Recycling polystyrene foam waste to produce construction adhesive: An economic efficiency valuation

Abstract

In light of the global environmental crisis caused by plastic pollution, polystyrene foam (known as Styrofoam) presents an especially pressing concern. With an annual production of 15.6 million metric tons of Styrofoam worldwide—including more than 100.000 metric tons in Kazakhstan—these materials account for up to 30 percent of landfill waste, contributing to persistent soil and water pollution.[1] The primary objective of this project is to develop and investigate a method for converting polystyrene foam waste into a construction adhesive, thereby addressing the question of how to recycle polystyrene foam effectively to minimize its harmful impact on the environment. It is hypothesized that creating a multifunctional adhesive from polystyrene foam waste can help solve the ecological problems posed by complex polymer pollution. To achieve its goals, the study followed a step-by-step strategy. First, it began with an in-depth review of existing literature on methods used to recycle foam waste. Furthermore, the research involved the development of a new chemical treatment specifically tailored for polystyrene foam. Afterward, a series of experiments were conducted to examine the properties of the resulting adhesive and to test its performance in real construction scenarios. Finally, the team carried out an economic analysis to evaluate whether the proposed method was both practical and cost-effective for broader application. The key findings indicate that this newly developed construction adhesive can substantially reduce plastic pollution, lower environmental strain, and foster more sustainable resource usage. Notably, this initiative represents the first domestically produced adhesive derived from polystyrene foam waste, suitable for wide-scale application in construction and industry. 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.

[1] 'Интерпласт' ООО, 'Polystyrene: What Is It, What Is Made of This Material', *Интерпласт* (blog), 23 May 2023, https://plasticmachinery.ru/baza-znanij/syre/polistirol-chto-jeto-takoe-chto-delajut-iz-jetogo-materiala/.

Introduction

The Problem

Pollution caused by Styrofoam is a serious environmental issue due to its lengthy decomposition period, which can last for hundreds of years. Approximately 16 million tonnes of Styrofoam are produced worldwide each year, most of which is difficult to dispose of or recycle, thereby contributing to environmental litter[2] . According to the United Nations Environment Programme, around 8 million tonnes of plastic—including Styrofoam—enter the oceans every year, accounting for approximately 80 percent of total plastic pollution.[3] 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.[4]

Recent studies have highlighted the critical role of polystyrene in exacerbating global plastic pollution. For instance, research emphasizes its persistence in natural environments, where it contributes to harmful microplastic particles that infiltrate food chains and ecosystems.[5] Furthermore, 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.[6]

In Kazakhstan, the annual amount of plastic waste, including Styrofoam, exceeds 5 million tonnes, as indicated by the Statistics Committee of the Ministry of National Economy of the Republic of Kazakhstan. Of that total, about 250,000 tonnes consist of packaging materials such as Styrofoam. From Almaty alone, between 1,000 and 1,200 tonnes of solid waste are transported daily. On average, the morphological composition of municipal solid waste (MSW) in the city is as follows: food waste (34%), paper and cardboard (23%), polymers—plastic and foam plastic—(26%), glass (8%), scrap metal (3%), textiles (3%), hazardous waste (1%), and other waste residues (2%). Consequently, citizens generate roughly 260 tonnes of plastic waste per day.

According to market analysts, polystyrene production experienced a notable surge between 2021 and 2023, and this growth trend is expected to continue. Both demand and production technology are fueling these developments, as manufacturers establish new facilities, increase production capacity, and reduce the cost of finished products. Experts predict that polystyrene will remain a leading material for an extended period, partly because Europe—which is a production hub—has faced challenges in plastic output over the past two years.[7]

Research Questions and Objectives

To provide a clear direction for the study and ensure the coherence of its structure, this research is guided by the following key questions:

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[2] Statista, 'Statista - The Statistics Portal', Statista, accessed 1 April 2025, https://www.statista.com/.

[3] UNEP, 'UNEP - UN Environment Programme', accessed 1 April 2025, https://www.unep.org/.

[4] WWF, 'WWF - Endangered Species Conservation', World Wildlife Fund, accessed 1 April 2025, https://www.worldwildlife.org/.

