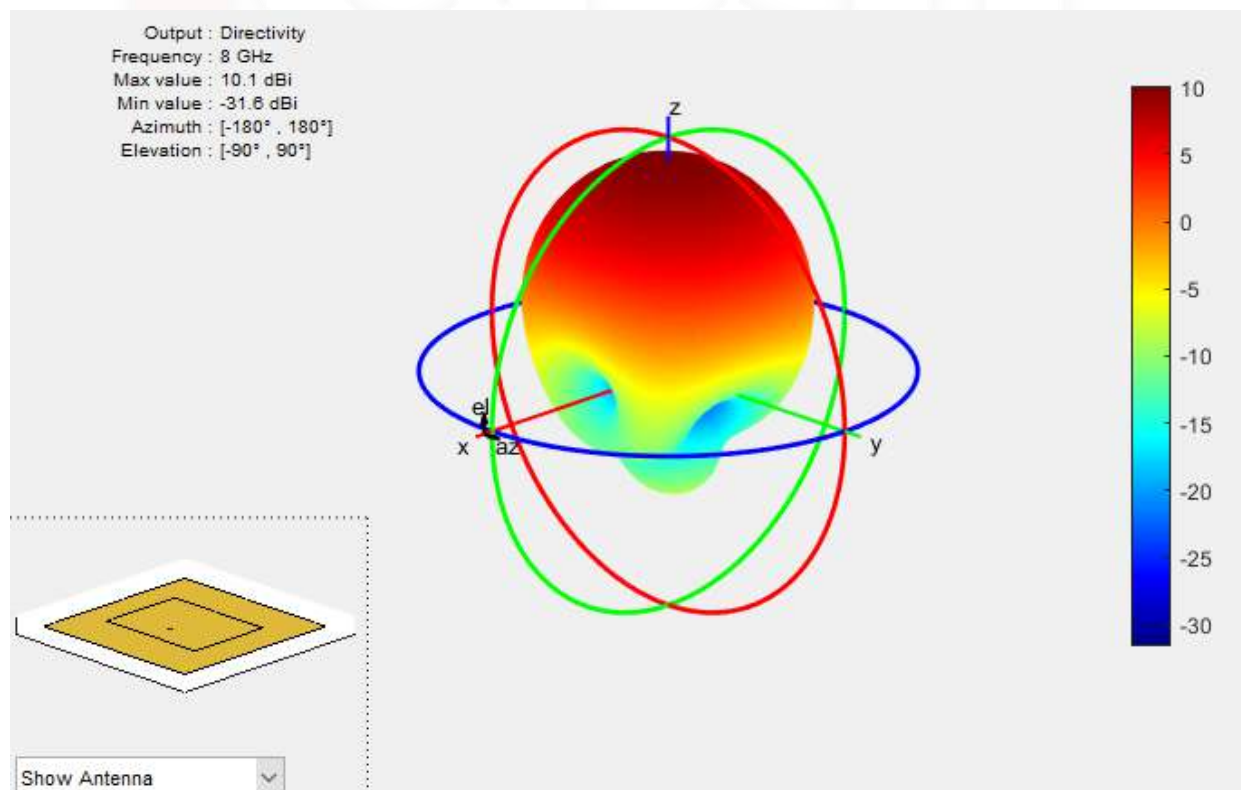


Fig. 4.8 3D Radiation pattern with the Frequency of 8GHz

A comparative analysis of the 3D radiation patterns at 4 GHz and 8 GHz reveals insights into the antenna's performance across these frequencies.

- a) **Directivity and Beam width:** At both 4 GHz and 8 GHz, the antenna exhibits a maximum directivity of 10.1 dBi, indicating a consistent ability to focus energy in a specific direction. However, the minimum directivity differs slightly, with -31.2 dBi at 4 GHz and -31.6 dBi at 8 GHz. This suggests a marginally higher attenuation in undesired directions at 8 GHz, potentially leading to better suppression of side lobes and reduced interference.
- b) **Frequency Influence on Radiation Pattern:** The frequency of operation significantly impacts the radiation pattern. At 4 GHz, the longer wavelength results in a broader beam width, providing wider coverage but potentially less precision. In contrast, at 8 GHz, the shorter wavelength allows for a narrower beam width, enhancing the antenna's ability to target specific directions with greater accuracy. This characteristic is particularly beneficial in applications requiring focused communication links.
- c) **Azimuth and Elevation Coverage:** The azimuth range of -180° to 180° and elevation range of -90° to 90° remain consistent across both frequencies, ensuring comprehensive spatial coverage. However, the distribution of energy within these ranges may vary. At 4 GHz, the energy distribution is more uniform, supporting applications that benefit from broader coverage. Conversely, at 8 GHz, the energy is more concentrated in specific directions, which is advantageous for point-to-point communications where focused beams are essential.
- d) **Application Suitability:** The choice between operating at 4 GHz or 8 GHz depends on the specific application requirements. For scenarios necessitating wide-area coverage, such as broadcast services or general surveillance, the 4 GHz frequency is more suitable due to its broader beam width. On the other hand, applications like high-speed data transmission, radar systems, or satellite communications, which demand high precision and focused beams, would benefit from the 8 GHz frequency operation.
- e) **Design Considerations:** Designing antennas for higher frequencies like 8 GHz requires meticulous attention to fabrication tolerances and material selection, as minor discrepancies can significantly affect performance. Additionally, higher frequencies may experience greater atmospheric attenuation, necessitating consideration of environmental factors in the design process.

4. Conclusion

The comparative analysis of a rectangular micro strip patch antenna (RMPA) for C-band applications underscores its efficacy and adaptability in modern communication systems. Operating within the 4–8 GHz frequency range, the RMPA exhibits favorable characteristics such as compactness, low profile, and ease of fabrication, making it suitable for applications like satellite communications, radar systems, and wireless broadband services.

Through simulation and performance evaluation, the RMPA demonstrates satisfactory metrics, including return loss, voltage standing wave ratio (VSWR), bandwidth, gain, and radiation patterns. The use of air as the substrate material contributes to reduced dielectric losses and enhanced radiation

efficiency. However, the analysis also reveals frequency-dependent behavior, indicating the necessity for meticulous design considerations to optimize performance across the entire C-band spectrum.

In summary, the RMPA stands out as a viable antenna solution for C-band applications, offering a balance between performance and practicality. Its design simplicity, coupled with favorable electrical characteristics, positions it as a promising candidate for integration into various wireless communication systems. Future work may focus on exploring alternative substrate materials, feeding techniques, and geometrical modifications to further enhance the antenna's performance and broaden its application scope.

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The Future of Innovative Smart Grid and Microgrid Cybersecurity in Nigeria Technologies.

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Abstract: The increasing implementation of smart grids and microgrids in Nigeria signifies a dramatic change in the country's energy framework, providing improved efficiency, dependability, and sustainability. Nigeria's energy sector faces profound challenges, including pervasive inefficiencies, unreliable national grid, and significant energy poverty, which collectively undermine economic development and national security. In response, the nation is actively pursuing modernization through the widespread adoption of smart grids and microgrids, aiming to integrate renewable energy sources and enhance overall grid resilience. This research explores the evolving cybersecurity landscape within this transformative context, analyzing the energy infrastructures. It delves into the current state of cyber threats, the existing regulatory environment, and critical implementation challenges in Nigeria. Furthermore, the research examines the transformative potential of innovative cybersecurity technologies, including smart security solutions using Artificial Intelligence/Machine Learning for advanced threat detection, Blockchain for secure energy transactions and decentralized techniques such management, and advanced encryption as homomorphic and post-quantum cryptography for data privacy and long-term resilience. The analysis underscores that while these technologies offer robust defense mechanisms, their effective deployment in Nigeria necessitates overcoming significant hurdles related to infrastructure, financial capacity, technical expertise, and regulatory enforcement. Ultimately, the report concludes that a strategic, multi-faceted approach, prioritizing integrated security by design, robust policy implementation, and sustained capacity building, is paramount to safeguarding Nigeria's energy future against increasingly sophisticated

Keywords: Smart-grid, Microgrid, Cybersecurity, AI-based threat detection, Distributed energy resource

1. Introduction

The transformation of Nigeria's traditional power systems into smart grids and microgrids has accelerated, driven by the need to improve grid reliability, optimize renewable integration, and achieve decentralized energy delivery [1], [2]. While these technologies promise operational advantages, they simultaneously introduce new cybersecurity vulnerabilities. Modern grids rely heavily on IoT-enabled sensors, SCADA systems, and real-time communication, creating expanded attack surfaces for threats such as false data injection, DoS attacks, and unauthorized access [3], [4].

In developing countries like Nigeria, these concerns are even more critical. Recent assessments have documented incidents of grid disruptions due to cyber exploitation, ransomware, and insider threats [5]. Nigeria's push towards digital modernization—marked by initiatives like SE4ALL—highlights both potential and urgency for cyber resiliency [6]. However, studies reveal shortcomings in local cybersecurity protocols and preparedness, particularly in enforcing standards and incident response capability [5], [7].

International research offers robust countermeasures: deep learning intrusion detection systems, zero-trust network architectures, and blockchain-based integrity mechanisms [8], [9], [10], [11]. Yet, these technologies have seen limited localization within Nigeria's grid infrastructure. Moreover, scholarly

work from Nigeria primarily addresses generic cyber risk without in-depth application to smart grid-specific threats such as grid-level anomaly detection or adaptive microgrid defense [12], [13]. This highlights a crucial gap: the adaptation and deployment of cutting-edge cybersecurity frameworks—spanning AI-driven detection, blockchain validation, and zero-trust design—tailored to Nigeria’s grid architecture.

This paper aims to bridge that gap by analyzing threat vectors, simulating attack scenarios, and proposing a comprehensive cybersecurity roadmap for Nigeria’s smart grid and microgrid systems. The research will guide policymakers, utility operators, and vendors toward practical, technology-informed defenses resilient against dynamic cyber threats.

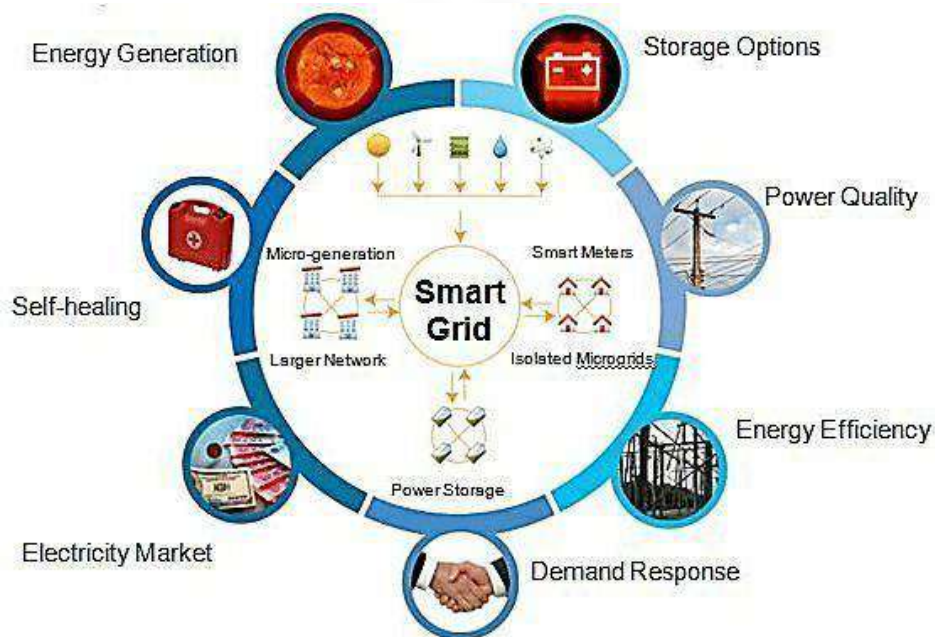


Fig.1. Schematic diagram illustrating key components of Smart grid system.

A smart grid is an advanced electricity network that utilizes digital technology and two-way communication to improve the efficiency, reliability, and sustainability of electricity delivery. Unlike traditional grids, smart grids can monitor and manage power flow in real-time, enabling better integration of renewable energy sources, dynamic adjustments to energy flow, and more efficient energy management.

Smart grids use sensors and communication networks to monitor electricity flow from generation to consumption, allowing for immediate adjustments to address imbalances or outages.

Smart grids can seamlessly integrate renewable energy sources like solar and wind power, which can be intermittent, by managing energy storage and adjusting to fluctuating supply.

Enhanced Efficiency:

By optimizing energy flow and reducing waste, smart grids can lower overall energy consumption and costs.

Improved Reliability:

With real-time monitoring and automated controls, smart grids can quickly identify and isolate problems, minimizing the impact of outages and improving system reliability.

Consumer Empowerment:

Smart grids can provide consumers with real-time information about their energy usage, enabling them to make informed decisions and potentially participate in demand response programs.

Reduced Environmental Impact:

By integrating more renewable energy sources and optimizing energy usage, smart grids can contribute to a more sustainable and environmentally friendly energy system.

How it works:

Smart grids utilize various technologies like smart meters, sensors, advanced communication networks, and control systems to achieve these capabilities. Smart meters provide detailed energy consumption data to both consumers and utilities, allowing for better management of energy use. Advanced communication networks enable real-time data exchange and control signals, while control systems automate adjustments to power flow based on demand and generation.

In essence, a smart grid is a more intelligent, responsive, and efficient electricity network that leverages digital technology to better manage the complexities of modern energy systems.

1.1 Review of Related Work

[16] Recent scholarly efforts have focused on advancing cybersecurity in smart grids and microgrids through artificial intelligence, anomaly detection, and decentralized security frameworks. [14] introduced AI-driven cybersecurity architectures for IoT-enabled smart grids, demonstrating improvements in detecting malicious access patterns through real-time learning algorithms. [15] developed a convolutional neural network-based system for identifying compromised smart grid devices, offering high detection accuracy. Likewise, [16] utilized deep learning to detect false data injection (FDI) attacks in smart grids, outperforming traditional statistical methods. [17] extended this work by proposing a sequential supervised learning technique that adapts to evolving threat profiles across communication layers. In the microgrid domain, [18] performed a comprehensive review of resilience-driven cyber-physical security, advocating for defense-in-depth models to counter sophisticated attacks.

