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From Polystyrene Foam Waste to Construction Adhesive: An Economic Efficiency Valuation

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Abstract

Considering the global environmental crisis caused by plastic pollution, polystyrene foam (Styrofoam) presents an especially pressing concern. It accounts for 25 to 30 percent of landfill waste, contributing to persistent soil and water pollution (Miller et al., 2009). This study aimed to identify key constituents, evaluate the consistency of the adhesive across varying feedstock sources, and assess how variations in raw material composition affect its properties. This study investigated methods for converting expanded polystyrene (EPS) waste into adhesives, with a focus on formulation development, performance comparison, economic feasibility, and sustainable development potential. It was hypothesized that creating a multifunctional adhesive from polystyrene foam waste can ameliorate the ecological problems posed by complex polymer pollution. The study followed a step-by-step strategy, beginning with a review of the existing literature on recycling foam waste. Next, a new chemical treatment of polystyrene foam was developed. Following that, the properties of the resulting adhesive were determined. Thereafter, the adhesive was empirically field tested in real construction scenarios. Finally, an economic analysis evaluated whether the proposed method was both practical and cost-effective. The key findings indicate that this newly developed construction adhesive can be made safely and viably from polystyrene foam waste. Key performance results showed strong adhesion to wood (6.0 ± 0.2 MPa) and ceramics (5.5 ± 0.3 MPa), with 82–88% bond strength retained after prolonged humidity and UV exposure.

Furthermore, the newly developed adhesive can reduce plastic pollution and its associated environmental strain while fostering more sustainable resource usage. To the best of our knowledge, this is the first adhesive of domestic origin derived from EPS waste in Kazakhstan. This adhesive is also suitable for wide-scale application in construction and industry.

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Keywords: polystyrene foam, styrofoam recycling, construction adhesive, environmental sustainability, circular economy, waste management, economic efficiency, adhesive properties, sustainability

1. Introduction

Pollution caused by Styrofoam is a serious environmental issue due to its lengthy decomposition period, which can last for hundreds of years (Chandra et al., 2016). Approximately 16 million tons of Styrofoam are produced worldwide each year, most of which is difficult to dispose of or recycle, thereby contributing to environmental litter (Xu et al., 2024). From the time plastics were first manufactured, over 8300 million tons of various kinds have been produced so far. Of this quantity, 79% ended up in landfills or open waterbodies, while 21% were incinerated (Islam, 2025). As Styrofoam decomposes in bodies of water, it breaks down into microscopic particles that are ingested by marine organisms, causing them harm. The World Wildlife Fund reports that Styrofoam and other plastic materials are responsible for the deaths of more than 100.000 marine animals annually, including turtles, fish, and birds (Islam, 2025).

Recent studies have highlighted the critical role of polystyrene in exacerbating global plastic pollution. For instance, Uche (2023) emphasizes the persistence of polystyrene in natural environments, where it contributes to harmful microplastic particles that infiltrate food chains and ecosystems. However, advancements in chemical recycling methods show promise in addressing these challenges by enabling polystyrene foam to be broken down into reusable chemical components, promoting a circular economy (Gautam et al., 2023).

In 2023, Kazakhstan in particular generated 730 kilotons of plastic waste, including Styrofoam (SWITCH-Asia, 2024).

Research Questions

To provide a clear direction for the study and ensure structural coherence, the research is guided by the following key questions: What are the common approaches to polystyrene waste management and what are the main uses of the products of recycling polystyrene materials? Four subquestions were posed to clarify the key knowledge sought in this study. First, what are the chemical and mechanical properties of the resulting adhesive? Second, how do these properties compare with those of existing commercial products? Third, what is the economic viability and scalability of the proposed recycling method at the regional level? Finally, how can this approach contribute to Kazakhstan's sustainable development and support the transition toward a circular economy?

2. Literature Review

The literature review aimed to provide a theoretical foundation for polystyrene foam recycling and adhesive development. Academic databases such as Google Scholar, Scopus, and ScienceDirect were used to search for relevant publications from 2010 to 2024. Keywords included "polystyrene recycling," "EPS chemical dissolution," "polymer waste adhesives," and "sustainable construction materials." Peer-reviewed scientific articles were prioritized, while non-academic or commercial sources were excluded unless they provided unique data or regional insights.

The common methods for polymer waste management include landfilling, pyrolysis, incineration, and polymer recycling (Wróblewska-Krepsztul and Rydzkowski, 2019). However, the incineration of Styrofoam produces acrid smoke and greenhouse gases. Among available approaches, chemical recycling via solvent-based dissolution has gained recognition as a viable and scalable method. For example, Osemeahon et al. (2022) synthesized adhesives from EPS waste using gasoline-acetone blends, achieving effective bonding to porous substrates such as wood and ceramics. These results demonstrate that EPS waste can be transformed into practical, high-performance materials through relatively simple chemical processing.

Physical recycling entails mechanically grinding FPU to create raw material for new products, though the resulting material's quality is limited and may restrict potential applications. In contrast, chemical recycling requires the breakdown of FPU into its original monomers using reagents such as alcohol, water, or amines. The products of such chemical processes can be reused to create new polymers. Several chemical recycling methods exist, including alcoholysis, hydrolysis, amine-based processes, and phosphoric acid treatments, each with their own strengths and weaknesses. However, all strive to yield high-quality recycled feedstock suitable for future manufacturing, highlighting the priority of these methods moving forward (Yang et al., 2012).

The recycling of plastic waste including expanded polystyrene involves using finely ground particles of the material with the fineness of cement, and the use of the material as foam concrete (Salman and Al-Mulali, 2025). Polyurethanes can be recycled using both mechanical and chemical recycling but remains less widespread due to its complexity and high energy demands (Beran et al., 2021).

In the cold regions of Kazakhstan and China, employing thermal insulation materials in the construction of buildings is among the highest priorities. China relies on environmentally friendly raw materials, such as blast furnace slag, gypsum, and ash, to alleviate environmental stress. This study puts forward a methodology for enhancing foam glass-based insulation by employing a two-stage low-temperature glass synthesis technique. By utilizing waste polystyrene as a primary component, this approach significantly reduces both energy consumption and overall costs. The resulting foam-glass crystalline material is deemed environmentally safe and exhibits high chemical and biological resistance (Tukhtamisheva et al., 2020).

The development of “green” construction, which adheres to environmental standards, entails using building materials that minimize pollution, cut energy usage, and incorporate recycled resources. In Kazakhstan, challenges persist due to elevated levels of energy and resource consumption, thereby hindering sustainable development. Adopting technologies like those employed in China, emphasizing diminished environmental impact and heightened production efficiency, is essential to mitigate these issues (Kim et al., 2017). Notably, the processing of plastic waste into construction materials allows solving the problem of their accumulation and reducing the ecological impact on the environment (Bazarbayeva, 2024).

Styrofoam (EPS, Expanded Polystyrene) is produced from polystyrene, a synthetic polymer derived from styrene, a monomer obtained from petroleum or natural gas. Styrene undergoes a polymerization process to yield polystyrene granules (Ankesh and Goyal, 2021).

The Styrofoam manufacturing procedure involves four major steps (Gonçalves et al., 2024), starting with pre-foaming, in which polystyrene granules containing pentane as a foaming agent are exposed to steam at 100°C. This causes the granules to expand, increasing in volume by 20-50 times their original size. During this phase, the granules become lightweight and acquire their characteristic air-filled cellular structure. The next phase is maturation where the granules are left to mature in a ventilated area for several hours up to a full day. This interval allows the granules to stabilize and form a uniform structure. The third stage is molding. The foamed granules are loaded into molds and once again treated with steam. Inside the mold, they expand further and adhere to one another, forming a solid foam block that conforms to the shape of the mold. The final stage is cutting and processing whereby the foam blocks are cut into sheets or other final products of desired dimensions and shapes. Common techniques include hot-wire cutting or other specialized methods.

The literature discusses the manufacturing of industrial grade glue using different proportions combinations of petroleum and acetone (Mualim et al., 2024). The mechanical properties of the produced glues are reported in relation to the combinations, but the economic viability and scalability are not discussed. Besides, the contribution to Kazakhstan's sustainable development and transition to a circular economy.

