ISSN No. 2971-785X Research Article

NIGERIAN JOURNAL OF ENGINEERING RESEARCH UNICROSS (NJERU)

https://njerunicross.com

Volume 2, Issue 2, 2025

Optimizing Biodiesel Production from Underutilized Non-Edible Oils Based on Metaheuristic Grey Wolf Technique

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Received: 29TH SEPT 2025 Reviewed: 20TH OCT 2025 Accepted: 24TH NOV 2025

ABSTRACT

Biodiesel from non-edible feedstocks has gained significant attention due to its reliability, cost-effectiveness, and environmental benefits compared to conventional fossil fuels. Mucuna bean seed and Gmelina seed are abundant non-edible resources in Nigeria and other regions, making them promising feedstocks for biodiesel production because of their favorable oil content and composition. In this study, the Grey Wolf Optimization (GWO) algorithm was employed to optimize biodiesel production from Mucuna bean seed and Gmelina seed oils and to analyze the interactive effects of key process parameters. The parameters investigated included reaction time, stirring speed, methanol-to-oil molar ratio, catalyst concentration, and temperature. The GWO results revealed that the combination of catalyst concentration and reaction time yielded the highest biodiesel output at 93.5%, while catalyst concentration with temperature achieved 80%. Interactions between stirring speed and methanol/oil ratio resulted in 65% yield, whereas temperature combined with speed produced the lowest yield of 38.7%. These findings demonstrate that the GWO algorithm effectively optimized the biodiesel production process from these feedstocks, providing valuable insights into parameter interactions and highlighting opportunities to enhance the efficiency and sustainability of biodiesel production.

Keywords: *Greywolf (GWO), Biodiesel, Optimization, Mucuna bean seed, Gmelina seed.*

I. INTRODUCTION

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II. METHOD

Escalating concerns over climate change, fossil fuel depletion, and energy insecurity have intensified the global pursuit of renewable, clean, and sustainable energy alternatives [1]. Among renewable options, biodiesel stands out as a promising substitute for conventional diesel due to its biodegradability, lower greenhouse gas emissions, and compatibility with existing diesel engines without significant modifications [2]. Biodiesel is typically produced via transesterification of triglycerides from vegetable oils or animal fats with short-chain alcohols, resulting in fatty acid methyl esters (FAMEs) suitable as fuel substitutes [3]. Traditionally, edible oils such as soybean, palm, and rapeseed have been primary biodiesel feedstocks [4]. However, their use raises ethical and sustainability concerns, including competition with food supply, land-use conflicts, and rising food prices [5]. These issues have shifted research toward non-edible oilseed crops that can be grown on marginal lands with minimal inputs, alleviating the food-versus-fuel dilemma while supporting rural development and energy diversification. Among these, Mucuna pruriens (velvet bean) and Gmelina arborea (white teak) have gained attention as potential non-conventional biodiesel feedstocks. Both are fast-growing, hardy plants that thrive under suboptimal soil and climatic conditions [6]. Ecologically, Mucuna is valued for its nitrogen-fixing ability and soil enrichment, while Gmelina contributes to agroforestry and carbon sequestration [7]. Studies report promising biodiesel yields from these plants. [7] achieved an optimal 68.79% biodiesel yield from Mucuna bean seed oil at 78°C, solvent-to-solid ratio of 4:1, and 35 minutes reaction time. Ref [8] explored heterogeneous catalysis of Gmelina seed oil transesterification using clay-based catalysts synthesized from clay and NaOH, examining the physico-chemical properties and kinetic modeling of the reaction [9]. The study in [10] investigated pyrolytic treatment of Gmelina biomass, analyzing energy yields at different temperatures and residence times. This study explores the hybrid use of Mucuna bean seed oil and Gmelina seed oil for biodiesel production, employing a titanium oxide catalyst combined with a Grey Wolf Optimization approach for yield profiling. This hybrid substrate and optimization methodology remain underexplored, marking this research as a novel contribution to biodiesel process optimization. A recent study by [11] provided a comparative analysis of oil yields from big and small seeded varieties of Ricinus communis, reinforcing the importance of feedstock selection in optimizing biodiesel production processes.