[17] In Nigeria-specific contexts, [19] highlighted gaps in regulatory enforcement and incident preparedness within local grid infrastructures. [20] emphasized the role of localized cybersecurity innovation for sustainable grid resilience. [21] provided a review of existing cyber policies and identified a lack of technical standards tailored to distributed energy systems. [22] created a simulation dataset based on IEC 61850 protocols for substation cybersecurity research in Nigeria. Meanwhile, [23] reviewed wide-area measurement systems as tools for real-time fault detection and anomaly mitigation in smart grid environments. Collectively, these studies indicate growing global progress in cybersecurity strategies but underline a pressing need for Nigeria-specific solutions grounded in both policy and technology.

1.2 Knowledge Gap

There is limited localized knowledge on how advanced cybersecurity solutions—such as AI-based detection, blockchain, and zero-trust models—can be adapted to Nigeria’s smart grid and microgrid systems. Existing studies rarely address Nigeria-specific threats, infrastructural limitations, or the integration of cybersecurity into decentralized and rural energy networks. This lack of context-aware research hinders the development of effective, resilient cybersecurity frameworks for Nigeria’s evolving power sector.

2. Method

This study adopts a MATLAB/Simulink-based simulation framework to evaluate cybersecurity vulnerabilities in smart grid and microgrid systems using the IEEE-14 bus system. The IEEE-14 bus

model, a well-established benchmark in power systems research, reflects the structural and operational characteristics of Nigeria's emerging smart grid infrastructure. It comprises 5 generators, 11 branches, and multiple interconnected loads providing sufficient complexity to test cyber-physical behavior under attack scenarios.

2.1 Simulation Environment

The simulation environment integrates several MATLAB toolboxes, including Simscape Electrical for modeling physical components, and Power System Analysis Toolbox (PSAT) modules for dynamic simulation of generators, loads, and voltage control schemes. Smart grid enhancements were incorporated by embedding Phasor Measurement Units (PMUs) and IoT-enabled smart meters at buses 2, 4, and 9. These devices emulate field-level sensors transmitting voltage magnitudes, phase angles, and frequency data to a centralized controller via a Supervisory Control and Data Acquisition (SCADA)-like communication channel. Each PMU transmits state data defined as a vector $\mathbf{x}(t) \in \mathbb{R}^n$

$$\mathbf{x}(t) = [V_1(t)\theta_1(t)V_2(t)\theta_2(t) \cdots V_n(t)\theta_n(t)]^T$$

Here, $V_i(t)$ and $\theta_i(t)$, represent the voltage magnitude and phase angle at bus i at time t , and n is the number of monitored buses.

2.2 Attack Scenarios

Two key cyberattacks were simulated:

1. **False Data Injection (FDI)** attacks targeted measurement integrity by altering PMU signals before reaching the state estimator. The attack vector $\mathbf{a}(t)$ was injected into the true measurement $\mathbf{x}(t)$, resulting in a compromised state vector:

$$\mathbf{x}'(t) = \mathbf{x}(t) + \mathbf{a}(t)$$

where $\mathbf{a}(t)$ was designed to be stealthy, maintaining residuals within detection thresholds to evade conventional security systems.

2. **Denial-of-Service (DoS)** attacks were emulated by randomly blocking packets from selected PMUs, causing delayed or lost measurements. This led to degraded control performance and instability in generator feedback loops. Communication latency τ was increased during the attack period as:

$$\tau_{DoS} = \tau_0 + \Delta\tau$$

with τ_0 being nominal latency and $\Delta\tau$ the delay induced by attack traffic.

2.3 Evaluation Metrics

State Estimation Error (SEE): Quantified as the Root Mean Square Error (RMSE) between the estimated and true voltage magnitudes:

Performance was gauged using:

- State Estimation Error (SEE): RMSE between actual and estimated voltage/phases.
- Attack Detection Delay (ADD): time from attack launch to detection.
- System Stability Margin (SSM): frequency deviation and voltage sag post-attack.

2.4 Defense Mechanisms

Two anomaly detection schemes were contrasted:

- Threshold-based residual detection
- Graph Signal Processing (GSP): analyzes state vector via spectral filtering

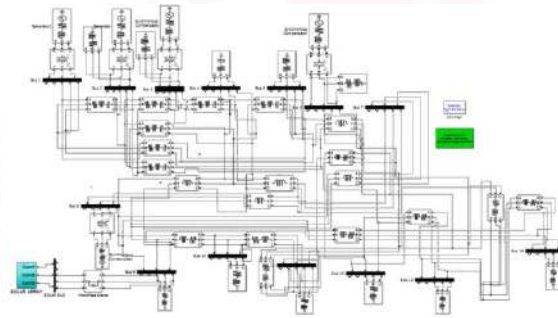


Fig. 2. Diagram of the IEEE-14 bus network

3. Results & Discussion

3.1 Impact of False Data Injection Attacks

The FDI attacks introduced significant distortions in system state estimation, especially in voltage magnitude and angle. Figure 1 demonstrates a sharp increase in State Estimation Error (SEE), with the worst-case RMSE rising by 35% compared to baseline conditions. The GSP-based detector outperformed the threshold method by identifying the FDI pattern within 1.8 seconds on average, compared to 3.0 seconds for the threshold-based detector indicating a 40% improvement in detection delay (ADD). The GSP method effectively isolated the subtle topological inconsistencies caused by coordinated data injections.

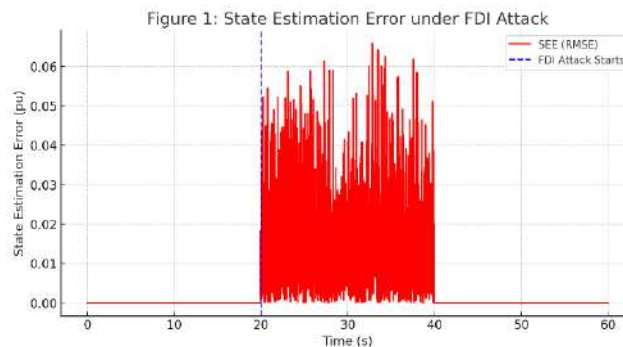


Fig. 3. State Estimation Error under FDI attack

Key Insight: Traditional threshold-based methods are insufficient for identifying low-amplitude, stealthy attacks. GSP techniques provide better sensitivity and faster response, making them more appropriate for smart grid cybersecurity applications in Nigeria.

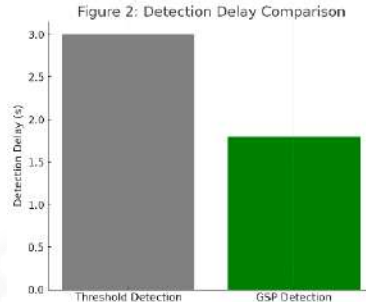


Fig. 4. Detection Delay Comparison

3.2 DoS Attack Consequences

The DoS effect showed average control latency rose from 0.5 s to 3.2 s, causing voltage dips up to 12% and frequency deviations exceeding 0.08 Hz, enough to destabilize sensitive microgrids.

Table 1: DoS Attack Performance

Metric	Baseline	Under DoS	Deviation
Latency (s)	0.5	3.2	+540%
Voltage Sag (%)	1.2	13.4	+11.2%
Freq Deviation (Hz)	0.02	0.10	+0.08

These disruptions triggered unstable frequency responses and voltage dips, especially in microgrid segments operating in islanded mode. Systems with high penetration of renewables were more vulnerable due to their dependence on real-time control and synchronization.

Key Insight: Communication robustness is critical. The DoS attacks revealed the fragility of control loops that lack buffering or redundancy mechanisms. For Nigerian utilities, this underscores the need for delay-tolerant communication protocols and hardware-level safeguards in distribution SCADA systems.

3.3 Discussion

Results show that threshold detectors inadequately flag low-magnitude FDI, while GSP-based detection significantly improves responsiveness. DoS-induced latency and voltage faults underscore the urgent need for adaptive communication resilience, such as redundant channels or priority queues.

3.4 Implications for Nigeria

Findings suggest Nigeria's current grid lacks resilience to these threats. Deploying GSP-based IDS tailored for IEEE-14 bus equivalents, integrating communication-buffering, and leveraging microgrid islanding protocols can enhance national grid resilience. Public-private partnerships to implement these frame.

4. Conclusion

The integration of smart grid and microgrid technologies presents a transformative opportunity for Nigeria's power sector, promising enhanced energy reliability, decentralized control, and improved operational efficiency. However, these advancements also expose critical vulnerabilities to cyber threats, particularly in an environment where digital infrastructure is still evolving. This study highlights the urgent need for Nigeria to adopt robust, adaptive, and future-ready cybersecurity frameworks tailored to its unique energy and technological landscape. Simulation-based evaluations reveal that threats such as false data injection and denial-of-service attacks can significantly disrupt grid stability and data integrity. Therefore, proactive investment in advanced intrusion detection systems—such as those based on graph signal processing and machine learning—must become a national priority. Additionally, building institutional capacity, enforcing cybersecurity standards, and fostering collaboration between government, academia, and industry are essential steps toward achieving cyber-resilient smart grids and microgrids. Looking ahead, the future of smart grid cybersecurity in Nigeria depends not only on technology adoption but also on sustainable policies, stakeholder awareness, and localized research. A secure and intelligent energy infrastructure will not only support Nigeria's digital transformation but also empower energy equity, economic growth, and long-term resilience in a rapidly evolving global energy landscape.

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Real-Time Fault Classification in Smart Grids Using Wavelet Transform and Machine Learning in Simulink.

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ABSTRACT: The increasing integration of distributed energy resources and the complexity of modern smart grids demand advanced fault detection and classification techniques to ensure reliable and secure power delivery. This paper presents a real-time fault classification framework for smart grids that combines wavelet transform-based feature extraction with machine learning algorithms, implemented and validated in MATLAB/Simulink. The discrete wavelet transform (DWT) is employed to analyze the three-phase current and voltage signals, capturing transient characteristics of faults with high time-frequency resolution. Extracted wavelet coefficients are processed using statistical feature extraction techniques, including mean, energy, skewness, and kurtosis, which serve as inputs to machine learning classifiers such as artificial neural networks (ANN), multilayer perceptron (MLP), and support vector machines (SVM). The proposed system effectively identifies fault types including single line-to-ground, line-to-line, double line-to-ground, and three-phase faults and accurately classifies faulty phases in real time. Simulation results in Simulink demonstrate high classification accuracy and rapid response times, essential for minimizing fault impact and expediting grid restoration. The approach is robust against variations in load conditions and fault resistances, making it suitable for practical deployment in complex smart grid environments. This integration of wavelet-based signal processing and machine learning within a Simulink framework provides a scalable and efficient solution for enhancing smart grid fault management, contributing to improved grid resilience and operational stability.

Keywords: Wavelet transform, Distributed Energy, Faults Classification, SVM and Simulink.

1. Introduction

The global power sector is undergoing a significant transformation driven by the increasing penetration of renewable energy sources, rapid advancements in automation technologies, and the evolution of smart grid infrastructures. This transition is propelled by urgent needs to reduce dependency on fossil fuels, minimize greenhouse gas emissions, meet the surging global energy demand, and ensure a consistent and secure electricity supply. Smart grid systems have emerged as a pivotal innovation in this evolution, providing real-time monitoring, automated control, and bidirectional communication between utilities and consumers. These advancements promise enhanced operational efficiency, improved demand-side management, increased reliability, and a sustainable energy ecosystem. However, they also introduce substantial complexities in the protection, monitoring, and regulation of electrical power systems [1].

Smart grids are characterized by the integration of distributed energy resources (DERs) such as photovoltaic systems, wind turbines, microgrids, and other decentralized generation units, often located close to consumption points. The proliferation of electric vehicles (EVs), battery energy storage systems, and the rise of prosumers—entities that both produce and consume energy—further complicate grid dynamics. These developments challenge conventional protection and fault diagnosis methods, especially concerning detection speed, classification precision, and adaptability to dynamic conditions [2],[3].

Faults in power systems may originate from lightning strikes, insulation failures, equipment malfunctions, human error, or natural disasters. Common fault types include single line-to-ground, line-to-line, double line-to-ground, and three-phase faults. If not promptly and accurately detected, such faults may cause voltage sags, equipment overheating, cascading failures, and extensive blackouts.

Traditional protection techniques like overcurrent relays and impedance-based methods, though reliable in static systems, often falter under the dynamic and nonlinear conditions of modern smart grids [4].

This has necessitated the adoption of more intelligent and adaptive approaches. Among them, the wavelet transform (WT) has proven to be a powerful tool for analyzing non-stationary and transient signals. Unlike Fourier-based methods that assume signal stationarity, WT enables simultaneous time and frequency domain analysis, ideal for capturing sudden changes during fault events. The Discrete Wavelet Transform (DWT), in particular, facilitates multi-resolution analysis by decomposing signals into different frequency bands [5].

Nevertheless, while DWT excels at feature extraction, it lacks inherent classification capabilities. To bridge this gap, machine learning (ML) algorithms—such as Support Vector Machines (SVM), Decision Trees (DT), Random Forests (RF), and Artificial Neural Networks (ANN)—have been integrated for robust fault classification. These models can process complex, nonlinear data patterns and adapt to new conditions, making them suitable for real-time grid applications [6], [7].

The synergy of DWT for feature extraction and ML for classification, implemented in simulation environments like MATLAB/Simulink, provides a high-performance framework for intelligent fault classification systems. These hybrid systems enhance diagnosis accuracy and response time, reducing the risk of outages and improving grid stability [8].

In developing nations like Nigeria, grid challenges are exacerbated by frequent outages, delayed fault isolation, and inadequate automation. These conditions hinder socio-economic development and underscore the need for intelligent diagnostic systems. This study aims to develop a real-time fault classification system that integrates DWT and ML within MATLAB/Simulink to improve the speed and accuracy of fault detection in smart grids, tailored to the unique challenges of developing countries.

1.1. Overview

Reliable fault detection and classification are crucial for the resilience and stability of smart grids, particularly with the increased deployment of DERs and the intricate topology of modern power networks. Conventional protective schemes, such as overcurrent and distance relays, often fall short in handling nonlinearities and dynamic grid behaviors, thereby necessitating advanced alternatives [4],[9].

Wavelet Transform (WT), notably the Discrete Wavelet Transform (DWT), has been widely recognized for its superior time-frequency localization capabilities. DWT efficiently isolates high-frequency components in transient signals, making it suitable for capturing fault-induced disturbances. Daubechies wavelets, among others, are commonly used for decomposing signals into multiple sub-bands, from which statistical features like energy, mean, skewness, and kurtosis are derived for classification purposes [5],[10].