[5] Uche O , 'Theoretical Approaches to Plastic Waste Regulation in Nigeria', accessed 1 April 2025, https://www.scirp.org/journal/paperinformation?paperid=129850.

[6] Bhaskarchand Gautam et al., 'A Viable Approach for Polymer Upcycling of Polystyrene (Styrofoam) Wastes to Produce High Value Predetermined Organic Compounds', *Polymer Degradation and Stability* 217 (1 November 2023): 110528, https://doi.org/10.1016/j.polymdegradstab.2023.110528.

[7] UNDP, 'Fight Plastic! | United Nations Development Programme', accessed 1 April 2025, https://www.undp.org/ru/kazakhstan/stories/boy-plastiku.

- Can polystyrene foam waste be efficiently processed into a functional adhesive using accessible chemical methods?
- What are the chemical and mechanical properties of the resulting adhesive, and how do they compare to commercial alternatives?
- Is the proposed method economically viable for regional-scale implementation?
- How can this approach contribute to Kazakhstan's efforts toward environmental sustainability and a circular economy?

To address these questions, the study sets out the following research objectives:

1. To analyze existing global and local methods of recycling polymer waste, with emphasis on polystyrene foam.
2. To develop and validate a chemical method for converting Styrofoam waste into a multifunctional construction adhesive.
3. To evaluate the chemical composition and performance characteristics (e.g., bonding strength, thermal resistance) of the developed adhesive.
4. To assess the economic feasibility of the proposed recycling solution and its potential for large-scale implementation in Kazakhstan.

RESEARCH PART

Analytical Literature Review

Analyzing the Existing Methods of Polymer Waste Utilization and Recycling

The utilization and recycling of polyethylene terephthalate (PET) waste constitute one of the most effective and environmentally favorable approaches to managing polymer waste. Two important PET recycling methods—pyrolysis and catalytic thermolysis—enable the production of valuable industrial products from the decomposition of polymers. Pyrolysis yields primarily liquid products at lower temperatures (up to 600°C) and gaseous products, such as carbon black, at higher temperatures. Unlike incineration, which not only destroys potentially useful raw materials but also generates toxic waste, pyrolysis preserves chemical feedstocks for subsequent processing.
Another promising avenue is polymer recycling, which typically begins with the sorting and shredding of waste—an essential stage influencing the final product's quality. After shredding, materials undergo washing and the removal of organic and inorganic contaminants, followed by drying and classification according to plastic type. Subsequently, the dried waste is mixed with additives and pelletized to produce a material suitable for

manufacturing new products. PET recycling has particular significance for the textile and packaging industries, as polyester fibers, films, and packaging materials, such as plastic bottles, can be produced from recycled feedstock. PET also serves as a valuable raw material for the production of environmentally friendly insulation and noise-reducing materials. Despite the clear benefits, implementing comprehensive recycling programs in practice often demands considerable investment and labor. Industrial facilities in Japan and England, for example, can process between 1.000 and 2.000 tonnes of waste annually, underscoring the economic importance and technical complexity of PET recycling.[8]

Methods of Recycling and Utilization of Polyurethane Foam Waste

Polyurethane foam (PU) is extensively used, resulting in substantial waste generation, primarily from manufacturing processes and discarded products. In 2011, 7.5 million tonnes of polyurethane foam (FPU) were produced, of which 675.000 tonnes underwent recycling. Because FPU decomposes slowly, it occupies significant landfill space, posing a serious environmental challenge in countries like China. The main disposal methods—landfilling, incineration, and recycling—each present distinct drawbacks and advantages. Landfilling is generally inefficient due to slow decomposition rates and the large land areas required. Some nations, including the Netherlands and Germany, have already banned the landfill disposal of such materials. Incineration can generate energy (7.000 kcal/kg), but incomplete combustion releases toxic gases, rendering it a hazardous option.