A. *Feedstock Collection and Preparation*

Processed Gmelina and Mucuna seeds were obtained from local agricultural processing plants. The seeds were first ground using an industrial blender to increase surface area for drying and extraction. The ground samples were then air-dried under ambient conditions to reduce moisture content, which is critical for efficient oil extraction. After drying, the samples were sieved to ensure uniform particle size and subsequently stored in airtight containers to prevent moisture uptake and contamination. Oil extraction was performed using a Soxhlet extractor with an appropriate solvent, ensuring thorough recovery of bio-oil from the feedstocks. The extracted oil was subjected to a transesterification process to convert triglycerides into fatty acid methyl esters, producing pure biodiesel (B100). To evaluate fuel performance and compatibility, the 100% biodiesel was blended with conventional diesel at varying volumetric ratios to create blends such as B10, B20, B30, and B40, enabling further testing and characterization of fuel properties.

B. *Grey-Wolf Optimization Approach.*

Additionally, [12] postulated the Grey-wolf optimizer (GWO) as an innovative swarm intelligence technique The GWO algorithm mimics the leadership hierarchy and hunting mechanism of grey-wolves in nature and the wolves are known to reside at the top of the food chain as top-level predator. Also, the wolves animate in groups that averagely consists of five to twelve wolves and these wolves are grouped into four categories such as alpha (α), beta (β), delta (δ), and omega (ω) and this pattern is employed for simulating the leadership hierarchy. In addition, it adopts the three (3) main steps of hunting (a) searching for prey (b) encircling prey and (c) attacking the prey [13-15]. According to the hierarchy of wolves as illustrated in Fig. 2, the group is led by the (α), followed by the (β)

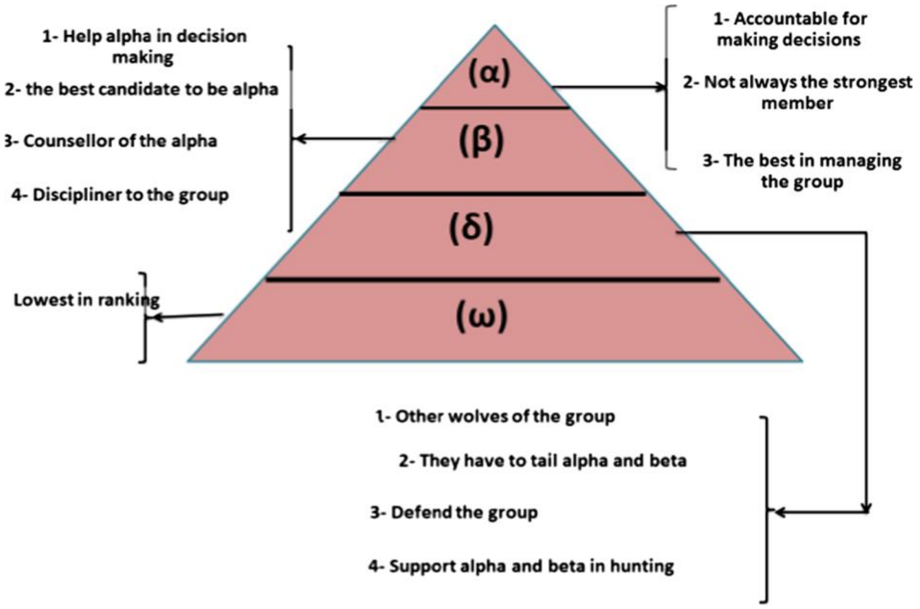


FIG. 2. GREY-WOLF PREDATING POSITION DIAGRAM

TABLE 1: GWO ATTRIBUTES AND OPTIMIZED RESULTS

Parameters	***Optimized setting***
Catalyst concentration	5
temperature	70ºC
time	100 minutes
speed	60 Rpm
Methanol/oil molar ratio	6:1
Optimized yield	93.5%