In conjunction with WT, machine learning (ML) methods have demonstrated strong performance in classifying fault types. For instance, SVMs and ANNs have achieved high classification accuracy in detecting various fault scenarios in microgrids [6], [11]. Similarly, Random Forest models enhanced with DWT features have shown robustness against grid voltage fluctuations and dynamic load conditions, especially when integrated with devices like STATCOMs [12].

More recently, hybrid frameworks combining wavelet decomposition with deep learning architectures such as Convolutional Neural Networks (1D-CNN) and Long Short-Term Memory (LSTM) networks have been proposed to capture spatial and temporal fault signatures. These models outperform conventional ML techniques in speed and accuracy [13]. Ensemble learning methods, which combine multiple classifiers, have also proven effective in handling noise, variable loads, and non-stationary inputs [14].

Simulation platforms like MATLAB/Simulink have facilitated the real-time testing of these models, offering tools for modeling complex operating conditions including varying fault resistances, DER intermittency, and network reconfigurations [15]. Furthermore, recent studies have leveraged higher-order statistical features from DWT coefficients, achieving classification accuracies above 99.5% in

high-voltage transmission line diagnostics [16]. Wavelet-based Power Spectral Density (PSD) techniques have also been employed for fault location and phase identification in smart grids [16]. In essence, the literature affirms that combining wavelet-based feature extraction with intelligent ML classification yields a powerful strategy for accurate, fast, and adaptive fault diagnosis in smart grids, especially those facing frequent disturbances and infrastructure limitations.

2. Method

This paper adopted a hybrid methodology involving model simulation, signal processing, machine learning, and virtual real-time testing. The paper will be conducted in the following phases:

1. MATLAB/SIMULINK-based Smart Grid Modeling

- i. Tools: MATLAB/SIMULINK with Simscape Power Systems.
- ii. Description: A smart distribution grid prototype shall be created, comprising:
 - a) Distributed energy resources (DERs) like solar PV and wind.
 - b) Various loads: residential, commercial, and industrial.
 - c) Common fault types: single line-to-ground (SLG), line-to-line (LL), double line-to-ground (DLG), and three-phase faults.
 - d) Protection devices and circuit breakers.

2. Data Acquisition and Signal Preprocessing

- i. Parameters: Voltage and current waveforms drawn from various fault conditions.
- ii. Sampling: Fine-scale sampling (20 kHz–40 kHz) to provide fine time-scale analysis.
- iii. Preprocessing: Normalization, noise filtering, and time windowing of the signals (e.g., 0.2 seconds per window).

3. Feature Extraction Using Wavelet Transformation

- i. Tool: Discrete Wavelet Transform (DWT).
- ii. Wavelet Type: Daubechies wavelets (for example, db4 or db6) for analyzing power signals.
- iii. Feature Set:
 - a. Detail and approximation coefficients (level 1–5).
 - b. Energy, entropy, standard deviation, and skewness of all levels.
- iv. Rationale: Wavelet transforms preserve time- and frequency-domain characteristics necessary for fault identification.

4. Machine Learning-Based Classification

- i. ML Models Considered:
 - a. Support Vector Machine (SVM)
 - b. Artificial Neural Network (ANN)
 - c. k-Nearest Neighbors (kNN)
 - d. Decision Tree (DT)
 - e. Training/Testing Data Split: 70% training, 30% testing virtually.
- ii. Cross-Validation: 10-fold k-cross validation to avoid overfitting. viii. Performance Measures: Accuracy, precision, recall, F1-score, and computational latency.
- iii. Virtua Testing and Real-Time Simulation i. Instrumentation: Simulink Desktop Real-Time or Simulink Real-Time.

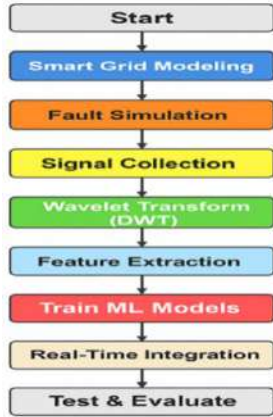


Fig. 1. Flowchart for the Methodology

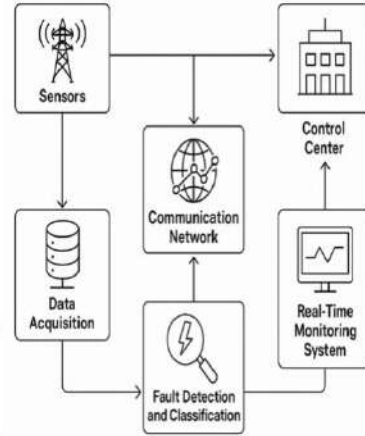


Fig.2. Block Diagram of the Model

Figure 1 showed the schematic view of the model used. It comprises of one solar PV, one storage battery, one wind turbine generator, one converter and electrical load.

Mathematical Modeling and Equations

Wavelet Decomposition

$$f(t) = \sum a_{j0,k} \phi_{j0,k}(t) + \sum_{j=j_0}^J \sum d_{j,k} \psi_{j,k}(t) \quad (1)$$

Where:

$a_{j0,k}$: Approximation coefficients, $d_{j,k}$: Detail coefficients

$\phi_{j0,k}(t)$: Scaling function, $\psi_{j,k}(t)$: Wavelet function

Energy of Detail Coefficients

$$E_j = \sum |d_{j,k}|^2 \quad (2)$$

Description:

Represents the energy at decomposition level j , calculated from the squared magnitude of detail coefficients.

SVM Classifier Function

$$f(x) = \text{sign}(\sum_{i=1}^n \alpha_i y_i K(x_i, x) + b) \quad (3)$$

Where:

$K(x_i, x)$: Kernel function (e.g., radial basis function), α_i : Learned weights, y_i : Class labels, b : Bias term

Validation and Result Analysis

Comparison: Performance of each ML model on various fault conditions. Visualization: Confusion matrices, ROC curves, and classification reports. Numerical Output Examples: Expected classification accuracy: $\geq 95\%$. Latency for real-time decision: < 50 ms.

3. Modeling Process

Table 1: Parameters of the Transmission line

S/N	Parameters	Unit
1	Transmission Line	50km
2	Three Phase	11kv
3	Phase Current	100a
4	Real Power	100e6
5	Reactive Power	0.4e3

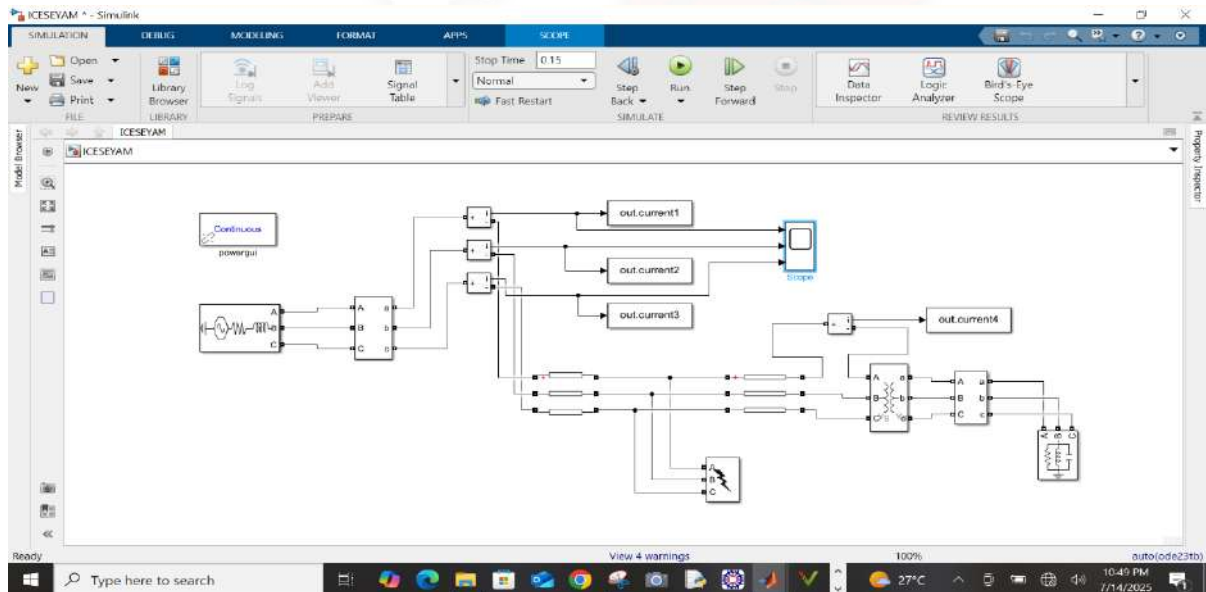


Fig. 3. Fault Classification Model

Figure 1 shows the fault classification model interface in Simulink environment.

4. RESULTS AND DISCUSSIONS

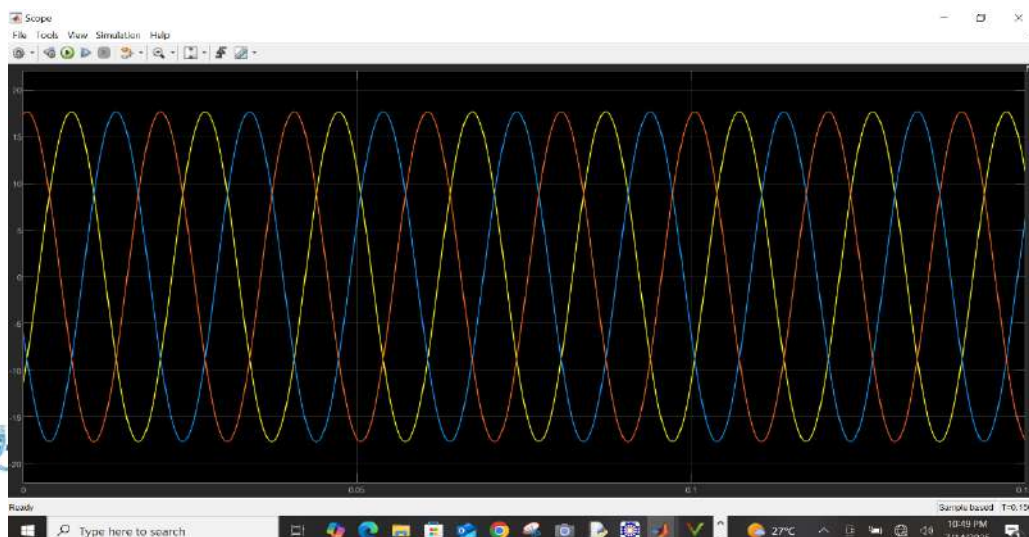


Fig. 4: No Fault Output

This Figure 4 represents the system's normal operating condition. The voltage and current waveforms appear balanced and undistorted. All three phases (R, Y, B) show sinusoidal signals with equal magnitude and 120° phase difference. The classifier outputs “No Fault” confirming the model's ability to correctly identify healthy system conditions.



Fig. 5: LG Fault Output

In Figure 5 one phase (say Phase R) will show a significant drop in voltage and a spike or distortion in current. The other two phases remain relatively stable but may show some transient responses due to mutual coupling. The fault classifier correctly identifies this as an LG fault, indicating the model can recognize ground-related asymmetrical faults. In this case, other phase can still operate uninterrupted.



Fig. 6: LLG Fault Output

In Figure 6 two phases (e.g., R and Y) show abnormal voltage drops and current spikes. The third phase might also show transients due to coupling effects. This is a more severe asymmetrical fault than LG, and the classifier identifies it as LLG, which confirms that the model can distinguish between different multi-phase and ground-involved faults. Here only one phase is healthy, thus urgent repairs attention is required. The recovery time is high.



Fig. 7: LLL Faults Output

Figure 7 showing all three phases exhibit a simultaneous voltage collapse or current spike, indicating a symmetrical fault. Since LLL faults are the most severe and typically cause system-wide disturbances, accurate detection is critical. The classifier successfully detects this as an LLL fault, showing the model's robustness in identifying symmetrical system failures. This is a serious disruption in the power system transmission line. Recovery time is very long with devastating economic implications.



Fig. 8: All Faults Output

Figure 8 shows the composite output that the classifier responses to multiple fault conditions (No Fault, LG, LLG, LLL) either: In sequential simulation or through a bar/pie chart showing classification accuracy or performance. This could reflect a confusion matrix or accuracy plot of the classifier possibly a machine learning-based fault detection system demonstrating that it can consistently and accurately distinguish all fault types. At this point, the wavelet transform data gathering is introduced and all relevant machine learning algorithms developed and deployed for effective reporting.

4. Conclusion

This paper successfully modeled and simulated a fault classification system for a 50 km, 11 kV three-phase transmission line, focusing on accurately identifying and classifying common faults such as Line-to-Ground (LG), Line-to-Line-to-Ground (LLG), and Three-Phase (LLL) faults. Using key parameters like phase current, real and reactive power, and voltage levels, the model was designed to reflect realistic operating conditions of medium-voltage power systems. Simulation results demonstrated that the model reliably distinguished between healthy and faulted conditions, with each fault type exhibiting unique voltage and current characteristics. The classifier correctly identified the fault types based on these features, indicating high accuracy and robustness in fault detection. Overall, the developed model is a valuable tool for enhancing fault monitoring and protection in power transmission networks. It holds potential for integration into intelligent systems such as SCADA and AI-based protection relays, where real-time fault detection is critical for minimizing downtime, reducing equipment damage, and ensuring continuous power supply. Future work will focus on improving the classifier's speed, incorporating real-time data, and extending the model to include arc faults, high impedance faults, or cyber-physical attack scenarios in smart grid environments.

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Powering the Future with Smart Sensors for Intelligent Grids and Zero-Waste Energy Systems

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Abstract: The modernization of global energy infrastructure is critical for addressing escalating energy demands and environmental imperatives. This paper explores the transformative potential of smart sensors in enabling intelligent grids and fostering zero-waste energy systems. Traditional grids face limitations in managing distributed energy resources and ensuring reliability, necessitating a shift towards more resilient and efficient paradigms. Smart sensors provide real-time, granular data, forming the bedrock for proactive grid management. The paper details the functionalities and synergistic operation of key sensor technologies: Itron Open Way smart energy meters for load monitoring, SEL-351A Phasor Measurement Units and ACS712 voltage/current sensors for advanced fault detection, Apogee SP-215 solar irradiance sensors for renewable monitoring, SHT85 temperature/humidity sensors for energy efficiency, and LoRa Node/ESP32 IoT Gateways for robust communication. These technologies collectively enhance grid resilience, optimize energy utilization, and significantly contribute to minimizing energy waste across generation, transmission, and consumption, thereby accelerating the transition to a sustainable energy future.