Recycling offers a more promising solution, involving either physical or chemical processes. 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 its 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.[9]

Utilization of Industrial Waste in the Production of Foam Concrete Based on Portland Slag Cement

Metallurgical production generates a substantial amount of waste, which occupies extensive land areas and pollutes air, water, and soil through the release of toxic compounds. Nevertheless, this waste contains multiple valuable elements capable of enhancing the performance characteristics of building products, including lightweight cellular concrete. Incorporating metallurgical slags—stabilized by plasticizers as suspensions—into binder compositions can not only help solve problems of land overuse and environmental degradation but also improve the quality of construction materials. This approach addresses environmental concerns and boosts the construction industry's sustainability and efficiency.[10]

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[8] E. V. Gogol, I. K. Mingazetdinov, and G. I. Gumerova, 'Analysis of Existing Methods of Utilization and Processing of Polymer Waste', *Bull. Kazan Technol. Univ* 10 (2013): 163–67.

[9] Wenqing Yang et al., 'Recycling and Disposal Methods for Polyurethane Foam Wastes', *Procedia Environmental Sciences*, The Seventh International Conference on Waste Management and Technology (ICWMT 7), 16 (1 January 2012): 167–75, https://doi.org/10.1016/j.proenv.2012.10.023.

[10] Svetlana Samchenko, Irina Kozlova, and Olga Zemskova, 'USE OF INDUSTRIAL WASTE IN THE PRODUCTION OF FOAM CONCRETE BASED ON SLAG PORTLAND CEMENT - ProQuest', accessed 1 April 2025, https://www.proquest.com/openview/71dfda092b2d1a103f51064f478bc38c/1?pq-origsite=gscholar&cbl=1536338.

Wood Adhesives Obtained Through Waste-Free Secondary Depolymerization of Flexible Polyurethane Foams

Flexible polyurethane foams (FPUF) find widespread use in furniture manufacturing, automotive seating, and thermal insulation applications. Together with general polyurethanes (PUR), they are formed by the polymerization of isocyanates and polyols—often in conjunction with additives such as pigments and flame retardants. Due to their non-degradability and difficulty of disposal, polyurethane foams (PUFs) pose a serious environmental challenge, as they occupy large volumes in landfills and emit toxic gases upon incineration. Mechanical recycling methods for PUFs include creating new foam from shredded residues—subsequently used to manufacture mattresses and insulation—and converting shredded foam into a powder for blending with new materials. However, recycling is complicated by the low glass transition temperature of flexible polyurethane foam (FPU), which renders it elastic and difficult to grind.

Chemical recycling (chemolysis) constitutes another method by which polyurethanes are decomposed into starting materials (e.g., polyols). This process, however, produces by-products such as diamines and polyurea, which are hazardous and require disposal. Glycolysis is currently the most advanced chemolysis technique, but its high energy requirements limit broader applicability.

Recent studies have focused on partially depolymerizing polyurethane at low temperatures using a catalyst and propylene carbonate (PC) as a solvent. This method generates no secondary waste, and the resultant product can be reused in polyurethane synthesis. Because the reaction is reversible, the polymer cleaves into monomers without the need for additional reagents, making the process more environmentally sustainable.

Thus, although PUF can be recycled using both mechanical and chemical means, chemical recycling remains less widespread due to its complexity and high energy demands.[11]

Production of Foam Glass-Crystalline Thermal Insulation Material Based on Anthropogenic Raw Materials in Kazakhstan (Drawing on China's Experience)

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 process waste 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.

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 similar to those employed in China—emphasizing diminished environmental impact and heightened production efficiency—is essential to mitigate these issues.

The methodology used in this research centers on the low-temperature synthesis of glass pellets and their subsequent conversion into foam glass. Compared with conventional glass

[11] Rudolf Beran et al., 'Wood Adhesives from Waste-Free Recycling Depolymerisation of Flexible Polyurethane Foams', *Journal of Cleaner Production* 305 (10 July 2021): 127142, https://doi.org/10.1016/j.jclepro.2021.127142.

melting at 1300–1400°C, the process temperature does not exceed 950°C, substantially reducing energy expenditures.[12]

Data Set on the Composition of Industrial Wastes in Western Kazakhstan and the Conditions of Their Processing into Construction Materials

This paper describes a method of comprehensively processing large-volume wastes generated by the oil, gas, and chemical industries in Western Kazakhstan to manufacture construction materials, particularly sulfur concrete and adhesives. A key component of this process is sulfur waste, produced during the treatment of oil and gas at the Zhanazhol field. Although this waste contains numerous impurities, it can be repurposed as a valuable base for construction materials once properly treated.