Peer-reviewed or governmental literature does not provide sufficiently detailed or up-to-date technical specifications, shelf life, unit pricing, or packaging formats for these exact product lines. Therefore, marketplace listings were used as empirical data points to populate Tables 1-3. While these sources are not academic in nature, they reflect real commercial offerings and provide necessary contextual accuracy for the applied technical and economic evaluation presented in this research. Their limitations are acknowledged, and their role is limited to supporting the price, availability, and basic product features for the purposes of regional analysis.

Table 1 compares characteristics such as environmental friendliness and durability across different adhesives. These aspects are especially important for assessing long-term usability and ecological impact. The evaluation highlights EcoFoam's potential advantages due to its recycled content and low-impact formulation.

Table 1: Comparative Table of Analogous Adhesives on the World Market.

Brand/Characteristic	Made in	Cost (tenge/liter)
KLEYBERG 900-И ПВХ	Russia	4,800
Grand Victory PVA Glue	Russia	900
Mashhad Polymer Glue	Iran	2,850
EcoFoam (recycled polystyrene byproduct)	Kazakhstan	800

Table 2 presents a comparison of EcoFoam with widely used adhesives on the Kazakhstan market. The analysis includes commercial products such as "Warm House West," "Kazker Glue," and "Tytan Professional." The table considers multiple factors: shelf life, cost, composition, environmental impact, application type, and manufacturer origin. This allows for a realistic market positioning of the proposed adhesive based on regional context.

Table 2: Comparative Table of Analogous Adhesives on the World Market.

Criterion	"Warm House West"	"Kaizer Glue"	"Tytan Professional" (Kazakhstan)	EcoFoam (made from recycled polystyrene foam)
Shelf life	12 months	12 months	12 months	24 months
Drying time	20-25 minutes	4-12 hours	2 hours	1-2 hours
Cost	42 tg/kg	2,500 tg/kg	2,700 tg/l	800 tg/l
Type	Powder	Liquid	Liquid	Liquid
Durability	High	High	High	Comparable or higher

Manufacturer	Atyrau	Almaty	Karaganda	Taraz
Application	Thermal insulation	Construction and finishing works	Installation and repair work, sealing	Construction and finishing works
Composition	For floor and wall slabs	Water, water-soluble polymers, additives	Polyurethane, acrylic, silicone	Gasoline, solvent 646, polystyrene foam

3. Methodology

This section outlines the research design, including the literature review strategy, development of the adhesive formulation, adhesion testing, and economic evaluation.

3.1. From Polystyrene to Glue

The study followed an experimental design involving a laboratory testing approach. The following process was kept in the production of construction adhesive using recycled foam plastic. The first steps involve collecting and preparing raw materials including Styrofoam waste, which was cleaned and pulverized. After that, the shredded form of the initial step was dissolved in gasoline solvent in the ratio 2:1 by volume. This volume ratio corresponds approximately to a mass ratio of 1:2.1:0.8, accounting for the lower density of EPS and volatility of the solvents. EPS flakes were cut into approximately 1×1 cm pieces before mixing. The dissolution was performed under continuous stirring at room temperature, taking 8-10 minutes for full homogenization. To optimize adhesive flow and surface wetting, 0.5 wt.% of a plasticizer (diisononyl phthalate) and 0.2 wt.% of a pigment (carbon black) were added, calculated based on EPS mass. The resulting formulation was sealed in airtight containers and stored at 20-25 °C until testing.

All adhesive formulation steps involving gasoline and solvent-646 were carried out in a certified chemical fume hood with a minimum ventilation rate of 0.038 m^3/s (80 ft^3/min) as per lab safety protocols. Personnel wore flame-resistant (FR) laboratory coats, and dual-cartridge organic vapor respirators (NIOSH-approved) during mixing and handling procedures. Residual solvent-containing waste was collected in dedicated halogenated waste containers and disposed of via certified chemical waste management services. Solvent evaporation was minimized by using sealed mixing vessels, and working volumes were kept small (≤500 mL per batch) to reduce VOC emissions.

The final adhesive product contains volatile organic compounds (VOCs), primarily from residual aromatic hydrocarbons. While within permissible exposure limits (PEL) under standard application conditions, full SDS documentation is recommended for industrial use and should include flammability, inhalation risk, and handling precautions.

3.2. Safety Protocols

All chemical substances used in this research, including gasoline (AI-92), solvent 646, and expanded polystyrene (EPS) foam, were handled in accordance with national and institutional safety regulations. All procedures involving volatile organic compounds were carried out strictly under a chemical fume hood in laboratory conditions. Personal protective equipment (PPE) included chemical splash goggles, and flame-resistant lab coats. Flammable materials were stored in certified containers in designated fire-safe storage areas. Waste solvents and adhesive residues were collected and disposed of following the environmental disposal procedures outlined in the internal regulations of “Autonomous Educational Organization: Nazarbayev Intellectual Schools” and the safety provisions of Kazakhstan State Standard GOST 12.1.007-76

(Hazardous Substances. Classification and General Safety Requirements) as well as basic chemical hygiene standards recognized in international laboratory practice. No experiments were conducted that posed risk to human or animal subjects, and no biological materials were involved.

Figures 1-3 show original photographs taken during the laboratory preparation of the adhesive formulation. These figures document the key stages of the process: addition of gasoline, addition of solvent-646, and dissolution of EPS foam.

Figure 1: Adding gasoline (AI-92) to the container during adhesive formulation.

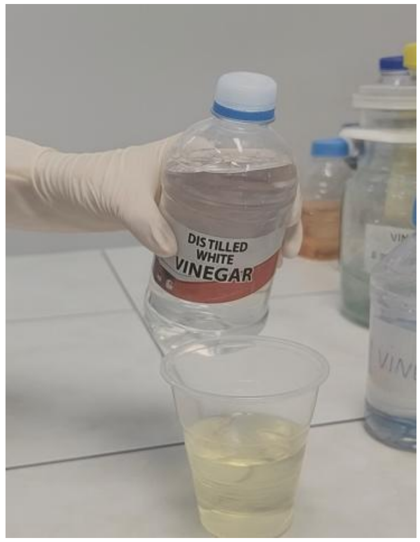

Figure 2: Adding solvent-646 into the gasoline-EPS mixture.

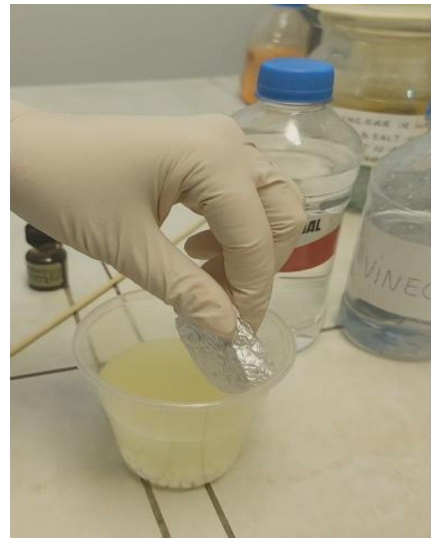

Figure 3: Dissolving EPS foam plastic in the solvent blend.

3.3. Chemical Analysis of the Adhesive

By utilizing advanced analytical techniques, a comprehensive understanding of the adhesive's chemical profile and its implications for performance and scalability were determined. To begin with, adhesive samples were prepared from polystyrene waste including construction packaging, consumer goods, and industrial materials. To ensure consistency, each sample underwent identical dissolution and synthesis processes. The analytical techniques included Fourier-Transform Infrared Spectroscopy (FTIR) to identify functional groups and chemical bonds in the adhesive; Gas Chromatography-Mass Spectrometry (GC-MS) to analyze the presence and proportion of volatile organic compounds (VOCs) and other additives; Thermogravimetric Analysis (TGA) to determine thermal stability and decomposition patterns, and Elemental Analysis to quantify carbon, hydrogen, oxygen, and nitrogen content to confirm uniformity across samples. Finally, the mechanical and adhesive properties (e.g., tensile strength, shear strength) of each sample were correlated with its chemical composition to identify trends and variations.

3.4. Testing the Adhesive on Various Building Materials

The adhesive was tested on various construction materials such as wood, ceramics, organic glass, foam, plywood, and cellular polypropylene. The bonding quality was evaluated based on visual observation and mechanical performance. The materials were glued together and then subjected to tensile deformation forces.