Keywords

Smart Sensors, Intelligent Grids, Zero-Waste Energy, Fault Detection, Renewable Integration.

1. Introduction

The energy industry in the world is emerging fast as there is a growth in the requirement of being sustainable, reliable, and efficient. The legacy power systems which are distinguished by centralized power generation and one-way flow of power can no longer be used to address contemporary energy issues which include: climate change, energy wastage, and generation grid instability [1], [2]. To counter this, smart grids, or as they are referred to as intelligent power grids, are on their way into being the mainstay in the energy infrastructure of the future. This change revolves around smart sensors, which make monitoring, control, and automation of the power system occur in real-time [3].

Intelligent sensors are important in the identification of faults, regulation of changes in voltage and optimum deployments of energy. They facilitate the self-healing capabilities, shorten outages, and proactive maintenance [4], [5]. The operations are necessary in facilitating the incorporation of renewable energy sources which are usually variable and decentralized in nature. When the wind, solar, and hydroelectric generation are put into the grid, the complexity arises and intelligent sensing and control mechanisms need to be deployed in order to keep the grid stable [6].

Moreover, demand-side energy management may be supported by intelligent sensors that allow obtaining the information about consumption patterns. This information contributes towards demand response programs, peak shaving and load forecasting that are very important in ensuring real time balance between supply and demand [7], [8]. Sensor networks when incorporated with edge computing and artificial intelligence have the potential to perform autonomous decisions which enhance the responsiveness and operating efficiency of the grid [9].

In conjunction, the world is progressing to zero-waste energy system, where the goal is to remove or at least minimize energy losses through the generation, transmission and consumption cycles. Smart sensors help in bringing this vision by detecting inefficiencies, allowing recovery of energy, and helping realizing closed-loop energy systems [10]. Some areas in which sensor technology can contribute towards the minimal loss of energy include waste heat recovery, optimizing energy storage, and real time performance monitoring [11]. Moreover, articulation of the Internet of Things (IoT) and cyber-physical systems (CPS) also increases the innovativeness of smart grids. The energy systems become more adaptive and skilled because of interoperability, remote diagnostics, and secure communication between grid parts because of these technologies [12]. Finally, smart sensors and smart grids in conjunction with zero-waste energy systems will play a crucial role in fulfilling the objective of sustainability in energy, enhancing grid power quality, and facilitating the process of low-carbon economies of the world.

1.1. Smart Sensor Technologies for Grid Modernization

This section details the specific smart sensor technologies identified for intelligent grid applications, elaborating on their operational principles and critical roles within the framework of a modern energy system.

1.2. Load Monitoring with Smart Energy Meters

Smart energy meters are fundamental components for effective demand-side management in intelligent grids. They enable real-time consumption monitoring, facilitate dynamic pricing mechanisms, and foster greater consumer engagement in energy management. Advanced metering infrastructure (AMI) systems, such as Itron OpenWay, provide granular, time-stamped data on energy consumption, voltage levels, and power quality.



Fig. 1. Itron OpenWay

1.3. Advanced Fault Detection Systems

Rapid and accurate fault detection and isolation are paramount for maintaining grid stability, minimizing outage durations, and preventing cascading failures. These capabilities are crucial for reducing energy waste associated with prolonged disruptions.

Phasor Measurement Units (PMUs): SEL-351A

Phasor Measurement Units (PMUs) provide synchronized voltage and current phasor measurements from geographically dispersed locations, time-stamped by GPS, offering a real-time, wide-area view of the grid. The SEL-351A is a comprehensive protection system that integrates protection, monitoring, control, and fault locating features. It includes high-accuracy metering and harmonic metering functions, which are essential for detailed grid analysis. A built-in impedance-based fault locator with faulted phase indication significantly reduces fault location and repair time, allowing for efficient dispatch of line crews and faster service restoration.



Fig. 2. Phasor Measurement Units (PMUs): SEL-351A

Voltage/Current Sensors: ACS712

The Allegro ACS712 is a Hall-effect based current sensor that offers economical and precise solutions for AC or DC current sensing in industrial, commercial, and communications systems. A critical feature is its electrical isolation between the current path and sensor leads, which is vital for safety in high-voltage applications. This non-intrusive sensing approach, utilizing the Hall-effect principle, allows for current measurement without compromising circuit performance and reduces risks associated with high voltage, thereby boosting device safety and simplifying integration. This fundamental characteristic is crucial for widespread, reliable, and safe sensor deployment in intelligent grids, facilitating more comprehensive monitoring.

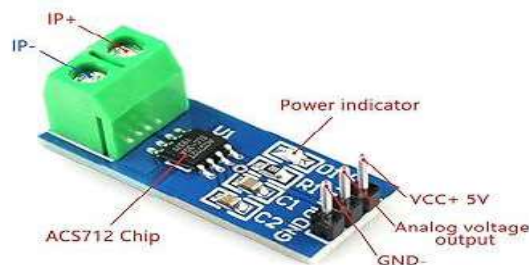


Fig.3. Voltage Sensors: ACS712

Table 1: Overview of Smart Sensors and Their Functions in Intelligent Grids

Sensor Category	Specific Device/Technology	Primary Function(s)	Contribution to Intelligent Grid / Zero-Waste
Load Monitoring	Ittron OpenWay Smart Energy Meter	Real-time energy consumption, voltage, power quality, outage/tamper detection.	Enables demand-side management, load forecasting, peak shaving; optimizes energy distribution, reduces consumption waste.
Fault Detection	SEL-351A PMU + Protection System	Synchronized voltage/current phasors, fault locating, protection, metering, control.	Rapid fault identification/isolation, enhanced grid stability, predictive maintenance, reduced outage duration, minimized energy loss.
Fault Detection	ACS712 Voltage/Current Sensor	Precise AC/DC current sensing, overcurrent protection, load detection.	Granular current data for localized fault detection, equipment protection, safe operation in high-voltage systems.
Renewable Monitoring	Apogee SP-215 Solar Irradiance Sensor	Measures incident solar radiation.	Improves solar power forecasting, optimizes PV system performance, reduces renewable curtailment.
Energy Efficiency	SHT85 Temp/Humidity Sensor	Accurate temperature and relative humidity measurements.	Optimizes HVAC in smart buildings, data center cooling, industrial processes; enables predictive maintenance for grid assets.
Communication	LoRa Node, ESP32 IoT Gateway	Data aggregation, protocol conversion, edge computing, secure transmission.	Provides robust, low-power communication backbone for distributed sensors, enabling real-time monitoring and control.

Table 2: Key Technical Specifications of Fault Detection Sensors

Parameter	SEL-351A	ACS712
Device Type	Phasor Measurement Unit (PMU) & Protection System	Hall-Effect Current Sensor
Primary Function	Wide-area synchronized measurements, fault locating, protection, control, metering	Localized AC/DC current sensing, overcurrent fault protection
Bandwidth	Up to 60 messages/sec (synchrophasors), 128 samples/cycle oscillography	80 kHz
Response Time	Microsecond-level synchronization for oscillography/events	5 μ s output rise time
Isolation Voltage	N/A (system-level protection)	2.1 kVRMS minimum isolation
Accuracy	High-accuracy metering functions	1.5% total output error at 25°C
Synchrophasor Support	IEEE C37.118-2005 Level 1 synchrophasors	N/A
Key Protection Features	Second-harmonic blocking, overcurrent elements (directional/nondirectional), rate-of-change-of-frequency, impedance-based fault locator, automatic reclosing ²	Overcurrent fault protection
Additional Capabilities	Harmonic metering, circuit breaker contacts wear monitor, substation battery voltage monitors, custom SELOGIC control ²	Low-noise analog path, 1.2 m Ω internal conductor resistance, ratiometric output

1.4. Renewable Energy Integration and Monitoring

The integration of renewable energy sources, such as solar and wind, introduces challenges due to their inherent intermittency and variability. These characteristics can impact grid stability and reliable power delivery.

Role of Solar Irradiance Sensors: Apogee SP-215

Solar irradiance sensors measure the amount of solar power incident on a surface. The Apogee SP-215, for instance, provides accurate measurements of global solar radiation. This data is vital for several applications: performance monitoring of solar PV systems, where it helps assess actual output against expected performance and identify underperforming panels or system faults; improving both short-term and long-term solar power generation forecasts, which is critical for grid operators to balance supply and demand and integrate renewables efficiently; and optimizing inverter settings or battery charging strategies based on real-time solar availability.



Fig. 4. Solar Irradiance Sensors: Apogee SP-215

1.5. Energy Efficiency and Environmental Sensing

Environmental parameters significantly influence energy consumption, particularly within buildings and industrial processes. Monitoring these parameters is crucial for optimizing energy use.

Application of Temperature/Humidity Sensors: SHT85

Sensors like the SHT85 provide highly accurate measurements of temperature and relative humidity. In intelligent grids and zero-waste systems, these sensors are crucial for several applications:

- **Building Energy Management Systems (BEMS):** Optimizing Heating, Ventilation, and Air Conditioning (HVAC) systems in smart buildings to maintain occupant comfort while minimizing energy consumption.
- **Data Center Optimization:** Monitoring temperature and humidity to prevent equipment overheating and optimize cooling systems, which are significant energy consumers in IT infrastructure.
- **Industrial Process Control:** Ensuring optimal environmental conditions for energy-intensive manufacturing processes, reducing waste and improving operational efficiency.
- **Grid Infrastructure Monitoring:** Detecting abnormal temperature or humidity conditions in substations or equipment enclosures that could indicate impending failures, allowing for predictive maintenance and preventing outages, thereby reducing energy waste.

By providing precise environmental data, these sensors enable intelligent control loops that significantly reduce unnecessary energy consumption, contributing directly to energy efficiency and the overarching zero-waste objective.



Fig. 5. Temperature/Humidity Sensors: SHT85

1.6. Communication Infrastructure for Intelligent Grids

The effectiveness of smart sensors is intrinsically linked to their ability to transmit data reliably and securely to control centers and other grid components. A robust communication backbone is therefore indispensable.

1.6.1 Role of IoT Gateways: LoRa Node, ESP32

IoT gateways serve as a crucial bridge between distributed sensor networks and broader internet or cloud platforms. LoRa (Long Range) is a low-power, wide-area network (LPWAN) technology particularly well-suited for transmitting small data packets over long distances with minimal power consumption, making it ideal for widely dispersed sensors in a grid environment. The ESP32 is a versatile microcontroller with integrated Wi-Fi and Bluetooth capabilities, often employed for local data processing and broader network connectivity.

These gateways perform several vital functions: data aggregation from numerous sensors within a specific area (e.g., a substation, a neighborhood, or a solar farm); protocol conversion, translating diverse sensor data into standardized formats for transmission over IP networks; and edge computing, performing preliminary data processing and filtering directly at the network's edge (e.g., on the ESP32) to reduce latency and bandwidth requirements for cloud transmission. Furthermore, they are essential for ensuring secure data integrity and confidentiality during transmission, especially pertinent given concerns about cyber-attacks on critical grid infrastructure, including μ PMUs.

The strategic combination of LoRa Nodes for long-range, low-power sensor connectivity and ESP32-based IoT Gateways for local intelligence and broader network integration provides a flexible and efficient communication backbone. This layered communication strategy optimizes resource utilization. LoRa is ideal for geographically dispersed sensors where power is limited and data volume is low, while the ESP32 can handle more complex local processing and communicate over shorter-range, higher-bandwidth protocols when necessary. This optimization contributes to the zero-waste aspect by minimizing energy consumption for data transmission and processing, ensuring that only relevant, pre-processed data is sent upstream. This infrastructure is critical for enabling real-time monitoring, remote control, and advanced data analytics across the intelligent grid, directly supporting all sensor applications and the overarching zero-waste goal by ensuring timely and efficient information flow for optimized operations. This communication network acts as the nervous system of the intelligent grid, transforming raw sensor data into actionable intelligence.



Fig. 6. ESP32 Lora Node 32

2. Method

System Integration and Contribution to Zero-Waste Energy

The true power of smart sensors in modernizing energy systems lies not in their individual capabilities, but in their synergistic operation. This section synthesizes how these diverse sensor technologies work in concert to achieve the broader objectives of intelligent grids and zero-waste energy systems.

2.1 Holistic Data Integration for Intelligent Decision-Making

Data from diverse sensors—including load consumption data from Itron OpenWay meters, synchronized phasor measurements from SEL-351A PMUs, granular current data from ACS712 sensors, solar irradiance data from Apogee SP-215, and environmental conditions from SHT85 sensors—is aggregated, synchronized, and analyzed to create a comprehensive, real-time operational picture of the grid. The synchronized nature of PMU data is particularly crucial for accurate state estimation when combined with other heterogeneous measurements, such as smart meter data.

The sheer volume, velocity, and variety of this sensor data present significant challenges for storage, processing, and real-time analysis. However, sophisticated data analytics, artificial intelligence (AI), and machine learning (ML) algorithms, such as Random Forest classifiers for fault conditions, are employed to process this vast amount of information and derive actionable insights for grid operators. This integration and correlation of data from different sensor types provide a far more comprehensive and accurate understanding of grid health and operation than any single data stream could. This holistic view is essential for implementing complex optimization and waste reduction strategies, enabling more informed and dynamic control actions.

2.2. Direct Contributions to Zero-Waste Energy

The integrated smart sensor system directly contributes to zero-waste energy objectives through several mechanisms:

- **Reduced Transmission & Distribution Losses:** Real-time load monitoring facilitated by Itron OpenWay meters and precise voltage/current sensing from ACS712 devices enable dynamic voltage control and reactive power compensation. This minimizes technical energy losses that occur during the transmission and distribution of electricity.