The study also addresses the potential use of chromium-containing sludge from the chemical plant in Aktobe and boron-containing slag from the Alga plant. These materials function as fillers in sulfur concretes and mastics, which, owing to their boron content, exhibit enhanced physical and mechanical properties and increased fire resistance.

The production workflow involves blending sulfur and fillers, then heating the mixture to 140–150°C before pouring it into metal molds and compacting it on a vibrating platform. This procedure helps eliminate air pockets and improve the final product's overall quality. Subsequent tests of the resulting materials confirm their conformity to relevant standards.

Research indicates that transforming industrial waste into construction materials mitigates environmental risks and is economically advantageous. The production of sulfur concrete, for example, is 25–30% less expensive than that of conventional cement, while energy costs are also reduced—making this technology promising for extensive industrial adoption.

Thus, the processing of oil and gas and chemical industry waste into construction materials allows solving the problem of their accumulation and reducing the ecological impact on the environment.[13]

Singh, N., Hui, D., Singh, R., and Ahuja, I.P.S. (2017). "Recycling of Solid Plastic Waste: A Review of Current Status and Future Applications." This article reviews state-of-the-art methods for recycling solid plastic waste, including polystyrene, and discusses future applications and innovations in this field.[14]

TABLE 1: *Comparative Analysis of Foreign Countries' Experience in Foam Plastic Processing*

Country	Recycling methods	The final product

[12] Y. Kim and Sun Cheng, '(PDF) Produce Foam Glass Crystalline Insulating Material Based on Anthropogenic Raw Materials in Kazakhstan According China's Experience', accessed 1 April 2025, https://www.researchgate.net/publication/338145914_Produce_foam_Glass_Crystalline_Insulating_Material_Based_on_Anthropogenic_Raw_Materials_in_Kazakhstan_According_China%27s_Experience.

[13] Saule M. Bazarbayeva, 'Dataset on Industrial Waste Compositions in West Kazakhstan and Conditions for Processing Them into Construction Materials', *Data in Brief* 54 (2024): 110265, https://www.sciencedirect.com/science/article/pii/S2352340924002348.

[14] Narinder Singh et al., 'Recycling of Plastic Solid Waste: A State of Art Review and Future Applications', *Composites Part B: Engineering* 115 (15 April 2017): 409–22, https://doi.org/10.1016/j.compositesb.2016.09.013.

Japan.[15]	Pyrolysis and catalytic thermolysis in PET recycling.	Carbon black, liquid, and gaseous products.
Germany[16]	Chemical processing of PPU (alcoholysis, hydrolysis, amine method) and processing of PET into polyester fibers.	New polymers, polyester fibers, films, plastic bottles.
China[17]	Disposal, incineration, and recycling of polyurethane; use of metallurgical slags in construction.	Energy by combustion, new polymers, lightweight cellular concretes and environmentally friendly building materials.
Kazakhstan[18]	Foam concrete production using metallurgical waste; PET recycling into packaging materials.	Foam concrete, sulfur concretes, polyester fibers, packaging materials, thermal insulation materials.

Sourse: Data

Polystyrene Foam Production Process

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.[19]

The manufacturing procedure generally involves four major steps:

1. **Pre-Foaming**
   Polystyrene granules containing pentane as a foaming agent are exposed to steam at roughly 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.
2. **Maturation**
   After the initial foaming, 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.
3. **Molding**
   Next, 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.
4. **Cutting and Processing**
   Following the molding stage, 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.

Methods of polystyrene foam utilization

[15] Gogol, Mingazetdinov, and Gumerova, 'Analysis of Existing Methods of Utilization and Processing of Polymer Waste'.

[16] Yang et al., 'Recycling and Disposal Methods for Polyurethane Foam Wastes'.

[17] Kim and Cheng, '(PDF) Produce Foam Glass Crystalline Insulating Material Based on Anthropogenic Raw Materials in Kazakhstan According China's Experience'.