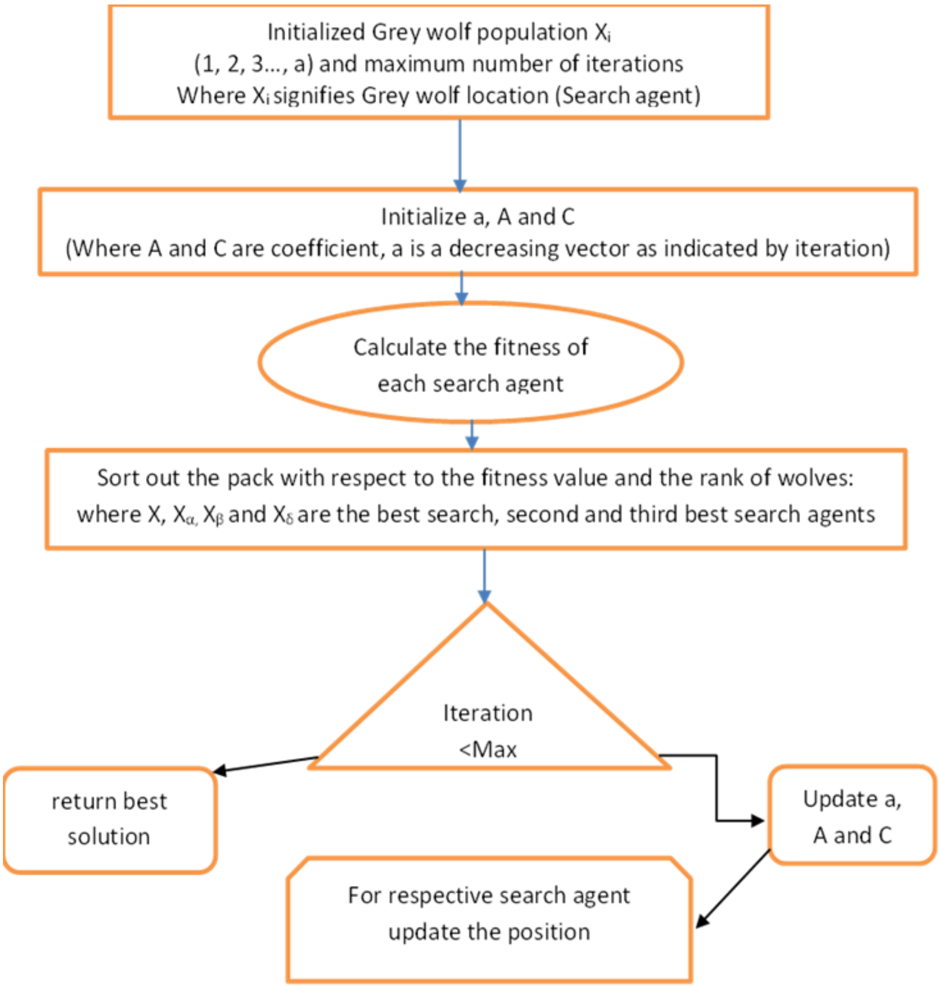


Fig. 3: GREY-WOLF APPLICATION FLOWCHART FOR ITERATING THE RESPECTIVE SEARCH AGENTS

that helps the (α) in decision making. The (β) augments the (α) commands in the group and gives feedback to the (α). Meanwhile, the minimum rank among the grey wolves (ω) are the last wolves that are allowed to eat the prey and the role of the (δ) wolf is as a scout, hunter, caretaker, sentinel, and elder [12]. The best solution for the GWO algorithm can first be detected as (α) and then determined as (β), (δ) and (ω), respectively. During hunting time, the wolves incline to enclose their prey. The equations (2.1) and (2.2) signified the encircling conduct.