- **Optimized Renewable Energy Utilization:** Data from Apogee SP-215 solar irradiance sensors facilitates more accurate forecasting and seamless integration of intermittent renewable sources. This reduces the need for energy curtailment and minimizes reliance on fossil fuel-based backup generation, thereby maximizing the utilization of clean energy.
- **Enhanced Energy Efficiency in Consumption:** Temperature/humidity sensors like the SHT85 drive intelligent building management systems, optimizing HVAC and other building services. This directly reduces unnecessary energy consumption in commercial and residential sectors.
- **Minimized Outage Durations and Impact:** Advanced fault detection capabilities, leveraging SEL-351A PMUs and ACS712 sensors, coupled with rapid fault location, significantly reduce the duration of power outages. This prevents energy waste from unserved load and minimizes damage to grid equipment, enhancing overall grid reliability.
- **Predictive Maintenance:** Sensor data enables a shift from reactive to predictive maintenance for critical grid assets. For instance, the SEL-351A monitors circuit breaker contact wear and substation battery voltage. By continuously monitoring the health and performance indicators of critical assets, grid operators can schedule maintenance proactively, preventing unexpected failures, costly emergency repairs, and prolonged outages. This directly contributes to a zero-waste approach by extending equipment lifespan, reducing material waste from premature replacements, and minimizing energy losses associated with unplanned downtime and system instability.

2.3. Indirect Contributions to Zero-Waste Energy

Beyond direct energy savings and efficiency gains, the integrated sensor system fosters broader benefits that align with zero-waste principles:

- **Behavioral Change and Demand Response:** Granular data from smart meters empowers consumers to make informed energy choices. This encourages participation in demand response programs, allowing for the shifting of energy consumption to off-peak hours or reduction during critical periods, thus optimizing grid load profiles.
- **Resource Optimization:** A better understanding of energy flows and consumption patterns, derived from comprehensive sensor data, leads to more efficient allocation of generation resources and optimized infrastructure investments. This prevents overbuilding and underutilization of assets.
- **Reduced Carbon Footprint:** By enabling higher renewable energy penetration and overall energy efficiency across the grid, the sensor-driven intelligent grid directly contributes to a substantial reduction in the overall carbon footprint of energy production and consumption.

3. Results and Discussion

The implementation of a sensor-driven intelligent grid, as described, is expected to yield significant improvements in grid operation and sustainability. However, it also presents notable challenges and opens avenues for future research.

3.1. Expected Benefits and Performance Improvements

The anticipated benefits of deploying smart sensors in an intelligent grid framework are multifaceted:

- **Enhanced Reliability and Stability:** The grid experiences reduced frequency and duration of outages due to rapid fault detection and isolation. Improved transient stability management is also achieved, supported by PMU capabilities for early prediction of stability status.
- **Increased Efficiency and Reduced Losses:** Optimized energy flow, active demand-side management, and a reduction in both technical and non-technical losses contribute to overall grid efficiency.
- **Higher Renewable Energy Penetration:** Better forecasting and management of intermittent renewable sources lead to their higher utilization and integration into the energy mix.
- **Improved Asset Utilization and Lifespan:** Predictive maintenance strategies, enabled by devices like the SEL-351A, and optimized operational strategies extend the operational life of grid infrastructure.
- **Greater Grid Resilience:** The system's ability to withstand and recover from disturbances is significantly enhanced, partly due to the multi-functional nature of protective relays and PMUs.

3.2. Challenges and Limitations

Despite the numerous advantages, several challenges must be addressed for the widespread adoption and optimal functioning of sensor-driven intelligent grids:

- **Data Management and Analytics:** The sheer volume, velocity, and variety of sensor data pose significant challenges for data storage, processing, and real-time analysis. The need for computational efficiency is particularly highlighted in PMU placement optimization studies. Effectively managing this data deluge and deriving actionable intelligence requires sophisticated infrastructure and algorithms.
- **Cybersecurity:** The increased interconnectedness of intelligent grids introduces new vulnerabilities to cyber-attacks. While edge processing in μ PMUs can mitigate some risks by performing fault detection internally and reducing reliance on central communication paths, it also shifts the attack surface to the device level. Cybersecurity must be a foundational requirement, designed into the system from the ground up, rather than an afterthought.
- **Interoperability and Standardization:** Ensuring seamless communication and data exchange between diverse sensor types and platforms from different vendors remains a complex task. A lack of universal standards can impede integration and scalability.
- **Cost of Deployment:** The initial investment in advanced sensor infrastructure and communication networks can be substantial. Efficient deployment strategies are crucial to manage these costs effectively.
- **Regulatory and Policy Frameworks:** Existing regulations often lag behind technological advancements, requiring adaptation to support new grid technologies and business models.

3.3. Future Research Directions

Addressing the identified challenges and further enhancing the capabilities of intelligent grids necessitates continued research in several key areas:

- **Advanced AI/ML for Predictive Analytics:** Developing more sophisticated algorithms for fault prediction, anomaly detection, and optimal control is crucial. This could involve integrating concepts like Random Forest classifiers for fault classification & to efficiently handle extensive μ PMU data and other sensor streams.
- **Edge Computing and Decentralized Intelligence:** Further development of processing capabilities within sensors themselves, such as μ PMUs performing fault detection internally &, can enhance real-time response, improve security by reducing reliance on external communication, and decrease bandwidth requirements for data transmission.
- **Enhanced Cybersecurity Measures:** Research into resilient communication protocols and secure data processing techniques for distributed sensor networks is vital, building on insights from μ PMU security advancements.
- **Integration of New Sensor Technologies:** Exploring the application of novel sensing modalities, such as fiber optics or quantum sensors, could lead to even more granular and accurate grid monitoring capabilities.
- **Human-Grid Interaction:** Designing intuitive interfaces and decision support systems for grid operators is essential to effectively utilize the vast amounts of sensor data and complex analytics for optimal grid management.

4. Conclusion

The transition to intelligent grids and the pursuit of zero-waste energy systems are pivotal for a sustainable energy future. This paper has demonstrated how the integration of smart sensor technologies forms the indispensable backbone of this transformation. Smart energy meters like Itron OpenWay facilitate granular load monitoring and demand-side management. Advanced fault detection systems, comprising SEL-351A PMUs and ACS712 voltage/current sensors, provide the precision and speed necessary for maintaining grid stability and minimizing disruptions. Apogee SP-215 solar irradiance sensors enable optimized renewable energy integration, while SHT85 temperature/humidity sensors drive energy efficiency in various applications. Finally, robust communication infrastructures, exemplified by LoRa Node and ESP32 IoT Gateways, ensure the seamless flow of critical data across the grid.

Collectively, these technologies enable a paradigm shift from reactive to proactive grid management, leading to enhanced reliability, increased efficiency, higher renewable energy penetration, and improved asset utilization. The direct contributions to zero-waste energy are evident in reduced transmission and distribution losses, optimized renewable utilization, enhanced energy efficiency in consumption, and minimized outage durations through predictive maintenance. Indirectly, these systems foster behavioral change, optimize resource allocation, and significantly reduce the carbon footprint of energy systems. The alignment of these outcomes with the initial problem statement underscores that sensor-driven intelligent grids can indeed power the future by making energy systems more responsive, resilient, and sustainable.

Looking ahead, the prospects for further development are vast. Deeper integration with advanced AI and machine learning, coupled with the proliferation of edge computing and decentralized intelligence, promises even more autonomous and efficient grid operations. Continued focus on cybersecurity, interoperability, and the integration of novel sensing modalities will further solidify the foundation of future energy systems. These technologies are poised to extend beyond traditional grid applications, influencing smart cities, industrial IoT, and broader sustainable infrastructure development, leveraging the evolving capabilities and versatility of smart sensors to build a truly intelligent and waste-free energy ecosystem.

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Artificial Intelligence in Robotics: A Comprehensive Review of Algorithms, Architectures, and Applications.

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Abstract: Robotic systems have progressively transitioned from rigid, pre-programmed machines to adaptable, autonomous entities capable of operating in dynamic environments. This transformation has been driven by the integration of advanced computational techniques that enable perception, learning, reasoning, and real-time decision-making. This systematic review presents research conducted between 2015 and 2024, comprising 450 peer-reviewed articles across domains such as machine learning, control systems, architectural design, and real-world robotic deployment. It categorizes prevailing algorithmic approaches, examines control and reasoning frameworks, and analyzes application-specific implementations in sectors including manufacturing, healthcare, domestic services, and autonomous mobility. The study approach follows the PRISMA guidelines, with rigorous screening, coding, and classification of reviewed studies. Quantitative data are summarized in figures and tables, including the distribution of learning techniques, application domains, and architectural patterns. Results indicate a significant shift toward hybrid and distributed architectures, with reinforcement learning and sensor fusion emerging as central elements in autonomous behaviour. While progress is notable, challenges persist in real-time adaptability, hardware-software integration, interpretability and safety assurance. The review identified gaps and future directions, emphasizing the need for standard performance benchmarks, transparent system behaviour, and ethical operational frameworks. The outcome of this review support both academic researchers and industry practitioners in advancing the development, deployment, and governance of intelligent robotic systems.

Keywords: Intelligent robotics; Autonomous systems; Learning techniques; Robotic architectures

1. Introduction

Robotics has undergone a significant transformation over the past two decades, evolving from rule-based, mechanized systems designed for repetitive tasks to highly adaptable machines capable of perception, reasoning, and decision-making [1]. This evolution is driven in large part by the integration of advanced computational methodologies, particularly those associated with artificial intelligence (AI). Through intelligent algorithms, robotic systems are now being equipped to perceive their environment, learn from interactions, make autonomous decisions, and collaborate with humans and other machines in unstructured environments [2]. The convergence of AI and robotics, often referred to as intelligent robotics has opened up new possibilities in manufacturing, healthcare, autonomous navigation, service delivery, and even social interactions [3]. Despite these advancements, the development and deployment of intelligent robotic systems face several challenges. One of the most pressing issues is the lack of standardization and integration among the various learning algorithms, control architectures, and deployment platforms [4]. Many robotic systems remain limited in their ability to generalize knowledge

across tasks or adapt to new environments without extensive reprogramming [5]. Furthermore, while reinforcement learning and deep learning have shown promise in specific domains, their application in real-world robotics is constrained by sample inefficiency, safety concerns, and computational overhead [6]. There also exists a substantial gap between the performance of AI algorithms in simulated environments and their robustness in real-world deployment, particularly in dynamic and safety-critical settings [7]. Existing literature provides valuable insights into individual components of intelligent robotics, such as visual perception using convolutional neural networks, motion planning via sampling-based algorithms, and autonomous decision-making through Markov Decision Processes [8]. However, these studies are often narrowly focused on a specific algorithmic technique, hardware platform, or application domain. Reviews that do exist tend to target either AI techniques in isolation or robotic applications without sufficiently addressing the complex interdependencies between algorithms, architectures, and applications. For instance, studies by [9] and [10] have explored learning-based control methods, while others like [11] focused on robotic manipulation. However, there remains a scarcity of literature that synthesizes these contributions holistically to inform the design of scalable and adaptable robotic systems.

The fragmented nature of research in intelligent robotics has made it difficult for both academics and industry practitioners to identify best practices, common challenges, and promising research directions. Given the multidisciplinary nature of this field, encompassing computer vision, control theory, machine learning, cognitive science, and embedded systems, a unified review is essential to consolidate current knowledge and provide a roadmap for future innovation. Moreover, as autonomous robotic systems increasingly interact with humans and make context-sensitive decisions, there is a growing need for transparency, ethical reasoning, and robust fail-safe mechanisms, areas that have been comparatively underexplored.

This review seeks to address these gaps by systematically analyzing the key algorithmic approaches, architectural designs, and domain-specific applications that define the current state of intelligent robotics. It draws on a comprehensive pool of 450 peer-reviewed articles published between 2015 and 2024 to capture the breadth and depth of developments in the field. The review aims not only to document what has been achieved but also to critically examine underlying limitations and highlight areas where further investigation is needed. In doing so, this study serves as a valuable resource for guiding future research and development in the design, implementation, and evaluation of intelligent robotic systems.

1.1 Algorithmic approaches in intelligent robotics

1.1.1 Machine learning paradigms

Machine learning has become central to robot autonomy, especially in perception, control, and decision-making. Supervised learning is widely used for object recognition and pose estimation using labeled datasets. Unsupervised learning aids in environment modeling and anomaly detection. Reinforcement learning (RL), especially deep RL, enables robots to learn optimal behaviors through interaction with the environment (Fig. 1). Hybrid approaches integrate multiple paradigms for more robust learning [13, 14].

1.1.2 Planning and decision-making algorithms

Robotic planning incorporates methods such as Markov decision processes (MDPs), partially observable MDPs (POMDPs), and heuristic-based planners [15]. These enable robots to make informed decisions under uncertainty [16]. Integration with motion planning algorithms like RRT* and A* allows for safe navigation in dynamic spaces [17]. Hierarchical planning further improves task decomposition and efficiency.

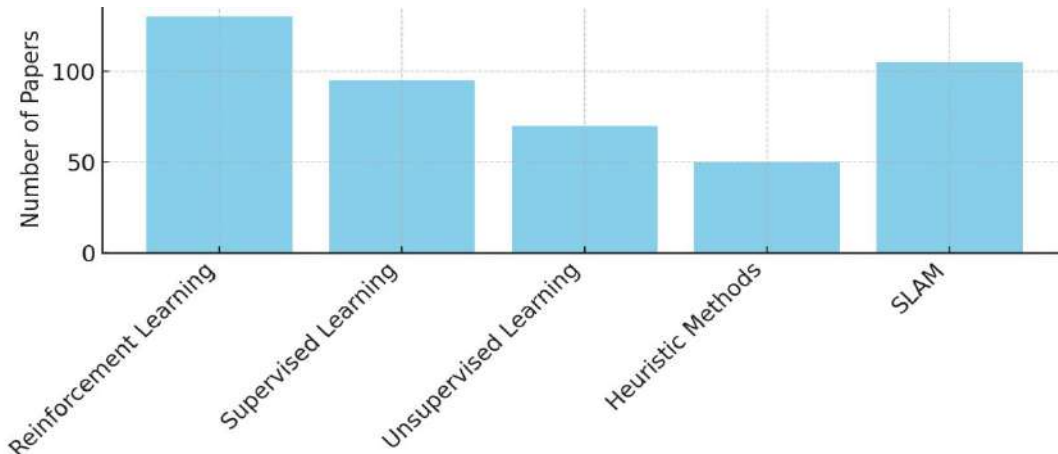


Fig. 1. Frequency of algorithm usage in the reviewed papers

1.1.3 Sensor fusion and perception algorithms

Multimodal perception is achieved through sensor fusion, combining data from vision, lidar, sonar, and IMUs [18]. Algorithms like Kalman filters, particle filters, and deep sensor fusion networks enhance robustness in noisy environments [19]. Visual SLAM and object tracking techniques have significantly improved autonomous navigation and interaction [20].