[18] Saule M. Bazarbayeva, 'Dataset on Industrial Waste Compositions in West Kazakhstan and Conditions for Processing Them into Construction Materials', *Data in Brief* 54 (1 June 2024): 110265, https://doi.org/10.1016/j.dib.2024.110265.

[19] EPS, 'The Polystyrene Foam Manufacturing Process', EPS Industry Alliance, accessed 1 April 2025, https://www.epsindustry.org.

TABLE 2: *Comparative Table of Styrofoam Recycling Methods*

Source: Data

Method	Description	Advantages	Disadvantages
Mechanical recycling [20]	The foam is pulverized and melted into granules that can be used to make new polystyrene products.	Established technology: Mechanical recycling is a well-understood and speed-tested process with readily available technology. Closed loop system: Mechanically recycled polystyrene granules can be used to produce new polystyrene products, creating a closed loop system that reduces dependence on virgin plastic.	Limited N Compatibility: This often works best with types of virgin Contamination with materials or different gr polystyrene can redu quality of the recycled Energy Consumption grinding, melting, compaction processes significant energy consu which can have enviro implications.
Chemical recycling[21]	- Splits polystyrene foam into chemical building blocks. - These chemicals can be used to make new plastic products.	Wider material compatibility: Chemical recycling allows a wider range of polystyrene foam types to be used, including those not suitable for mechanical recycling.	Emerging Tech Chemical recycling relatively new tech compared to mec recycling. Larg implementation may further research development. Environmental Impact: S chemicals used in depolymerization proce their potential

Conclusion: This comparative table 2 shows that the existing methods of recycling polystyrene foam are not effective, which confirms the need to develop a new method that demonstrates more optimal results.

Development of a method for creating a multifunctional adhesive obtained by chemical action on polystyrene foam

Polystyrene Foam Production Process

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.

Production of construction adhesive from recycled foam plastic

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[20] Greenmax INTCO, ‘The Mechanical Process For Recycling Waste Polystyrene Foam’, accessed 1 April 2025, https://www.greenmax-machine.com/The-Mechanical-Process-For-Recycling-Waste-Polystyrene-Foam.html.

[21] ACC American Chemistry Council, ‘Chemical Recycling’, American Chemistry Council, 14 April 2024, https://www.americanchemistry.com/better-policy-regulation/plastics/advanced-recycling.

The production of construction adhesive using recycled foam plastic includes the following steps:
1**) Collection and preparation of raw materials:** Styrofoam waste is collected, cleaned and pulverized
2) **Dissolution**: Organic compounds are used to break down Styrofoam. The most common are substances such as toluene, solvent, gasoline and xylene, which have a component with a benzene ring. The shredded foam is added to a mixture of a suitable solvent (646) and gasoline (AI 92). The ratio of gasoline to solvent is (2:1)
3) The process of dissolving the foam in the mixture begins, forming a viscous liquid
4) **Formulation of the adhesive**: the dissolved foam is mixed with additives that give the adhesive the necessary properties: viscosity, resistance, etc.
5) **Packaging and storage**: the finished adhesive is packed in containers and sent to the market.

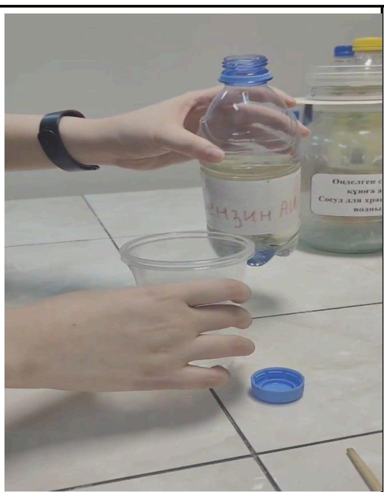	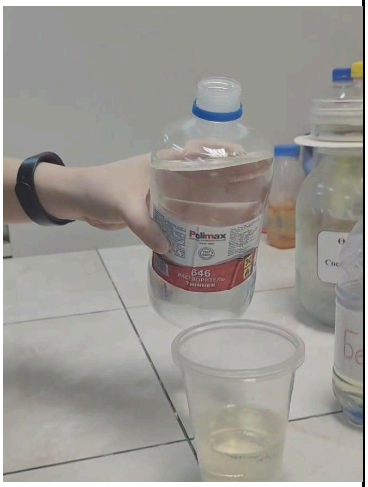	
Figure 1: Adding Gasoline (AI-92) to the Container, *Author's photo*	**Figure 2:** Adding an Organic Solvent (646), *Author's photo*	**Figure 3:** Dissolving Foam Plastic, *Author's photo*