$$D = |C \cdot X\text{victim}(t)\ XGWolf\ t| \quad (1)$$

$$X\ Gwolf\ (t+1) = X\ \text{victim}\ (t)\ A \cdot D \quad (2)$$

where *X victim* and *X Gwolf are* the position vector of the victim and the grey wolf, respectively; t is the current iteration, *A* and *C* are the coefficient vectors, which were estimated as:

$$A = 2 \cdot a \cdot r1\ a \quad (3)$$

$$C = 2 \cdot r2 \quad (4)$$

where *a* linearly decreases from 2 to 0 over iterations and $r1$ and $r2$ are random vectors [between 0 and 1]. Thus, a Grey-wolf can alter its position in the victim's planetary in any random location using the equations (2.3) and (2.4). Three of the finest solutions are kept, and then other hunt agents (ω) alter their positions according to the present excellent scene.

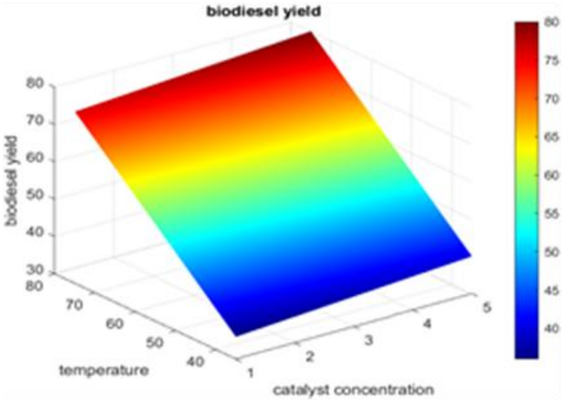
The GWO method commences with developing a random group of grey wolves, which can be displayed by candidates of the answer; and throughout the modeling, α, β, and δ wolves govern the probable state of the hunt. Overall, the Grey-wolf application flowchart for iterating the respective search agents is presented in Fig. 3

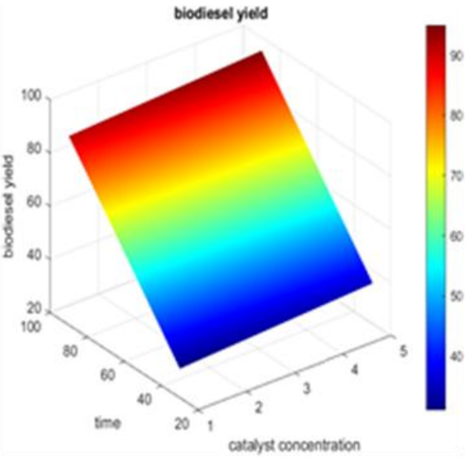
III. RESULTS AND DISCUSSION

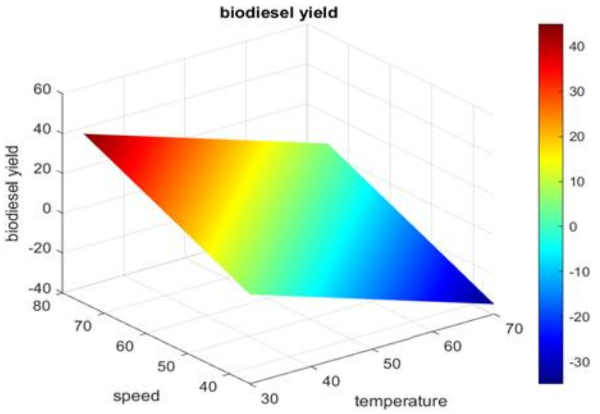
A. Oil Characterization And Optimization With GWO.