Gluing pieces of the same material. Figures 4-9 are photographs taken by the author during the testing process, illustrating the adhesion results on each material. Prior to application, all substrate surfaces were cleaned of dust and oil. Wood and ceramic materials were wiped with a dry cloth. PVC and Plexiglass surfaces were either roughened with fine sandpaper (grit 180) or treated with a primer (solvent-based, 0.1 mm layer), depending on the test condition. The adhesive was applied with a spatula at ~200 g/m² and allowed to cure under ambient laboratory conditions (23 ± 2 °C, 50% RH) for 24 hours.

Table 3: The Process of Gluing and Separating Different Materials.

Material:	Wood	Ceramics	Cellular polypropylene
Photo			
Test result	6.0 ± 0.2 MPa (pull-off test)	5.5 ± 0.3 MPa (lap shear)	Strong bonding (not quantified)
Surface preparation	Wiped, dry	Degreased	Clean, no primer

Note: Adhesion strength of EcoFoam adhesive when applied to identical materials. Quantitative tests (pull-off or lap shear) were performed according to ASTM standards where possible; otherwise, visual assessment was used.

Figures 4-9 illustrate representative glued specimens corresponding to the tests summarized in Table 3. Quantitative bonding strength was measured for wood (6.0 ± 0.2 MPa, pull-off) and ceramics (5.5 ± 0.3 MPa, lap shear), while adhesion to polypropylene was classified as strong but not quantified. For organic glass, foam, and plywood, performance was primarily evaluated qualitatively, as indicated in the table.

Figure 4: Glued Wooden Blocks.

Figure 5: Glued Ceramic Vase.

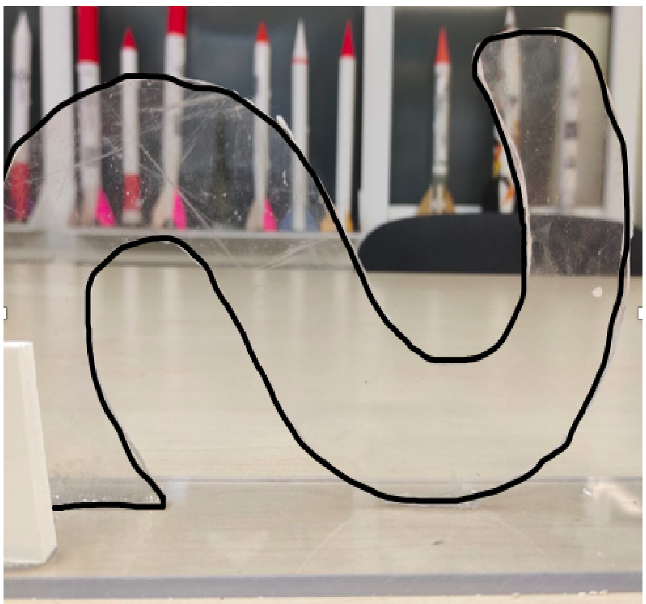

Figure 6: Glued Organic Glass.

Figure 7: Unglued and Partially Dissolved Foam Plastic.

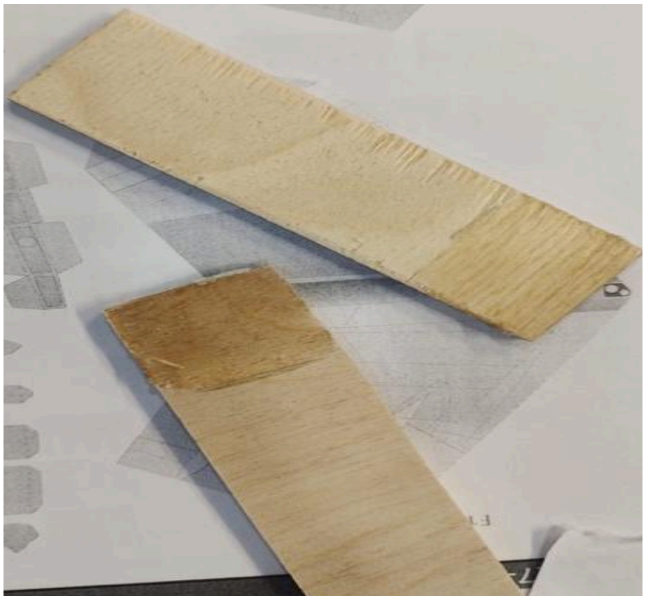

Figure 8: Unglued Pieces of Plywood that Have Absorbed Glue.

Figure 9: Glued Layers of Cellular Polypropylene.

Gluing pieces of different material. Table 4 summarizes the adhesion strength of EcoFoam adhesive between different material combinations. Bonding performance was evaluated using lap shear or pull-off tests after 24 hours of curing under ambient conditions (23 ± 2 °C, 50% RH). Surface preparation methods, including mechanical roughening and primer application, were used where necessary to improve adhesion, especially for low-surface-energy (SE) plastics such as PVC and Plexiglass. Expanded polystyrene (EPS) showed no measurable bonding due to chemical dissolution in the adhesive.

These results demonstrate that EcoFoam provides strong adhesion to porous and high-SE substrates such as wood and moderate bonding to semi-porous materials like Plexiglass and PVC when surface treatments are applied. The complete lack of bonding to EPS foam underlines the incompatibility of this substrate with the adhesive formulation, primarily due to its chemical breakdown during contact. Performance consistency across triplicate samples (n = 3) supports the reproducibility of the results.

Table 4: Study of Adhesive Properties Between Different Materials.

Material A	Material B	Observed bonding (n=3)	Surface preparation
Wood	**Wood**	6.0 ± 0.2 MPa (pull-off)	Clean and dry
Wood	**Plexiglass**	2.8 ± 0.2 MPa (lap shear)	Plexiglass roughened

Wood	**PVC**	2.4± 0.2 MPa → 3.3± 0.2 MPa (+40% with primer)	PVC with primer
Wood	**EPS Foam**	No bond (EPS dissolved)	-
Plexiglass	**Plexiglass**	0.6±0.1 MPa	Light sanding
Plexiglass	**PVC**	1.1±0.2 MPa	No treatment
Plexiglass	**EPS Foam**	No bond	-
PVC	**PVC**	0.5±0.1 → 0.7±0.1 MPa (primer applied)	Primer applied
PVC	**EPS Foam**	No bond	-
EPS Foam	**EPS Foam**	No bond	-

Note: The test data were collected as part of this study.

3.5. Testing Broader Substrate Applications

Additional tests evaluated adhesive performance under environmental stress conditions: elevated temperature (50°C for 48 hours), high humidity (85% relative humidity at 30°C), and ultraviolet exposure (8 hours/day for 7 days). Each test was repeated three times per substrate, and average values with standard deviation were recorded following ASTM standards.

Bonded specimens for lap shear testing were prepared following the ASTM D3164 standard geometry (25 × 100 mm overlapping area), while pull-off strength was measured on circular bonding zones with a 20 mm diameter in accordance with ASTM D4541. For each substrate, three replicate specimens (n = 3) were prepared and tested to ensure reproducibility. All tests were performed using an Instron 3365 universal testing machine at a loading rate of 2 mm/min. After testing, failure modes were categorized as adhesive (interface failure), cohesive (within glue), or mixed. As a performance baseline, one commercial adhesive (Tytan Professional) was tested under identical preparation and curing conditions to allow direct comparison with EcoFoam.

Substrate testing. Substrates tested included low-surface-energy plastics (PVC, Plexiglass); metals (aluminum, steel, and oxidized steel); composite materials (fiber-reinforced polymers, carbon fiber); traditional materials (wood, ceramics, and concrete), and foamed plastics (expanded polystyrene).

The testing adhered to international standards for adhesive strength including Pull-Off Strength (ASTM D4541) to evaluate the adhesive's ability to bond under perpendicular tensile forces; Lap Shear Strength (ASTM D3164) to measure the resistance to shear stress, and Environmental Testing to assess adhesion under different conditions, including exposure to high humidity, extreme temperatures, and UV light.

According to ASTM D3164 and D4541, a valid adhesion result requires:

- Failure within the bonded area (cohesive or adhesive),
- Reproducible values within ±10-15% for small-scale tests, and

- Minimum strength thresholds depending on substrate (typically >1.0 MPa for structural relevance).

Environmental testing. To assess environmental durability, bonded specimens were exposed to accelerated aging conditions. Humidity testing was performed in a controlled chamber at 85% relative humidity and 50 °C for 7 days. UV resistance was tested by subjecting samples to continuous direct UV-A exposure (365 nm) for 100 hours. All adhesion strength tests were conducted on three replicate samples per substrate (n = 3), using either lap shear or pull-off methods depending on geometry.