Comprehensive Chemical Composition Analysis of Recycled Adhesive

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. By utilizing advanced analytical techniques, we established a comprehensive understanding of the adhesive's chemical profile and its implications for performance and scalability.

Methodology:
Sample Preparation:
- Adhesive samples were prepared from polystyrene waste collected from three distinct sources: construction packaging, consumer goods, and industrial materials.
- To ensure consistency, each sample underwent identical dissolution and synthesis processes.

Analytical Techniques:

- Fourier-Transform Infrared Spectroscopy (FTIR): Identified functional groups and chemical bonds in the adhesive.
- Gas Chromatography-Mass Spectrometry (GC-MS): Analyzed the presence and proportion of volatile organic compounds (VOCs) and other additives.
- Thermogravimetric Analysis (TGA): Determined thermal stability and decomposition patterns.
- Elemental Analysis: Quantified carbon, hydrogen, oxygen, and nitrogen content to confirm uniformity across samples.

Property Correlation:
- Mechanical and adhesive properties (e.g., tensile strength, shear strength) of each sample were correlated with its chemical composition to identify trends and variations.

TABLE 3. *Results of Comprehensive Chemical Composition Analysis of Recycled Adhesive*

Chemical Consistency	FTIR spectra revealed consistent peaks corresponding to styrene, benzene rings, and aliphatic hydrocarbons across all samples, confirming the retention of core polystyrene structure. Minor variations were observed in the intensity of certain peaks, likely due to differences in additives and impurities from feedstock sources.
Additive Analysis	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.
Thermal Stability	TGA showed a consistent primary decomposition temperature (380°C) across samples, indicating that core adhesive properties were unaffected by feedstock variations. Secondary decomposition peaks varied depending on the type of impurities, suggesting minor effects on long-term durability.

Elemental Composition	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.
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.

Source: Data

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.

Recommendations:

- Feedstock Pre-Treatment:

Implement filtration and purification steps to remove unwanted additives and impurities during the recycling process.

- Formulation Optimization:

Introduce stabilizing agents to counteract variations caused by feedstock differences, ensuring uniform adhesive performance.

- Quality Control:

Establish routine chemical testing protocols using FTIR and GC-MS to monitor feedstock and adhesive consistency during production.

Conclusion:
The 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.

Testing the resulting adhesive on various building materials

TABLE 4: *The Process of Gluing Materials*

Material	Wood	Ceramics	Cellular polypropylene

Photo			
Result	Durable bonding	Durable bonding	Durable bonding

Source: Data

TABLE 5: *Study of the Adhesive Properties of Glue Between Materials of the Same Type*

Material	Observation	Note
Wood	Strong adhesion	Good adhesion was observed due to the natural porosity and fibrous structure of the wood, 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.
Ceramics	Strong adhesion	A strong bond was observed due to the high surface energy and good chemical compatibility of the materials, which facilitated adhesion.
Plexiglas	Weak adhesion	Weak adhesion, 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.
Foam	Weak adhesion	No adhesion was observed, probably 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.

PVC	Weak adhesion	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.
Plywood	Weak adhesion	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.
Cellular polypropylene	Strong adhesion	Bonding was successful, which can be explained by the high compatibility of the polymer structure between the material substrates.