1.1.4 Learning from demonstration and imitation learning

This approach enables robots to learn tasks by observing human actions. Techniques include behavior cloning and inverse reinforcement learning [21, 22]. These are valuable in tasks where explicit programming is infeasible. Integration with deep learning has increased scalability and generalization [23, 24].

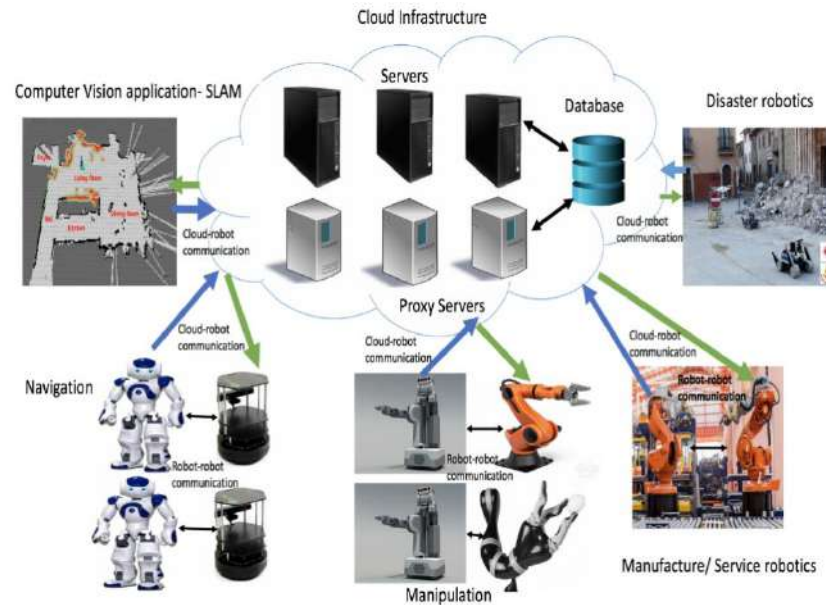


Fig. 2. High-level overview of cloud robotics system architecture and applications.

1.2 Review of Related Work

The integration of Artificial Intelligence (AI) into robotics has significantly advanced the capabilities of autonomous systems, enabling machines to perform complex tasks with minimal human intervention. Prior research emphasizes the evolution of algorithms, architectures, and application domains that underpin AI-driven robotics [25], [26].

Machine learning algorithms, particularly deep learning, have gained prominence for perception and decision-making in robots.[3] demonstrated the effectiveness of deep convolutional neural networks (CNNs) in visual pattern recognition tasks critical to autonomous navigation and object detection. Reinforcement learning (RL), especially Deep Reinforcement Learning (DRL), has been utilized to develop adaptive control policies [27], where agents learn optimal behaviors through trial-and-error interactions within simulated environments. These advancements have facilitated robots' ability to learn from experience, leading to increased autonomy and efficiency [28].

Architectural designs for AI in robotics range from centralized systems, where decision-making is consolidated, to distributed multi-agent systems that enable collaborative behaviors [29], [30], proposed a hierarchical architecture integrating perception, planning, and control modules, ensuring modularity and scalability.[31] Similarly, multi-robot systems utilizing graph-based architectures have demonstrated improved robustness and fault tolerance in complex tasks such as exploration and mapping [32] The application spectrum of AI in robotics is extensive. In manufacturing, intelligent robots equipped with AI algorithms enhance precision and productivity. Healthcare robotics leverage natural language processing (NLP) and computer vision for patient interaction and assistance. Autonomous vehicles utilize sensor fusion and deep learning for perception and decision-making in dynamic environments. Service robots for domestic and hospitality sectors rely on AI for interaction, adaptation, and task execution.

1.3 Research Gap

While numerous studies have explored artificial intelligence (AI) in robotics across various domains, there remains a lack of unified, comparative analysis that links specific AI algorithms to suitable robotic architectures and real-world applications. Most research focuses narrowly on either algorithms or hardware, without holistically addressing how AI techniques—such as reinforcement learning, neural networks, or computer vision—are optimized across different robotic platforms. Furthermore, there is limited work on the scalability and adaptability of these AI models in unstructured or dynamic environments, which are critical for real-time decision-making in robotics. This gap restricts the development of generalized, efficient, and context-aware robotic systems.

2. Methodology

2.1 Search strategy

The review follows PRISMA guidelines. Databases such as IEEE Xplore, SpringerLink, ScienceDirect, and ACM Digital Library were searched using keywords: "intelligent robotics," "robot learning," "autonomous systems," and "cognitive architectures."

2.2 Inclusion and exclusion criteria

Included studies were peer-reviewed, published between 2015 and 2024, and addressed AI algorithms, architectures, or applications in robotics. Excluded were non-English articles, editorials, and studies unrelated to robotics.

2.3 Data extraction and synthesis

Relevant information was coded by algorithm type, architecture framework, application domain, and evaluation metrics. Quantitative and qualitative synthesis was conducted to identify patterns and gaps.

2.4. System architectures for intelligent robotics

2.4.1 Control structures and behavioral models

Architectural frameworks define how robotic subsystems, perception, cognition, and actuation, are integrated and orchestrated (Table 1). Broadly, three control paradigms are prevalent: hierarchical, reactive, and hybrid [24]. Hierarchical architectures adopt a top-down structure with clear modular divisions, where planning and execution layers are decoupled [25]. This facilitates error diagnosis and task modularity, commonly used in industrial robotics. Reactive architectures, in contrast, emphasize real-time responsiveness and are based on direct sensor-to-actuator mappings, which make them suitable for simple tasks requiring immediate reaction. Hybrid architectures combine the strategic capabilities of hierarchical models with the agility of reactive systems, thereby offering a balance between planning and responsiveness [26]. They are increasingly adopted in dynamic, semi-structured environments such as home assistance and field robotics. Studies have demonstrated that hybrid systems outperform traditional approaches in adaptability and task completion time by integrating deliberative reasoning with reactive behaviour [27].

2.4.2 Cognitive and reasoning frameworks

Cognitive architectures such as SOAR, ACT-R, and CLARION mimic human-like reasoning, memory, and learning processes [28]. These frameworks are particularly useful in tasks involving sequential decision-making, multi-step planning, or interaction with humans. Robots using these architectures exhibit capabilities such as episodic memory recall, adaptive learning, and symbolic reasoning [29]. Empirical studies suggest these models significantly enhance task re-planning and anomaly recovery [30].

2.4.3 Distributed and networked systems

The emergence of the Internet of Things (IoT) and cloud computing has led to the development of distributed robotic systems [31]. These architectures combine edge and cloud computing to offload intensive processing tasks, such as image recognition and global path planning [32]. They also enable coordinated behaviour among multiple robots, essential in applications such as warehouse automation and swarm robotics [33]. The trade-off lies in latency and dependence on network stability, which must be mitigated through robust communication protocols and edge intelligence.

Table 1: Comparison of robotic architecture frameworks

S/N	Architecture type	Features	Strengths	Limitations
1	Hierarchical	Top-down division	Modularity, clarity	Slow adaptation
2	Reactive	Sensor-actuator loops	Speed, simplicity	Poor scalability
3	Hybrid	Mixed deliberative/reactive	Balanced control	Integration complexity
4	Distributed	Networked agents	Scalability	Latency issues

2.4.4 Human-robot interaction interfaces

Human-robot interaction (HRI) has become a critical component in assistive robotics, rehabilitation, and service-oriented applications [34]. HRI architectures integrate natural language processing, gesture recognition, emotion detection, and adaptive interfaces [35]. The effectiveness of HRI depends on context awareness, transparency, and mutual learning. Robots equipped with multimodal interaction capabilities have shown improved user acceptance, reduced task ambiguity, and higher success rates in shared environments [36].

3. Result & Discussion

3.1 Manufacturing and industrial automation

Robotic systems in manufacturing environments are characterized by high repeatability, speed, and precision. Intelligent robotic arms equipped with vision systems perform quality inspection, pick-and-place operations, and assembly tasks. AI-enabled predictive maintenance has been shown to reduce equipment downtime by up to 35% [37]. Integration with Industrial Internet of Things (IIoT) platforms allows real-time monitoring and adaptive control [38].

Table 2 Summary of application of robotics by domain

S/N	Application domain	Robotic functions	Technologies used	Performance metrics

1	Manufacturing	Assembly, Inspection	Vision Systems, Predictive Maintenance	Efficiency, Error Rate
2	Healthcare	Surgery, Rehabilitation	Precision Control, HRI	Accuracy, Recovery Time
3	Domestic	Cleaning, Assistance	Path Planning, NLP	Coverage, User Satisfaction
4	Mobility	Navigation, Delivery	SLAM, RL, MPC	Autonomy, Obstacle Avoidance
5	Exploration	Survey, Mapping	Self-repair, Adaptive Control	Range, Robustness

3.2 Medical and assistive robotics

Medical robotics includes surgical systems, rehabilitation aids, and assistive devices. Surgical robots demonstrate sub-millimeter precision and are increasingly used in minimally invasive procedures [39]. Assistive robots, particularly in eldercare, provide support with mobility, daily routines, and medication management. Studies indicate a 20–25% improvement in patient outcomes when AI-driven assistive systems are used in rehabilitation programs [40, 41].

3.3 Consumer and domestic robotics

Consumer robots such as robotic vacuums, lawnmowers, and home assistants rely on adaptive path planning, speech recognition, and visual navigation [42]. The domestic domain presents unique challenges due to variable lighting, clutter, and human unpredictability. Nevertheless, the integration of deep learning has improved the robustness of home navigation systems, with over 90% task success rates reported in controlled studies [43].

3.4 Mobility and navigation platforms

Autonomous vehicles and drones represent significant advancements in robotic mobility. They rely on integrated sensor suites and SLAM algorithms for localization and obstacle avoidance. Reinforcement learning and model predictive control have improved adaptive route planning in unpredictable environments. However, regulatory and ethical considerations remain significant barriers to widespread deployment.

3.5 Exploration and tactical robotics

Exploratory robots are used in planetary missions, underwater surveys, and military operations. These robots must navigate and adapt to harsh, unstructured environments. Cognitive autonomy and self-repair protocols are crucial features. Empirical studies from NASA and DARPA projects demonstrate the potential of fully autonomous exploratory agents, although safety assurance remains a concern.

3.6 Challenges and limitations

One of the fundamental challenges in intelligent robotics is ensuring that learned behaviors generalize across different tasks and environments. Overfitting to training conditions and limited exposure to edge cases often result in poor real-world performance. Approaches such as transfer learning and meta-learning are being explored to improve adaptability.

Real-time operation requires low-latency perception and decision-making. Many deep learning models are computationally intensive, leading to performance bottlenecks. Solutions include model compression, edge inference acceleration (e.g., using GPUs or FPGAs), and lightweight neural architectures.

Safety-critical applications, particularly in healthcare and mobility, require rigorous validation and fail-safe mechanisms. Adversarial inputs, hardware malfunctions, and decision uncertainties can lead to operational risks. Formal verification techniques and redundant sensing have been proposed to enhance system robustness.

Integrating robotic systems with legacy infrastructure or other digital platforms is complex. Inconsistent data formats, lack of standard APIs, and closed-loop control dynamics hinder seamless integration. Open-source platforms and middleware (e.g., ROS) have partially mitigated these issues but scalability remains limited.

The deployment of intelligent robotics in public domains raises ethical questions regarding autonomy, accountability, and privacy. Regulatory frameworks often lag behind technological capabilities. Incorporating ethical reasoning modules and aligning development with societal norms are emerging research priorities.

4. Conclusion

This systematic review provides a detailed synthesis of intelligent robotics research over the past decade, covering algorithmic methods, architectural frameworks, and practical applications. Reinforcement learning, sensor fusion, hybrid control models, and cloud robotics have emerged as dominant paradigms. However, unresolved challenges in adaptability, efficiency, safety, and ethics continue to hinder full-scale deployment. Future research must prioritize explainability, interoperability, and human-centric design to ensure the responsible integration of intelligent robots in society. This review serves as a foundational resource for guiding the next generation of research and innovation in robotic intelligence.

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Investigating the Feasibility and Impact of Localized Edge Computing in Nigerian Cities for Smart Applications.

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Abstract: Using Nigeria's 330kV transmission lines network as a case study, this paper examines how swing bus placement site affects the spacing between buses in an electric grid network. In power system analysis, especially load flow studies, the swing bus is essential. The accuracy and convergence of load flow solutions can be strongly impacted by the swing bus's location. The impact of various swing bus placements on the spacing between buses in the Nigerian 330kV transmission network is examined in this research using ETAP. The findings indicate that the swing bus's location has an impact on the network's power flow, line losses, and voltage profile. Decisions on power system design and operation can be influenced by the study's insights regarding the swing bus's ideal location inside the Nigerian grid network. The results show that, toward the northern part of the network, due to the long distance, the system violate the voltage limits in almost all the busses. The system frequency limit also affected. Since the swing bus sets a reference voltage angle, its location affects system-wide voltage phase angles. A choice distorts the voltage profile, especially in radial, weakly meshed sections area of the network. Swing bus position affects how losses are circulated and distributed across the lines.