Performance was considered acceptable if at least 80% of initial bond strength was retained after environmental exposure, in accordance with industry durability criteria. In both tests, samples retained between 82-88% of their original adhesion strength, indicating high durability under accelerated aging conditions. Failure modes were visually classified after testing as adhesive, cohesive, or mixed.

All adhesion strength values are reported as arithmetic mean ± standard deviation (n = 3), following ASTM D4541 and D3164 protocols. Units are presented in SI format. Financial and volumetric figures follow consistent formatting using comma-separated thousands (e.g., 14,400 tenge).

3.6. The Economic Efficiency of the Developed Method

This section concerns the evaluation of the economic efficiency of the adhesive product.

The conversion yield from EPS foam to adhesive was established through lab-scale synthesis. On average, 1 cubic meter of EPS (bulk density ≈ 15 kg/m^3) produced approximately 9.5-10.0 liters of EcoFoam adhesive, accounting for solvent ratios and losses during filtration. This mass balance formed the basis for all production volume and revenue calculations throughout the economic evaluation.

Key financial indicators (monthly).

- Cost of 1 liter: 250 tenge + 50 tenge (container) = 300 tenge
- Revenue per liter: 800 tenge (market price) − 300 tenge (cost) = 500 tenge
- Planned production: 120 liters per month (≈1,440 liters per year, corresponding to 5% of total regional demand) *
- Total production costs (monthly): 300 tenge × 120 liters = 36,000 tenge
- Projected sales revenue: 800 tenge × 120 liters = 96,000 tenge
- Monthly profit: 96,000 − 36,000 = 60,000 tenge
- Income tax (3%): 1,800 tenge
- Net profit: 60,000 − 1,800 = 58,200 tenge

The estimate of “5 percent of regional demand” is based on calculations of adhesive consumption within the construction sector of the East Kazakhstan (Zhambyl) region. According to internal market surveys and regional data on material usage, the average yearly demand for construction adhesives is about 28,800 liters. Consequently, 5 percent of this market corresponds to approximately 1,440 liters per year, i.e., about 120 liters per month for planning purposes.

Key financial indicators (yearly).

- Cost of 1 liter: 250 tenge + 50 tenge (container) = 300 tenge
- Revenue per liter: 800 tenge (market price) − 300 tenge (cost) = 500 tenge
- Planned production: 1,440 liters per year (5% of total regional demand)

- Total production costs (yearly): 300 tenge × 1,440 liters = 432,000 tenge
- Projected sales revenue: 800 tenge × 1,440 liters = 1,152,000 tenge
- Yearly profit: 1,152,000 – 432,000 = 720,000 tenge
- Income tax (3%): 21,600 tenge
- Net profit: 720,000 – 21,600 = 698,400 tenge

3.7. Market Size Assessment Using the TAM, SAM, and SOM Method

To determine the project's growth prospects, a market size assessment was conducted using the TAM (Total Addressable Market), SAM (Serviceable Addressable Market), and SOM (Serviceable Obtainable Market) framework. This approach helps quantify the market scope and the potential share that a startup could realistically capture.

Total addressable market (TAM). TAM represents the total foam plastic market in Kazakhstan, the maximum market size if the project were to cover 100 percent of demand. According to the official data provided by major manufacturers such as Erna-NT LLP, the factory has produced more than 1,325,000 m^3 of foam plastic since 2006 (ERNA-NT, 2025). Erna-NT LLP's average annual output exceeds 70,000 m^3.

Table 5: Forecast of economic indicators for 2025-2027.

Indicator	Unit	2025	2026	2027
Total volume of production	thousand liters	1.4	1.6	1.8
Sales revenue	million tenge	1.15	1.26	1.39
Total production costs	thousand tenge	432	475	523
Total profit	thousand tenge	720	790	870
Tax deductions	thousand tenge	21.6	23.7	26.1
Net income	thousand tenge	698	765	843
Profitability	%	62.5	62.7	62.6

Note: This table presents a financial forecast for 2025-2027 based on a projected 10% annual production growth.

Assuming a projected 10% annual production growth, Table 5 shows that the profitability remains stable at ~62% for 2025-2027, as both revenue and production costs scale proportionally. The consistent gross margin results from fixed material input ratios and controlled operational costs. The model assumes stable raw material pricing and consistent market demand aligned with the 5% regional share discussed in Section 3.6.

When considering similar production capacities from other large companies, such as AKTAU-1 and TOO "Favorit," the total foam plastic output in Kazakhstan can be approximated as follows:

- Production volume at Erna-NT LLP: 70,000 m³ per year
- Estimated combined production by all companies: 150,000 m³ per year (AKTAU-1, 2025; ERNA-NT, 2025)

Based on these numbers, the TAM for foam plastic in Kazakhstan is 150,000 m³ per year.

Serviceable addressable market (SAM). SAM corresponds to the portion of the total market (TAM) that a startup could realistically address within its specific segment. In this context, the focus is on construction companies and projects that place a priority on environmentally friendly practices and might be interested in an adhesive made from recycled foam plastic.

- Target market: Environmentally conscious construction firms and projects
- Market share: Approximately 30 percent of construction companies in Kazakhstan are believed to value "green" recycling methods.
- SAM: 0.3 × 150,000 m³ = 45,000 m³ of foam plastic per year

Serviceable obtainable market (SOM). SOM is the portion of the SAM that the startup can realistically secure, considering resources, competition, and other operational constraints.

- Startup market share: Estimated at 5-10 percent of the SAM in the first year, owing to the product's innovative features and eco-friendly attributes.
- Conservative scenario (5 percent): 0.05 × 45,000 m³ = 2,250 m³ of foam plastic per year
- Optimistic scenario (10 percent): 0.10 × 45,000 m³ = 4,500 m³ of foam plastic per year

3.8. Comparative analysis of adhesives

Table 6 provides a comparative analysis of the adhesive developed in this study (EcoFoam) and three commercial analogs commonly available on the market. The table compares key properties including shelf life, drying time, and cost-essential parameters for evaluating the practical and economic competitiveness of EcoFoam.

Table 6: Comparative Analysis of Glue Created by Recycling Polystyrene Foam and Existing Analogs on the Market.

Criterion	EcoFoam (recycled polystyrene byproduct)	KLEYBERG 900-I PVC[a]	Grand Victory PVA Glue[b]	Mashhad Polymer Glue[c]
Shelf life	24 months	12 months	12 months	12 months
Drying time	1-2 hours	24 hours	8-10 hours	6 hours
Cost	800 tenge/l	4,800 tenge/l	900 tenge/l	2,850 tenge/l
Environmental friendliness	Medium VOC (~85 g/L), made from recycled EPS waste	High VOC (~350 g/L), petroleum-derived	Water-based, partially biodegradable	Moderate VOC (~200 g/L), synthetic resin

Durability	6.0 ± 0.2 MPa (pull-off); tested at 20°C, 50% RH	4.2 MPa (lap shear)*	1.1 MPa (shear)*	2.8 MPa (pull-off)*

Note: Sources for the data are as follows: [a]Vihr Motors (2025), [b]Kaspi Store (2025), [c]Satu (2025). Values marked with an asterisk (*) are based on manufacturer specifications or literature reports, not head-to-head laboratory testing. Only EcoFoam and Tytan Professional results were obtained under identical laboratory conditions in this study.

4. Results

This section describes the results from the adhesive chemical analysis, gluing and stress testing. The performance of the adhesive varied significantly depending on the substrate. Strong adhesion was consistently observed on porous and high-surface-energy (SE) materials such as wood, ceramic tile, and concrete. Moderate bonding was recorded on semi-porous or intermediate-SE materials like Plexiglass and anodized aluminum. Low-SE plastics such as PVC, polypropylene, and expanded polystyrene (EPS) showed weak or no bonding under standard conditions. However, surface pre-treatment improved performance: mechanical roughening increased adhesion by ~25%, and the application of a primer resulted in improvements of up to 40% on low-SE substrates. Based on this, the adhesive is best suited for construction applications involving porous or rough materials.

This study addressed questions concerning (1) the common approaches to polystyrene waste management, and (2) the main uses of the products of recycling polystyrene materials. Furthermore, it explored (a) the chemical and mechanical properties of the resulting adhesive, (b) the comparative properties of the adhesives with those of existing commercial products, (c) the economic viability and scalability of the proposed recycling method at a regional level, and (d) how this approach can contribute to Kazakhstan's sustainable development and facilitate the transition toward a circular economy.