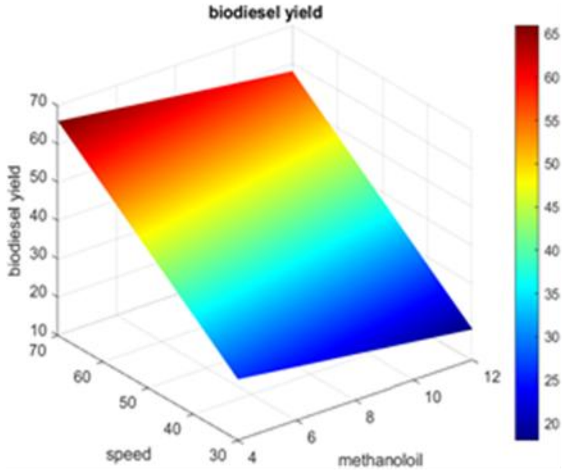
Both *Gmelina* and *Mucuna* bean seed oils exhibited favorable properties for biodiesel production. Specifically, *Gmelina* seed oil demonstrated superior oxidative stability, making it more resistant to degradation during storage, while *Mucuna* bean oil showed a higher free fatty acid (FFA) content, necessitating a pre-treatment step to reduce FFA levels and prevent soap formation during transesterification. To estimate and maximize the biodiesel productivity from these oils within a hybrid framework, optimization was performed using the Grey Wolf Optimization (GWO) algorithm implemented in MATLAB R2022b. The optimization model incorporated key input parameters including reaction time, stirring speed, methanol-to-oil molar ratio, catalyst concentration, and agitation speed. The objective was to determine the optimal combination of these variables to maximize biodiesel yield from the feedstocks. Table 1 presents the optimized variables obtained from the GWO model, highlighting the best-fit conditions and interactions among factors that contribute to maximizing biodiesel production efficiency.

Figures 4, 5, 6, and 7 illustrate the process optimization based on interactions between key process parameters. As shown in Figure 4, a biodiesel yield of 80% was achieved at a catalyst concentration of 5 wt% and a temperature of 70°C, indicating that yield improves with increasing catalyst concentration and temperature. Figure 5 demonstrates an even higher yield of 93.5% at a catalyst concentration of 5 wt% and a reaction time of 100 minutes, confirming that longer reaction times combined with sufficient catalyst enhance biodiesel production. In contrast, Figure 6 reveals a negative interaction between stirring speed and temperature. A biodiesel yield of 38.7% was obtained at 60 rpm and 45°C, but as the temperature increased to 70°C and the reaction time reached 70 minutes, the yield dropped by approximately 10%. This suggests that higher temperatures coupled with certain









agitation speeds may adversely affect the reaction. Figure 7 shows the effect of stirring speed and methanol-to-oil molar ratio on biodiesel yield. At 70 rpm and a methanol/oil ratio of 6:1, the yield reached 65%. However, increasing the methanol ratio beyond 6:1 resulted in a decline in yield to 60%, indicating that excessive methanol may inhibit optimal biodiesel production under the tested conditions.

IV. CONCLUSION

The experiment demonstrated that biodiesel yield is significantly influenced by the interaction of key process parameters. Increasing the catalyst concentration to 5 wt% and the temperature to 70°C enhanced biodiesel production, achieving a yield of 80%. Extending the reaction time to 100 minutes at the same catalyst concentration further improved the yield to an optimized value of 93.5%. However, the interaction between stirring speed and temperature revealed a negative effect, with biodiesel yield decreasing by approximately 10% when temperature increased to 70°C at 60 rpm agitation, indicating that certain combinations of these parameters can reduce efficiency. Additionally, the methanol-to-oil molar ratio was found to have an optimal value at 6:1 when combined with a stirring speed of 70 rpm, producing a 65% yield, but further increases in methanol ratio resulted in decreased yield. Overall, the optimal process conditions for maximizing biodiesel production from the hybrid feedstock were identified as a catalyst concentration of 5 wt%, temperature of 70°C, reaction time of 100 minutes, stirring speed of 60 rpm, and a methanol-to-oil molar ratio of 6:1, resulting in

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