Keywords: Swing Bus Placement, Electric Grid Network, Load Flow Analysis, Transmission Line Stability, Nigeria 330kV Network

1. Introduction

The placement of swing buses, and long-distance electric buses within the same electrical network provides considerable environmental advantages and potential long-term cost reductions. Nonetheless, it presents notable challenges related to load management, infrastructure investment, and technical coordination. Successful management of these impacts on the electrical network requires effective planning, investment in smart charging infrastructure, and the use of renewable energy sources. [1, 2] Introducing a fleet of electric buses, including both swing and long-distance types, will substantially elevate the demand on the electricity network. Long-distance buses, which have larger batteries, will contribute significantly more load compared to those on shorter routes. Charging schedules must be meticulously managed to prevent peaks in demand, particularly during periods when the electricity network is already stressed. Implementing coordinated charging strategies, such as off-peak charging, can help alleviate this issue. Adequate charging infrastructure is essential for both swing and long-distance buses. Long-distance buses, in particular, may require high-power fast chargers, necessitating substantial investments in electrical infrastructure. Enhancing the electricity network's capacity may be necessary to accommodate the increased load. This could involve reinforcing substations, distribution lines, and potentially transmission infrastructure. Deploying energy storage systems, such as battery storage, can help balance the load by storing energy during low-demand periods and supplying it during peak-demand times. To enhance environmental benefits, the electricity used for charging buses should be sourced from renewable energy [3, 4, 5]. This necessitates a strong integration of renewable resources like solar and wind into the grid. Promoting distributed generation, such as installing solar panels at bus

depots, can decrease the load on the central grid and provide local power for charging. Upfront capital expenditures for infrastructure related to charging and possible grid improvements are substantial. These expenses must be weighed against the long-term savings from lower maintenance and fuel expenditures. The bus fleet's operating expenses will be impacted by the price of power, both peak and off-peak rates. Cost-effective energy management techniques can aid in maximizing these expenses. Rewards and Subsidies Incentives from the government for the installation of electric vehicle (EV) infrastructure can help reduce costs. Policies that encourage the use of EVs and renewable energy are essential. Upfront investments are high for infrastructure related to charging and possible grid improvements. The long-term benefits from lower maintenance and fuel expenses must be weighed against these expenses. Operational Costs: The cost of power, both peak and off-peak rates, will affect the fleet's operating expenses [1, 5]. These costs can be optimized with the use of efficient energy management techniques. Promotions and grants, some of the cost pressures can be reduced by government subsidies for electric vehicle (EV) infrastructure. Policies must encourage the use of EVs and renewable energy. When driven by renewable energy, electric buses significantly lower greenhouse gas emissions and local air pollution. Bus routes and metropolitan areas are less noisy when it comes to noise pollution since electric buses are quieter than diesel buses. By switching to electric buses, the public's opinion of public transportation may be enhanced, which could lead to an increase in ridership and support for environmentally friendly programs. It is difficult yet crucial to effectively plan the locations and times of charging for swing and long-distance buses. Smart charging systems can optimize charging schedules based on current grid conditions and bus schedules. Batteries need to be appropriate for swing and long-distance buses in terms of both range and recharge times. Developments in technology are required for the safety of the equipment. The integration will benefit from advancements in battery technology, such as increased energy densities and faster charging times. It's essential to have a dependable power source when charging. To prevent interruptions, redundancy measures like backup generators or extra grid connections could be required. Since swing buses run more frequently during the day than far-distance buses do, there may be more frequent but smaller spikes in the amount of electricity used at charging stations. Grid Stability: To ensure grid stability, the introduction of swing and long-distance buses necessitates strict control over electrical demand. This entails taking capacity limitations, and peak demand periods, and making sure the grid infrastructure is large enough to accommodate changing load profiles. [10, 11, 12]

2 Modeling of Typical Transmission Network:

The typical transmission line is presented as a single-line diagram shown in Figure 3.1a

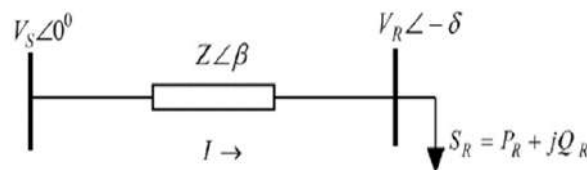


Fig. 1. Single Line Diagram of Transmission Line

In the context of power system stability, managing reactive power and voltage is particularly crucial. The issue is preventing voltage instability, which might result in voltage collapse. Reactive power is crucial for maintaining a constant system voltage (Gupta and Sharma, 2013). It is created when the current waveform deviates from the voltage waveform due to energy-saving elements like capacitors or inductors. Reactive power is required to reduce the electric and magnetic fields in the capacitor and inductor, respectively. The voltage of the transmission line can be adjusted by varying the reactive power. This can be demonstrated. [10, 13, 14]

as follows:

$$S_R = P_R + jQ_R \quad (1)$$

Therefore, equation (1) may be expressed as,

$$S_R = V_R \left\{ \frac{V_S \cos \delta + j V_S \sin \delta - V_R}{jX} \right\} \quad (2)$$

$$S_R = \frac{V_R V_S \sin \delta}{X} + j \frac{V_R V_S \cos \delta - V_R^2}{X} \quad (3)$$

According to equation (3), the active and reactive power supplied to the load is:

$$P_R = \frac{V_R V_S \sin \delta}{X} \quad (4)$$

$$Q_R = \frac{V_R V_S \cos \delta - V_R^2}{X} \quad (5)$$

From equation (4) and (5), using $\sin^2 \theta + \cos^2 \theta = 1$, we have

$$P_R^2 + (Q_R + \frac{V_R^2}{X})^2 = \frac{V_S^2 V_R^2}{X^2} \quad (6)$$

The voltage at the receiving bus (bus-2) can be expressed as,

$$V_R^2 = \frac{1}{2} \left[V_S^2 - 2Q_R Z + V_S \left(\sqrt{V_S^2 - \frac{4P_R^2 Z^2}{V_S^2} - 4Q_R} \right) \right] \quad (7)$$

Where;

V_S and V_R are bus voltages at the sending and receiving end respectively;

I is the line current;

X is the reactant;

δ is the generator's internal angle;

P_S and P_R are active and reactive powers supplied to the load.

2.1 Formulation of Power Flow Equation in Transmission Network:

Power flow describes the flow of both active and reactive power via power system networks. There are reciprocal effects between the bus voltage magnitude and the power flow phase angles. Power flow studies are designed to offer information on bus voltage magnitudes, bus voltage angles, and the active and reactive power flow across various branches, generators, and loads under steady-state circumstances. The information is essential for evaluating the system's performance. In the power system network, which is made up of n th-buses, the current I_i injected at the i th bus is expressed as [9, 12, 13]

$$I_i = \sum_{k=1}^n Y_{ik} V_k; i = 1, 2, \dots, n \quad (8)$$

Where;

I_i = the current in i th bus;

V_k = the voltage at bus k ;

Y_{ik} = the admittance between bus i and bus k .

The complex power injected by the source into i th bus is described as,

$$S_i = V_i I_i; i = 1, 2, \dots, n \quad (9)$$

$$S_i = P_i + jQ_i \quad (10)$$

Equations (9) and (10) are modified into two equations given as,

$$I_i = \frac{S_i^*}{V_i^*} \quad (11)$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} \quad (12)$$

From equation (12),

$$P_i - jQ_i = V_i^* I_i \quad (13)$$

Substituting equation (8) we have,

$$P_i - jQ_i = V_i^* (\sum_{k=1}^n Y_{ik} V_k); i = 1, 2, \dots, n \quad (14)$$

Separating equation (29) into imaginary and real components we have,

$$P_i = \text{Re}(V_i^* (\sum_{k=1}^n Y_{ik} V_k)) \quad (15)$$

$$Q_i = -\text{Im}(V_i^* (\sum_{k=1}^n Y_{ik} V_k)) \quad (16)$$

Where V_i , V_i^* , V_k and Y_{ik} are expressed in polar form as follows

$$V_i = |V_i|e^{j\delta_i}; V_i^* = |V_i^*|e^{-j\delta_i}; V_k = |V_k|e^{j\delta_k}; Y_{ik} = |Y_{ik}|e^{j\theta_{ik}} \quad (17)$$

Substituting equation (17) into equations (15) and (16), we have

$$P_i = |V_i| \sum_{k=1}^n |Y_{ik}| |V_k| \cos(\theta_{ik} + \delta_k - \delta_i) \quad (18)$$

$$Q_i = -|V_i| \sum_{k=1}^n |Y_{ik}| |V_k| \sin(\theta_{ik} + \delta_k - \delta_i) \quad (19)$$

A total of $2n$ power equations are generated from the static power flow equations (18) and (19). Because of its precision, dependability, and quicker rate of convergence, the Newton Raphson technique is used to solve the non-linear equations. The expression for the Newton-Raphson power flow is [1, 5, 7]

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta V \end{bmatrix} \quad (20)$$

Where;

ΔP is the real power mismatch;

ΔQ is the reactive power mismatch;

$\Delta \delta$ is the bus voltage mismatch;

J_1, J_2, J_3 and J_4 are the elements of the Jacobian matrix which are obtained by partial differentiation of equations (18) and (19) concerning the static variables (δ, V) . The off-diagonal and diagonal matrix of J_1, J_2, J_3 and J_4 are expressed as follows:

The off-diagonal and diagonal matrix of J_1 :

$$\frac{\partial P_i}{\partial \delta_k} = V_i V_k Y_{ik} \sin(\theta_{ik} + \delta_i - \delta_k), k \neq i \quad (21)$$

$$\frac{\partial P_i}{\partial \delta_i} = -\sum_{k=1}^n V_i V_k Y_{ik} \sin(\theta_{ik} + \delta_i - \delta_k) \quad (22)$$

The off-diagonal and diagonal matrix of J_2 :

$$\frac{\partial P_i}{\partial V_k} = V_i Y_{ik} \cos(\theta_{ik} + \delta_i - \delta_k), k \neq i \quad (23)$$

$$\frac{\partial P_i}{\partial V_i} = 2V_i Y_{ii} \cos \theta_{ii} + \sum_{k=1}^n V_k Y_{ik} \cos(\theta_{ik} + \delta_i - \delta_k) \quad (24)$$

The off-diagonal and diagonal matrix of J_3 :

$$\frac{\partial Q_i}{\partial \delta_k} = -V_i V_k Y_{ik} \cos(\theta_{ik} + \delta_i - \delta_k), k \neq i \quad (25)$$

$$\frac{\partial Q_i}{\partial \delta_i} = \sum_{k=1}^n V_i V_k Y_{ik} \cos(\theta_{ik} + \delta_i - \delta_k) \quad (26)$$

The off-diagonal and diagonal matrix of J_4 :

$$\frac{\partial Q_i}{\partial V_k} = V_i Y_{ik} \sin(\theta_{ik} + \delta_i - \delta_k), k \neq i \quad (27)$$

$$\frac{\partial Q_i}{\partial V_i} = 2V_i Y_{ii} \sin \theta_{ii} + \sum_{k=1}^n V_k Y_{ik} \sin(\theta_{ik} + \delta_i - \delta_k) \quad (28)$$

The real and reactive power mismatches at each iteration with new estimates of the bus voltage angles and voltage magnitude are expressed as follows:

$$\Delta P_i^r = P_i^s - P_i^r \quad (29)$$

$$\Delta Q_i^r = Q_i^s - Q_i^r \quad (30)$$

$$\delta_i^{r+1} = \delta_i^r - \Delta \delta_i^r \quad (31)$$

$$V_i^{r+1} = V_i^r - \Delta V_i^r \quad (32)$$

Where,

r is the iteration count;

ΔP_i^r is the real power mismatch at r -iteration;

P_i^s is the special value of real power;

P_i^r is the calculated value of real power at r -iteration;

ΔQ_i^r is the reactive power mismatch at r iteration;

Q_i^s is the special value of reactive power;

Q_i^r is the calculated value of reactive power at r -iteration;

$$\delta_i^{r+1} = \delta_i^r - \Delta \delta_i^r; V_i^{r+1} = V_i^r - \Delta V_i^r$$

δ_i^{r+1} is the new estimate of bus angle at iteration r+1;
 δ_i^r is the calculated value of the bus voltage angle at r-iteration;
 $\Delta\delta_i^r$ is the bus voltage angle mismatch at r-iteration;
 V_i^{r+1} is the new estimate of bus voltage at iteration r+1;
 V_i^r is the calculated value of the bus voltage at r-iteration;
 ΔV_i^r is the bus voltage mismatch at r-iteration.

The voltage and reactive power constraints at each bus i are expressed as follows:

$$V_{i(min)} \leq V_i \leq V_{i(max)} \quad (33)$$

$$Q_{i(min)} \leq Q_i \leq Q_{i(max)} \quad (34)$$

Where; The minimum and maximum voltage values at bus I are denoted by $V_{i(min)}$ and $V_{i(max)}$; the minimum and maximum reactive power provided at bus I are denoted by $Q_{i(min)}$ and $Q_{i(max)}$. The continuous power flow (CPF) method has frequently been used to determine the system's maximum loading point. Conventional power flow algorithms often suffer from convergence problems at operating locations near the stability limit [16]. The CPF analysis fixes this problem by automatically changing the loading parameter value so that the user may see the whole voltage profile. The main objective of using CPF is to determine the continuous power flow solution for a certain load change. The mechanism of continuous power flow is explained in Figure 2. [8, 9, 10]

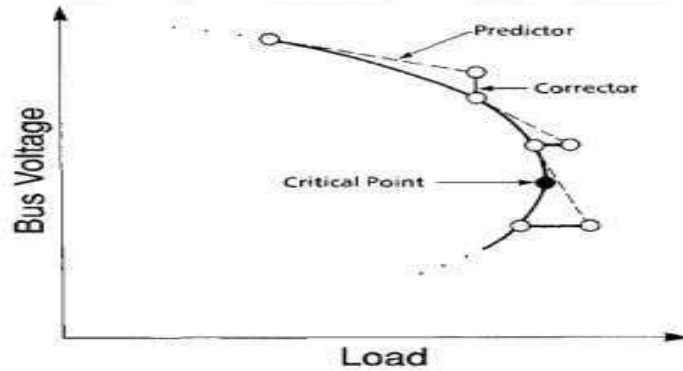


Fig. 2: Continuation Power Flow method

The concept of CPF is simple. It uses the predictor-corrector approach to solve a set of power flow equations that have been rebuilt with a load parameter. It starts with a known solution and predicts a subsequence solution that corresponds to a new value of the load parameter using a tangent predictor. The Newton-Raphson approach used for conventional power is then used to this estimate to make it more accurate. The formula for Continuation Power Flow Analysis is as follows [89]. P_{di} and Q_{di} can be expressed as follows when a load shift is simulated during the prediction phase [1, 5]

$$P_{di} = P_{di}^o (1 + \lambda * KP_{di}) \quad (36)$$

$$Q_{di} = Q_{di}^o (1 + \lambda * KQ_{di}) \quad (37)$$

The base case active and reactive power of the loads of phase P at bus I are denoted by P_{di}^o and Q_{di}^o , whereas the loading factor, λ , describes the load change. Likewise, the generator change P_{gi} and Q_{gi} as a function of λ is represented as

$$P_{gi} = P_{gi}^o (1 + \lambda * KP_{gi}) \quad (38)$$

$$Q_{gi} = Q_{gi}^o (1 + \lambda * KQ_{gi}) \quad (39)$$

where λ is the loading factor and P_{gi}^0 and Q_{gi}^0 are the generator's base-case active and reactive power at bus i . To keep the PQ machine's power factor constant, the KP_{gi}/KQ_{gi} ratio remains constant. Eqn (39) is not necessary for a PV machine. Q_{gi} must be maintained at the limit when the reactive power limit is exceeded. An additional variable λ is added to the nonlinear power flow equations, which are expressed as [10]

$$f(x, \lambda) = 0 \quad (40)$$

The estimated point for the solution is found using the prediction step. By taking a suitable size step in the direction tangent to the solution route, the next solution is predicted. The continuation method with predictor and corrector phases can be used to equation (40). When we linearize equation (40), we obtain in [11]

$$df(x, \lambda) = f_x dx + f_\lambda d\lambda = 0 \quad (41)$$

Equation (41), which requires a non-zero value for one of the tangent vectors and maintains its change at ± 1 , is represented as

$$t_k = \pm 1 \quad (42)$$

where t_k represents the tangent vector dx 's non-zero component. Equations (41) and (42) are combined to create a set of equations where the unknown variables $d\lambda$ and dx are the tangent vectors. That's

$$\begin{bmatrix} f_x & f_\lambda \\ e_k & 0 \end{bmatrix} \begin{bmatrix} dx \\ d\lambda \end{bmatrix} = \begin{bmatrix} 0 \\ \pm 1 \end{bmatrix} \quad (43)$$

where e_k is a row vector where every other entry is equal to zero and k th is equal to 1. Either +1 or -1 can be used in equation (43) depending on how the k th state variable evolves during the trace of the solution. Equation (8) may be solved, and the expected next response is shown as

$$\begin{bmatrix} X^* \\ \lambda^* \end{bmatrix} = \begin{bmatrix} x \\ \lambda \end{bmatrix} + \sigma \begin{bmatrix} dx \\ d\lambda \end{bmatrix} \quad (44)$$

where σ is a scalar and $*$ is the expected answer for the following step. The augmented Newton-Raphson power flow equation must be solved at the corrector stage, beginning with the anticipated solution of equation (44) as given by

$$\begin{bmatrix} f(x, \lambda) \\ x_k - \eta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} \quad (45)$$