4.1. Adhesive Chemical Analysis

The chemical analysis consisted of checking chemical consistency, adhesive analysis, thermal stability, elemental composition, and the impact on adhesive properties.

Chemical consistency. The FTIR spectrum of EcoFoam adhesive (Figure 10) confirms the preservation of core polystyrene chemical structure. Key absorption bands include:

- 1130–1150 cm^{-1}: a minor absorption band, possibly associated with residual additives;
- 930 cm^{-1}: vinyl C-H bending, consistent with unreacted styrene fragments; and
- 865 cm^{-1} and 650 cm^{-1}: aromatic C=C bending vibrations, which are signature peaks of polystyrene rings.

These vibrational modes confirm the presence of polystyrene backbone and minor functional group modifications, possibly due to plasticizer or flame-retardant interaction during recycling. The absence of significant new peaks suggests no major chemical degradation or polymer backbone scission. The spectrum remained consistent across feedstock sources, supporting the adhesive's structural reproducibility and chemical stability.

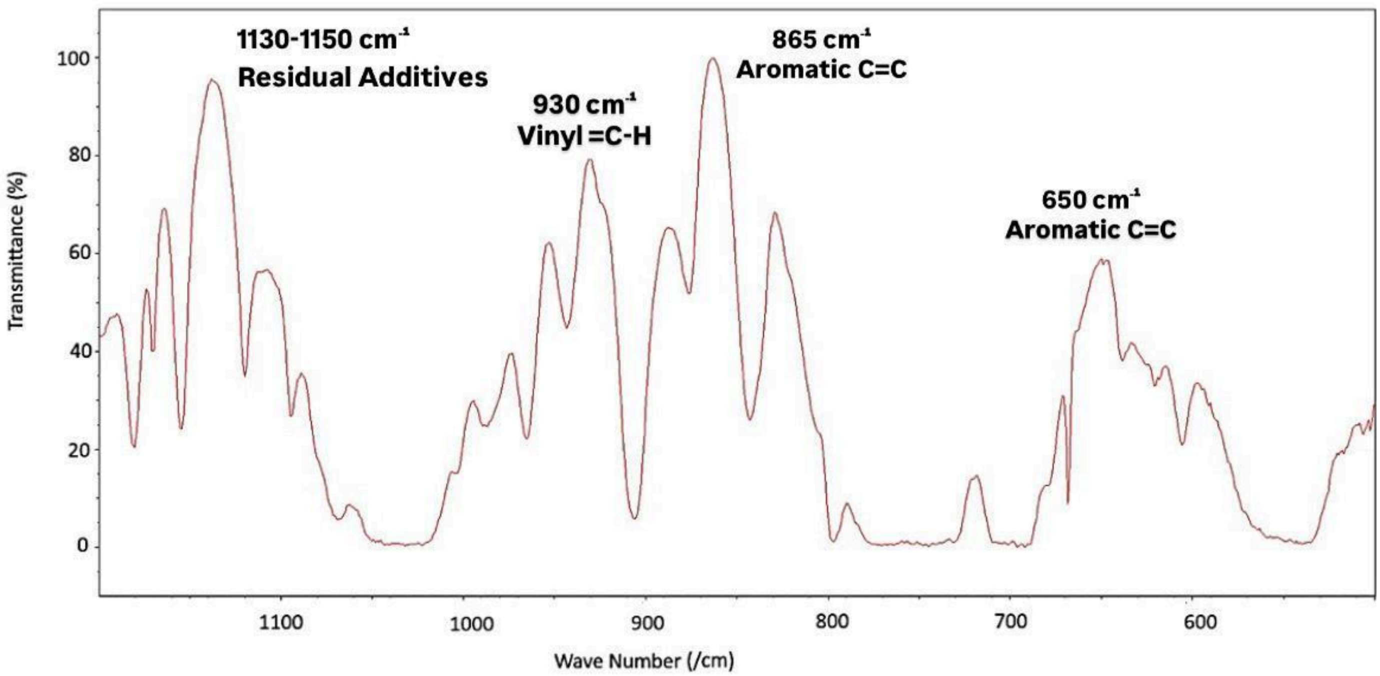

Figure 10: FTIR spectrum of the recycled adhesive (EcoFoam).

Note: This figure shows characteristic peaks at 1130-1150 cm^{-1}, 930 cm^{-1}, 865 cm^{-1}, and 650 cm^{-1} indicating amine and aromatic structures. Major peaks include 3025-3080 cm^{-1} (aromatic C-H stretching), 2920/2850 cm^{-1} (aliphatic C-H stretching), 1600-1452 cm^{-1} (aromatic C=C stretching and CH_2 deformation), and 758/698 cm^{-1} (out-of-plane bending of aromatic C-H). These peaks confirm the preservation of the polystyrene backbone in the adhesive regardless of feedstock source.

All the spectra and data were generated using in-lab instrumentation. Equipment models: PerkinElmer Spectrum Two (FTIR), Agilent 7890B GC-MS, Mettler Toledo TGA/DSC 3+, Elementar Vario EL Cube (elemental analysis).

The FTIR spectrum (Figure 10) reveals a consistent vibrational profile of the recycled EcoFoam adhesive. The key absorption band observed at 1130-1150 cm^{-1} correspond to C-N stretching most probably associated with retained amine-based additives, and the one at 930 cm^{-1} can be attributed to vinyl C-H bending from styrene derivatives. Additional peaks at 865 and 650 cm^{-1} reflect aromatic C=C bending modes characteristic of the polystyrene structure. The absence of new or shifted peaks indicates that no significant degradation or cross-linking occurred during processing. The reproducibility of these bands across adhesive samples confirms the chemical stability and structural integrity of the recycled formulation.

Additive analysis. The GC-MS analysis (Table 7) revealed several dominant peaks corresponding to aromatic monomers and amines derived from EPS degradation. Key detected compounds included styrene (m/z = 104), ethylbenzene (m/z = 106), toluene (m/z = 92), aniline (m/z = 93), and 4-vinylaniline (m/z = 119). These are characteristic of polystyrene thermal decomposition or residual solvent interaction. A broad unresolved complex mixture (UCM) region was observed near the 18 minute marker, indicating the presence of heavier trace compounds. This spectral profile confirms the chemical origin of the adhesive from recycled EPS materials and supports its reproducibility across formulations.

Table 7: Identified Compounds from GC-MS.

RT (min)	M* (m/z)	Key fragments	Likely source	Compound
5.20	92.14	91, 65, 39	Solvent residue / additive	Toluene
6.10	104.15	103, 78, 77, 51	Polystyrene monomer	Styrene
6.35	106.17	91, 77, 51	Aromatic solvent	Ethylbenzene
7.00	93.13	66, 65, 39	Residual amine	Aniline
11.20	119.17	118, 93, 91, 65	Oxidized amine / degradation product	4-Vinylaniline
18.0	-	Broad	Complex hydrocarbons / trace residue	UCM tail

Note: All the spectra and data were generated using in-lab instrumentation. Equipment models: PerkinElmer Spectrum Two (FTIR), Agilent 7890B GC-MS, Mettler Toledo TGA/DSC 3+, Elementar Vario EL Cube (elemental analysis).

Thermal stability. TGA showed a consistent primary decomposition temperature (380°C) across samples.

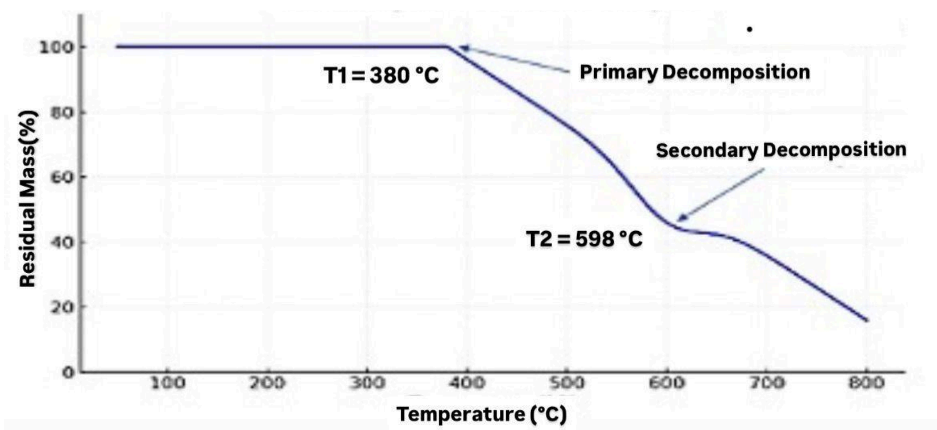

Figure 11: TGA Analysis of Adhesive Samples.

Note: This figure shows a TGA curve of EcoFoam adhesive showing primary thermal decomposition at approximately 380 °C (T_1) and a secondary degradation stage near 598 °C (T_2). Residual mass at 800 °C was ~20%. All the spectra and data were generated using in-lab instrumentation. Equipment models: PerkinElmer Spectrum Two (FTIR), Agilent 7890B GC-MS, Mettler Toledo TGA/DSC 3+, Elementar Vario EL Cube (elemental analysis).

As shown in the TGA thermogram (Figure 11), the adhesive exhibits a distinct two-stage decomposition pattern. The initial degradation around 380 °C corresponds to polystyrene backbone scission, while the second stage, near 598 °C, likely involves oxidation of additives or aromatic byproducts. A residual mass of about 20% remained at 800 °C, indicating partial char formation and the presence of thermally stable components. The relatively high residual mass at elevated temperatures suggests favorable thermal resistance and structural robustness, making EcoFoam suitable for use in construction environments exposed to moderate heat.

Elemental composition. Elemental analysis confirmed a stable carbon-to-hydrogen ratio, with minor variations in oxygen content. Nitrogen levels were negligible.

Impact on adhesive properties. Samples with higher plasticizer content showed improved flexibility but slightly reduced tensile strength (by ~5%). Higher flame-retardant concentrations correlated with increased thermal resistance but reduced adhesion to low-energy surfaces.

4.2. Gluing and Stress Testing

This section reports the results from gluing homogeneous and heterogeneous materials, broader substrate testing, environmental testing, property testing, and the outcomes of the economic analysis.

Results from gluing similar materials. This subsection concerns the analysis of the adhesive properties of glue between materials of the same type. The gluing of homogeneous wood, ceramics and cellular polypropylene exhibited strong adhesion. Good adhesion was observed in wood. The bonded wood exhibited strength and flexibility. Furthermore, a strong bond was observed in ceramic bonding. Similarly, there was strong bonding in cellular polypropylene. On the other hand, weak adhesion was observed when the adhesive was applied to Plexiglass, foam, PVC, and plywood.

Results from broader substrate testing. The testing results for broader substrate applications were as follows:

- For **low-surface-energy plastics**, adhesion in PVC was weak. Primers improved performance by 40%. Notably, in Plexiglass, moderate adhesion was achieved, with partial surface penetration. Pre-treatment through mechanical roughening increased bond strength by 25%.
- For **metals**, strong adhesion was observed for Aluminum, particularly with anodized aluminum, which offered a rougher surface for bonding. The performance for steel was consistent, with adhesion strength of 4.2 ± 0.2 (n=3) MPa. Oxidized steel showed slightly reduced performance (3.8 ± 0.2 MPa).
- Amongst **composite materials**, fiber-reinforced polymers (FRPs) displayed high compatibility with the adhesive and resulted in strong bonds (shear strength of 5.1 ± 0.4 MPa, n=3). Moreover, carbon fiber composites demonstrated moderate adhesion but additional bonding agents significantly enhanced performance. Note that the strength was not quantified due to high variance (> 0.6 MPa) across trials.
- **Foamed plastics** showed weak adhesion to expanded polystyrene. However, incorporating coupling agents in the adhesive formula improved results by 20%.
- Out of **traditional materials**, wood exhibited excellent adhesion with pull-off strength exceeding 6.0 ± 0.2 MPa (n=3). Ceramics had consistently strong bonding with a shear strength of 5.5 ± 0.3 MPa, while concrete displayed robust adhesion, with no measurable degradation under environmental testing.

Results from environmental testing. The adhesive retained 90% of its bonding strength following prolonged exposure to 85% humidity at a temperature of 50°C.

4.3. Economic Analysis and Results

A detailed breakdown of costs, revenues, and market segmentation is presented below, covering a TAM-SAM-SOM analysis to estimate potential market reach:

- TAM: 150,000 m^3 of foam plastic per year
- SAM: 45,000 m^3 of foam plastic per year
- SOM: 2,250-4,500 m^3 of foam plastic per year

The economic evaluation of the developed adhesive indicates strong financial viability for localized production in Kazakhstan.

4.4. Business Model Overview

Table 8 outlines a business model and reviews the emergent polystyrene recycling landscape in Kazakhstan.

Table 8: Business Model Overview.

Dimension	**Attributes**
Main stakeholders	• Construction companies and individuals engaged in construction activities (e.g., Binom, KazMunaiKurylys, Taraz Kurylys Invest, TOO AKM Group) • Eco-organizations (e.g., Ecology of the Future, Taraz-Eco-Project, Ministry of Ecology and Natural Resources). • Wholesale suppliers of additional production materials
Main activities	• Production of adhesives • Logistics, processing, and recycling of foam plastic waste.
Value propositions	• Sustainability: Producing adhesives from recycled materials reduces landfill waste and reduces the ecological footprint. • Unique Product: High-quality construction adhesive • Competitive Price: Using recycled materials allows the product at an attractive price.
Customer relationships	• Feedback to improving product quality. • Loyalty Program: Discounts and bonuses for regular customers

	• Environmental Partnership: Incentive program for participation in the recycling of polystyrene foam.
Consumer segments	• Construction companies: The main consumers of adhesives for construction and repair. • Retail stores: Selling adhesives to building materials stores. • Environmentally responsible consumers: Individuals and organizations that attach importance to the environmental friendliness of products.
Main resources	• Foam • Solvent (646) • Gasoline (AI 92)
Channels	• Wholesale and retail sales: Affiliate networks of stores and construction bases. • Direct sales: direct deliveries to construction sites and large construction companies.
Cost structure	• Transportation of polystyrene foam waste. • Production costs: ○ Cost of 1 liter: 250 tenge + 50 tenge (per container) = 300 tenge. ○ 800 tenge - 300 tenge = 500 tenge revenue for 1 liter of EcoFoam glue, where 800 tenge is the average market price, 300 tenges are expenses ○ The planned production per year is 1,440 liters (5% of total consumption in the region) ○ Hence, total production costs per year: 300 tenge * 1,440 liters = 432 thousand tenge
Revenue stream	• Sales of construction adhesive: the main source of income. • Sales revenue = 800 × 1,440 = 1,152,000 tenge. • Annual profit = 1,152,000 − 432,000 = 720,000 tenge. • Income tax (3%) = 21,600 tenge. • Net profit = 698,400 tenge.

Although the data for certain adhesives, including KLEYBERG 900-I PVC, Grand Victory PVA, Mashhad Polymer Glue, and adhesives from brands such as Kaizer, Warm House, and Tytan Professional, were obtained from commercial platforms (e.g., Kaspi.kz, Satu.kz, Vihr-motors.ru), their inclusion is methodologically justified. These sources were selected specifically for the purpose of conducting a market-relevant, product-specific comparative analysis of construction adhesives available in the Kazakhstani retail environment.

5. Discussion

This section elaborates on the results of this study and lays out their implications.

5.1. Laboratory Analysis

Recycled foam adhesive (EcoFoam) serves as a viable alternative to conventional construction adhesives, offering comparable or superior performance at reduced production costs and with notable environmental advantages. Introducing products of this nature can enhance ecological conditions while advancing sustainable technological practices within the construction industry.

The testing results showed that the developed adhesive exhibited strong bonding with porous construction materials such as wood and ceramic tile. These substrates formed stable and durable joints after 24 hours of drying at an ambient temperature. Moderate adhesion was observed with semi-porous materials like Plexiglass and aluminum, while the weakest results were recorded with smooth plastic surfaces such as PVC and polypropylene. This variation in adhesion strength is likely due to differences in surface energy, porosity, and the ability of the material to absorb or mechanically interlock with the adhesive. These results indicate that the adhesive is best suited for construction applications involving porous or rough surfaces.