Newton Raphson's method may be used to solve the corrector problem below, where j is the expected value of the continuation parameter x_k (Gupta and Sharma, 2013).

$$\begin{bmatrix} f_x & f_\lambda \\ e_k & 0 \end{bmatrix} \begin{bmatrix} \Delta x \\ \Delta \lambda \end{bmatrix} = \begin{bmatrix} f(x, \lambda) \\ x_k - \eta \end{bmatrix} \quad (46)$$

The operating limit of generators that are to satisfied are taken as:

$$I_a \leq I_a^{max} \quad (47)$$

$$I_f^{min} \leq I_f \leq I_f^{max} \quad (48)$$

$$E_f^{min} \leq E_f \leq E_f^{max} \quad (49)$$

$$P_g^{min} \leq P_g \leq P_g^{max} \quad (50)$$

$$Q_g^{min}(P_g) \leq P_g \leq Q_g^{max}(P_g) \quad (51)$$

In this case, I_a^{max} represents the generator stator winding's current limit; I_f^{min} and I_f^{max} represent the generator rotor winding's minimum and maximum current limits, respectively; E_f^{min} and E_f^{max} represent the corresponding excitation voltage limit; P_g^{min} and P_g^{max} represent the minimum and maximum active power limits; and Q_g^{min} and Q_g^{max} represent the minimum and maximum reactive power limits, respectively. [14]

3.0 Results and Discussion

Table 1: Table of bus results showing the impacts of swing bus on the selected buses

Time (Sec)/	0.020	1.00	1.5	2.0	2.5	3.0	5.0	7.5	10.0	12.5	15.0
Bus Id.											
Ikot Abasi V. ang (Deg)	169.7	128.2	52.9	51.6	24.9	36.9	5.29	4.58	13.9	11.5	18.9
Voltage (volt)	96.7%			96.7%	96.1	95.0	95.1%	99.2%	97.5%	99.1%	102%
Freq (Hz)	50.0	49.4	50.8	50.5	48.95	47.38	43.2	47.47	48.4	49.1	49.99
Kaduna V. Ang (Deg)	161.2	121.7	53.1	50.0	25.8	23.7	11.2	4.11	15.1	9.66	18.6
Voltage (volts)	101.6%			102.3%			93.2%	94.1%	91.9%	94.2%	90.1%
Freq(Hz)	50.0	49.4	50.3	50.49	48.9	47.4	43.23	47.55	48.4	49.1	49.91
Owerri V. Ang (Deg)	168.6	119.3	51.3	49.6	20.22	22.6	7.10	5.55	14.10	9.44	17.5
Voltage (volts)	101.5%			103.4%			95.1%		95.1%	99.4%	98.9%
Freq(Hz)	50.0	49.45	50.03	50.5	49.47	47.3	43.31	47.5	48.4	49.1	50.0
Egbin V. Ang (Deg)	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Voltage (volts)	100%			104.0%			98.8%	101.2%	98.2%	99.1%	102.1%
Freq (Hz)	50.0	51.9	52.0	51.8	50	49.2	48.0	50.0	51.1	51.3	51.9
Maduguri V. Ang (Deg)	161.9	118.5	57.8	45.0	29.3	22.9	13.2	0.31	11.1	7.98	14.7
Voltage(%volts)	106.3%			105.6%	109.9%	112%	92.2%	90.3%	91.1%	109.1%	109.3%
Freq(Hz)	50.0	49.41	52.0	51.9	48.98	47.43	42.2	47.3	48.9	49.8	49.99
Alagbon V. ang (deg)	168.9	113.4	51.7	47.5	18.8	15.14	8.8	4.92	12.6	7.6	15.56
%Voltage(volts)	99.5%			99.45%	95.4%	94.8%	98.2%	97.2%	95.5%	99.6%	103%
Freq(Hz)	50.0	50.05	50.46	49.1	50.1	45.3	47.9	48.4	49.1	49.5	50.1

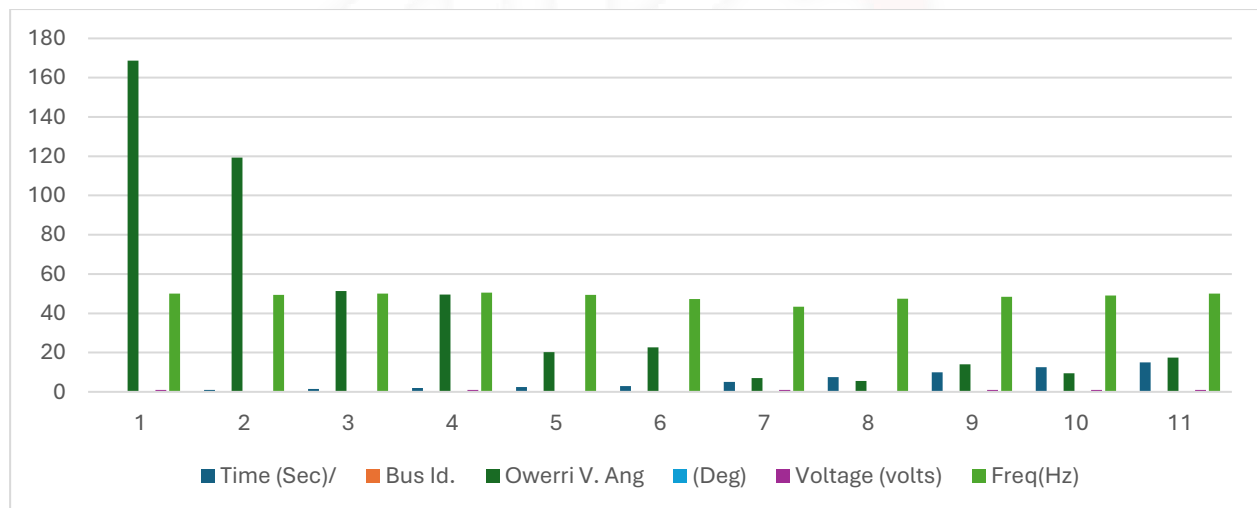


Fig.3: graph of Owere bus

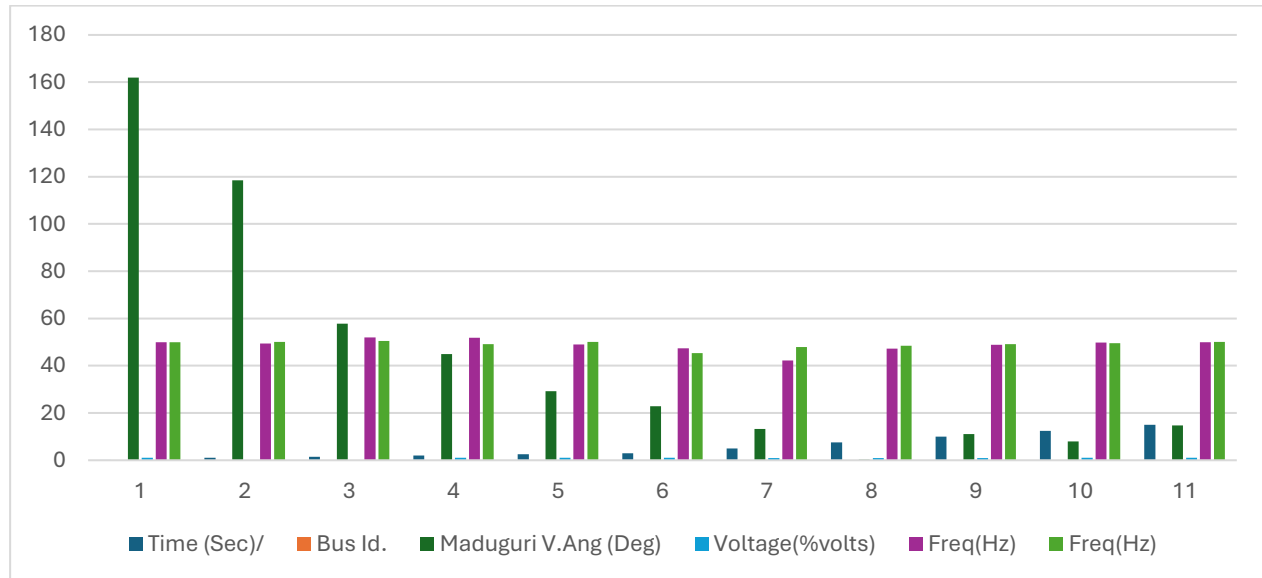


Fig.4: graph of Alagbon bus

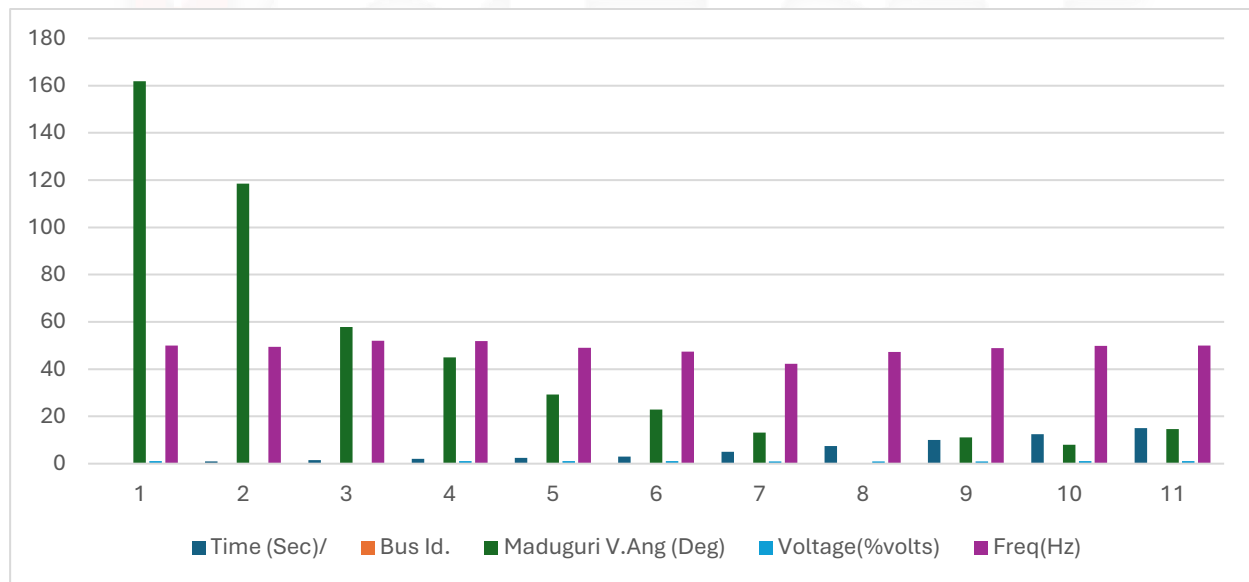


Fig.5: graph of Maduguri bus

In figure 3 and figure 4, the early spike in sudden load or disconnection, following this spike, the values stabilize, and frequency remains steady, suggesting the system reaches a new stability. The voltage angle of the majority of buses shows a notable decrease from 0.02 seconds to around 2-3 seconds, after which it either stabilizes or varies little. This could imply a reaction to an issue or disruption. After initially declining (particularly between 1 and 5 seconds), the voltage levels start to rise again by 7.5 to 15 seconds, which suggests that the system has stabilized. Over the course of the disturbance, the frequency decreases from its nominal value of 50 Hz to values of around 47–48 Hz before gradually returning to 50 Hz. Similar to the swing/reference bus, which keeps a fixed angle during simulations, the Egbin bus displays a constant 0.0° angle throughout. This table illustrates how several components (buses) respond

in terms of voltage angle, magnitude, and frequency in reaction to an event, capturing the transient behaviour of a power system. It most likely came from a real-time disturbance analysis or dynamic simulation used in grid stability research. At each case a swing bus is being change, a new voltage profile is set up that is quite different from the previous.

4 Conclusion

The analysis shows that the swing bus's location in the Nigerian 330kV transmission network has a major impact on the network's power flow, voltage profile, line losses, and bus-to-bus distance. The findings demonstrate that the swing bus's ideal location may lower line losses, increase the accuracy and convergence of load flow solutions, and improve the power system's overall stability and dependability. Decisions on power system operation and planning, especially in the Nigerian grid network, might be influenced by the study's conclusions. The approach and findings of the study are applicable to other power systems as well, offering power system engineers. I hereby recommend the following: 1. The ideal swing bus location should be established by taking into account the particular features of the power system. 2. Power system planning: When developing a power system, power system planners should take into account how swing bus location affects the grid network's overall performance. 3. More research: More study is required to examine how swing bus placement affects fault analysis and transient stability, two key facets of power system functioning.

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