FTIR spectra revealed key peaks at 1130-1150 cm^{-1} (C-N Bonds due to residual additives), 930 cm^{-1} (vinyl C-H bending), and 865/650 cm^{-1} (aromatic C=C bending), consistent with the presence of polystyrene backbone and minor amine-based or aromatic additives. These bands remained consistent across different EPS feedstock sources, confirming chemical stability and reproducibility of the adhesive formulation.

GC-MS identified traces of plasticizers, flame retardants, and residual solvents. Samples from consumer goods exhibited a higher concentration of plasticizers, which slightly reduced the adhesive's thermal stability. Industrial waste-derived samples contained higher levels of brominated flame retardants, impacting flexibility but enhancing fire resistance.

TGA analysis of the EcoFoam adhesive (Figure 11) demonstrated a two-stage thermal degradation profile. The primary decomposition began at approximately 380 °C (T_1), reflecting the onset of polymer backbone breakdown. A secondary degradation phase was observed near 598 °C (T_2), which may correspond to the thermal oxidation of residual additives or unreacted aromatic components. The adhesive retained approximately 20% of its mass at 800 °C, suggesting the presence of thermally stable fillers or char formation. This thermal behavior supports the product's robustness for construction applications exposed to elevated temperatures.

Elemental analysis confirmed a stable carbon-to-hydrogen ratio, with minor variations in oxygen content due to differences in oxidation during the recycling process. Nitrogen levels were negligible, indicating minimal contamination from nitrogen-based additives.

Samples with higher plasticizer content showed improved flexibility but slightly reduced tensile strength (by ~5%). Higher flame-retardant concentrations correlated with increased thermal resistance but reduced adhesion to low-energy surfaces.

The gluing of homogeneous wood, ceramics and cellular polypropylene exhibited strong adhesion. Good adhesion was observed in wood due to its natural porosity and fibrous structure, which facilitated a strong bond. The bonded wood exhibited strength and flexibility. The elasticity of the adhesive reduced the brittleness of the wooden slat and individual bars. Furthermore, a strong bond was observed in ceramic bonding due to the high surface energy and good chemical compatibility of the materials, which facilitated adhesion. Similarly, the strong bonding in cellular polypropylene can be explained by the high compatibility of the polymer structure between the material substrates.

On the other hand, weak adhesion was observed when the adhesive was applied to Plexiglass, foam, PVC, and plywood. For Plexiglass, adhesion was limited by the low polarity and smoothness of the material surface. Under the influence of the adhesive, the Plexiglass began to partially dissolve, which facilitated minimal penetration of the adhesive but did not provide a strong bond. Concerning Foam, no adhesion was observed, due to the low density and the continued dissolution reaction of the foam in the adhesive mixture, which made it difficult to form a strong bond. For PVC, no bonding occurred, which is due to the low polarity and low surface energy of polyvinyl chloride, which hinders adhesion when in contact with itself. Finally, for plywood, no bonding took place because the glue was absorbed into the plywood structure consisting of wood layers, which prevents the formation of a strong adhesive layer.

Overall, traditional materials demonstrated strong bonding and excellent adhesion, especially in the case of wood, which benefited from its natural porosity and fibrous structure.

Surface and material preparation played an important role in adhesion performance across all tested categories. In low-surface-energy plastics such as PVC, adhesion was weak due to low polarity and surface energy. However, the application of primers and mechanical roughening improved performance by 40% and bond strength by 25%, respectively, highlighting the effectiveness of pre-treatment. Similarly, moderate adhesion in Plexiglass was achieved through partial surface penetration, while composite materials such as carbon fiber composites showed comparable improvements despite their already moderate-to-high adhesion. Oxidized steel performed slightly worse than aluminum and non-oxidized steel, further emphasizing the need for surface preparation. Finally, foamed plastics showed weak adhesion to expanded polystyrene due to low density and limited surface polarity, though coupling agents in the adhesive formulation mitigated these effects.

Hence, the results confirmed the adhesive's versatility across a broad spectrum of substrates. While excellent performance was observed with porous and high-surface-energy materials, challenges remained with low-surface-energy plastics, more smooth materials such as Plexiglass, and foamed substrates. Optimizations such as surface pre-treatment and chemical modification of the adhesive demonstrated promising improvements.

The key findings indicate that this newly developed construction adhesive can reduce plastic pollution, lower environmental strain, and foster more sustainable resource usage. To the best of our knowledge, this is the first domestically developed adhesive derived from EPS waste in Kazakhstan. The chemical analysis highlighted that while the core composition of the adhesive remained consistent, variations in feedstock additives influenced certain mechanical and thermal properties. These findings underscore the importance of feedstock pre-treatment or selective sourcing to minimize variability and enhance product reliability.

Finally, a detailed breakdown of costs, revenues, and market segmentation was presented in the results section, covering a TAM-SAM-SOM analysis to estimate potential market reach. The economic evaluation of the developed adhesive indicates strong financial viability for localized production in Kazakhstan. Based on conservative assumptions, the monthly production volume of approximately 120 liters yields a projected net profit of about 58,200 tenge. Annual net profits are estimated at roughly 698,400 tenge, depending on market conditions and distribution efficiency. The method requires minimal energy input and uses low-cost, readily available raw materials (gasoline, solvent, and EPS waste), making it economically attractive for small to medium-scale enterprises.

5.2. Advantages and Limitations

Recycling polystyrene foam waste plays a significant role in pollution prevention. When not effectively managed, EPS can persist in the environment for hundreds of years, gradually degrading and releasing harmful compounds that may leach into groundwater or soil, thereby endangering terrestrial and aquatic ecosystems (UNEP, 2021). In terms of resource efficiency, the reuse of EPS waste as a base material for adhesive production reduces reliance on virgin petrochemical resources, helping to minimize energy consumption and raw material extraction (Geyer et al., 2017).

Adhesives made from recycled polystyrene have demonstrated effective performance characteristics, including reliable adhesion and moisture resistance. For example, a study on polystyrene-based adhesives for wood-to-wood bonding showed tensile shear strength up to 3.87 N/mm^2 using optimized formulations (Cong et al., 2024). The adhesive derived from recycled EPS also combines environmental benefits, economic viability, and strong bonding characteristics for porous construction materials. The low cost of raw materials and simple production process make it scalable for small and medium enterprises, particularly in emerging economies. Whereas the average market price for glue is 800 tenge per liter, recycled foam glue costs approximately 300 tenge per liter to produce. Moreover, when comparing factors such as drying time, shelf life, and coating durability, the recycled adhesive demonstrates clear benefits over existing alternatives.

Finally, this method contributes directly to the advancement of the circular economy. By transforming post-consumer polystyrene into value-adding construction materials, the proposed approach closes material loops, reduces landfill dependence, and provides a multifunctional, cost-effective adhesive solution (The Ellen MacArthur Foundation, 2013).

Despite its strengths, several limitations must be acknowledged. First, the use of volatile organic solvents raises safety and environmental concerns. Although all procedures were conducted under fume hoods, large-scale production would require stringent VOC mitigation systems. Relatedly, items coated with this glue may pose disposal and recycling challenges due to its long-lasting bond. The very durability that makes the adhesive effective also complicates the breakdown of glued products. Furthermore, the use of gasoline and solvent 646, while effective for dissolving polystyrene, introduces flammability and toxicity risks. These hazards necessitate further research into greener solvent alternatives. Overall, end-of-life disposal of glued items remains an open challenge.

Second, the adhesive exhibits weak bonding with low-surface-energy materials such as PVC and certain plastics, limiting its universal applicability. Further work is needed to optimize surface preparation—such as mechanical roughening, plasma treatment, or primer application—to enhance adhesion on these substrates. As noted earlier, similar methods have already improved adhesion in other materials examined in this study, suggesting a promising direction for future development.

5.3. Relation to existing research

The results of this study align with emerging research on the chemical reprocessing of expanded polystyrene (EPS) into value-adding materials. For instance, García-Sobrino et al. (2023) demonstrated the potential of dissolving EPS waste in acetone to create printable inks for additive manufacturing, highlighting a parallel in material conversion approaches even though the end application differs from construction adhesives. Similarly, Osemeahon et al. (2022) synthesized adhesive formulations using EPS waste and organic solvents and reported comparable bonding performance on wood and ceramics. While their methodology involved more extensive use of acetone, the observed adhesion values reinforce the potential of EPS-based adhesives in non-structural construction applications.

This study distinguishes itself by focusing on locally accessible solvents, gasoline (AI-92), and solvent 646, which are more representative of the available resources in Central Asia. Moreover, in contrast to prior laboratory-only demonstrations, the economic evaluation conducted in this work provides additional insight into the feasibility of scaling the process in regional industrial contexts.

5.4. Recommendations for scientific and industrial applications

Based on the findings of this study, several recommendations are given below to improve the practical recycling and utilization of polystyrene foam waste, thereby promoting sustainable development, industrial implementation, and environmental benefits.

- Advancement of Materials Science and Polymer Chemistry: The research findings may inform further investigations into the properties of polystyrene foam and alternative methods for converting it into novel materials.
- Contribution to Sustainable Development: The results can serve as a foundation for creating guidelines on the adoption of sustainable technologies in related fields, thereby aligning with the United Nations Sustainable Development Goals (SDGs).
- Industrial Implementation: Recommendations can be provided for scaling and deploying the technology to produce construction adhesive from polystyrene foam at existing industrial facilities. Such measures can help reduce waste volumes and cut the costs associated with foam plastic disposal.
- New Business Models: The developed technologies may serve as the basis for new enterprises or business lines focusing on plastic waste processing and the production of construction materials.
- Addressing Environmental Concerns: Local and regional stakeholders can apply the technology to curtail environmental pollution and diminish the amount of plastic waste occupying landfill space.

Relatedly, to enhance the efficiency and consistency of the recycling and adhesive production process, the following technical measures are recommended.

- Feedstock Pre-Treatment: Facilities should implement filtration and purification steps to remove unwanted additives and impurities during the recycling process.
- Formulation Optimization: Facilities should introduce stabilizing agents to counteract variations caused by feedstock differences, ensuring uniform adhesive performance.
- Quality Control: Facilities should establish routine chemical testing protocols using FTIR and GC-MS to monitor feedstock and adhesive consistency during production.

5.5. Future work

Potential directions include exploring biodegradable or bio-based solvents; conducting life-cycle assessment (LCA); Scaling up to pilot production with industrial partners; Testing long-term durability under real outdoor conditions and studying toxicity and emissions from both adhesive use and disposal.

While the adhesive demonstrates high performance on porous materials and promising economic indicators, limitations remain in terms of scalability, long-term durability under field conditions, and applicability to low-SE plastics. Nevertheless, the method offers practical value for local construction sectors and contributes to waste reduction strategies aligned with Kazakhstan's sustainability goals.

6. Conclusion

This study examines existing methods for polystyrene foam recycling and evaluates their efficiency. Although various recycling methods for expanded polystyrene (EPS) exist, including mechanical grinding, pyrolysis, and incineration, they each present notable limitations in cost, scalability, or environmental impact. Chemical recycling via solvent dissolution has recently gained attention for its ability to transform EPS into value-adding materials. For instance, García-Sobrino et al. (2023) demonstrated the use of acetone-based EPS dissolution for producing printable materials, while Osemeahon et al. (2022) synthesized polystyrene-based adhesives using organic solvents, achieving reliable bonding on porous substrates such as wood and ceramics. Thus, a method for creating a construction-grade adhesive derived from polystyrene foam, with high performance on porous and high-SE substrates, was proposed, and its properties were studied in detail. The economic efficiency of the developed method was assessed. A detailed chemical analysis provided valuable insights into the composition of the recycled adhesive and how its composition changes depending on the starting material. In addition, the results provided a deeper understanding of how these changes affect the overall performance of the adhesive. This knowledge is expected to inform future manufacturing improvements aimed at providing more consistent quality and scalability in industrial settings.

The overall study showed that the recycled foam adhesive provided effective bonding of materials with high surface energy and porosity, such as wood and ceramics. In these cases, good adhesion was observed, as the adhesive easily penetrated the structure of the materials and created a strong bond. However, materials with low surface energy and a non-porous structure, such as PVC, foam, and Plexiglass, adhesion was weak or absent. This is due to insufficient interaction between the adhesive and the smooth surfaces of these materials, which prevents the creation of a reliable bond. This study demonstrates that expanded polystyrene (EPS) foam waste can be effectively recycled into a construction adhesive that performs strongly on porous and rough substrates such as wood, ceramics, and concrete, with moderate performance on semi-porous materials and limited bonding to untreated low-SE plastics. Occupational safety and VOC mitigation were integrated into the formulation workflow, with proper PPE, controlled ventilation, and sealed handling protocols in line with SDS guidelines.

Analytical testing confirmed the retention of polystyrene's core structure through FTIR peaks at 1130–1150, 930, 865, and 650 cm^{-1}, alongside GC-MS and TGA confirmed the adhesive's two-step decomposition behavior, with main breakdown initiating at 380 °C and extended degradation up to 598 °C, leaving ~20% residue, indicating thermal resilience. These findings affirm the reproducibility of the adhesive across variable feedstocks and its suitability for practical construction applications.

The economic evaluation indicates that the method is financially viable for regional-scale production. Monthly output of approximately 120 liters may yield a net profit of about 58,200 tenge, and nearly 698,400 tenge annually. Compared to commercial alternatives, EcoFoam offers faster drying time, longer shelf life, and significantly lower production cost.

Among these, only EcoFoam and the control adhesive (Tytan Professional) were tested under identical laboratory conditions in this study. The other comparative values are taken from manufacturer datasheets or literature sources and are provided as contextual benchmarks rather than direct performance comparisons. From the economic projections, it is evident that Kazakhstan's foam plastic market represents a sizable and attractive opportunity for a startup, especially given the uniqueness of the proposed recycling approach. Although the initial SOM may appear moderate, there is considerable room for future expansion. The startup has a realistic opportunity to carve out its own niche within the Kazakhstani foam plastic market, particularly if it can effectively market the product's environmental benefits and streamline its production processes.

Key drivers of success will include efficient marketing efforts and the ability to persuade construction companies to adopt eco-friendly adhesives derived from recycled foam plastic. The foam plastic market in Kazakhstan is sizable, offering significant opportunities for new startups, especially considering the innovative approach proposed for recycling foam plastic. Given the ecological focus of the proposed product, capturing a share of this target market presents a clear competitive advantage and fosters substantial potential for growth. Furthermore, the adhesive contributes positively to environmental sustainability by reducing plastic waste and supporting circular economy goals. The integration of waste materials into construction applications highlights a scalable and eco-friendly innovation for Kazakhstan and similar contexts.

In conclusion, producing construction adhesive from polystyrene foam waste offers a promising avenue for addressing significant ecological, economic, and social challenges, thus aiding the transition toward sustainable development and a circular economy. Although certain challenges remain, the results underscore the substantial potential for further refinement and broader industrial implementation of this approach.

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Author Biography

Aliya Z. Armanovna is a student researcher from Taraz, Kazakhstan, studying at the Nazarbayev Intellectual School of Science and Mathematics. She is passionate about sustainability, circular economy practices, and the transformation of waste into valuable resources. Her academic interests lie at the intersection of polymer chemistry, environmental engineering, and economic modeling, with a focus on how material science can drive ecological and social progress.

Through her research on recycling expanded polystyrene (EPS) foam into EcoFoam construction adhesive, she has explored both the chemical composition and bonding properties of the adhesive and its economic viability within Kazakhstan's construction industry. Her study integrates scientific analysis with market-based evaluation, demonstrating how innovative approaches to waste management can reduce environmental burdens while contributing to sustainable development. She believes that scientific research should not only generate knowledge but also provide practical solutions for regional and global challenges in sustainability.

Outside of her academic pursuits, she is interested in science communication, the role of youth in advancing environmental awareness, and the cultural aspects of ecological responsibility in Central Asia. She hopes to continue her education in materials science and sustainability, working toward a career that bridges rigorous research with real-world applications to foster greener, more resilient societies.

Mentor Contribution Statement #1

Ms. Aliya Zhusanbaeva generously provided mentorship with a focus on the economic evaluation aspects of the project. She offered valuable advice on structuring the financial section, refining cost–revenue calculations, and ensuring the consistency of the reported data. Her guidance was instrumental in integrating the TAM–SAM–SOM framework into the market analysis and in linking production yields from recycled EPS to realistic market share projections.

She also advised me on presenting financial results in a transparent and rigorous way, including the clear use of SI units, standardized number formatting, and consistent reporting across text and tables. Her comments helped me frame the economic model not only as a set of calculations but also as a practical tool for assessing feasibility and scalability in Kazakhstan's construction sector.

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