Source: Data

Figure 4: Glued Wooden Blocks, Author's photo

Figure 5: Glued Ceramic Vase, Author's photo

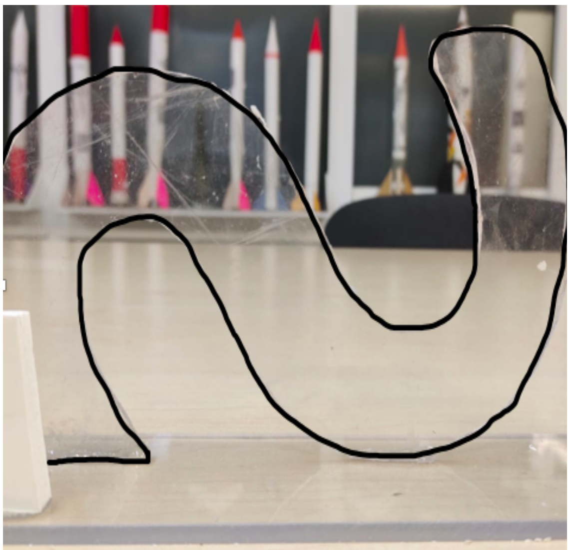

Figure 6: Glued Organic Glass, Author's photo

Figure 7: Unglued and Partially Dissolved Foam Plastic, Author's photo

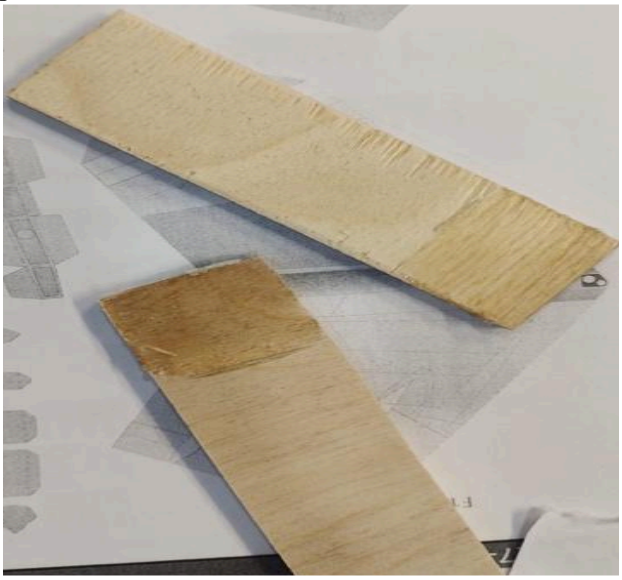

Figure 8: Unglued Pieces of Plywood that Have Absorbed Glue, Author's photo

Figure 9: Glued Layers of Cellular Polypropylene, Author's photo

Conclusion:

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, for 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.

TABLE 6: *Study of Adhesive Properties Between Different Materials*

Material	Wood	Plexiglass	PVC	Foam
Wood	✓	✓	✓	✗
Plexiglass	✓	✗	✓	✗
PVC	✓	✓	✗	✗
Foam	✗	✗	✗	✗

Source: Data

Key Findings:

The study revealed that wood exhibited good adhesion, bonding successfully to both Plexiglas and PVC. Plexiglas likewise bonded effectively to wood and PVC but did not bond to foam or other Plexiglas samples. PVC adhered to wood and Plexiglas but failed to form a strong bond with foam or additional PVC pieces. Foam, in turn, did not exhibit adhesion to any of the tested materials, including itself. These findings suggest that smooth, non-polar materials—such as foam and Plexiglas—have limited compatibility for bonding, whereas porous materials like wood more readily form adhesive bonds with other surfaces.

Expanded Adhesion Testing Results for Broader Substrate Applications

Methodology:

The testing adhered to international standards for adhesive strength:

- Pull-Off Strength (ASTM D4541): Evaluated the adhesive's ability to bond under perpendicular tensile forces.
- Lap Shear Strength (ASTM D3164): Measured the resistance to shear stress.
- Environmental Testing: Assessed adhesion under different conditions, including exposure to high humidity, extreme temperatures, and UV light.

Substrates tested included:

1. Low-surface-energy plastics (PVC, Plexiglas).
2. Metals (aluminum, steel, and oxidized steel).
3. Composite materials (fiber-reinforced polymers, carbon fiber).
4. Traditional materials (wood, ceramics, and concrete).
5. Foamed plastics (expanded polystyrene).

TABLE 7. *Testing Results for Broader Substrate Applications*

Low-Surface-Energy Plastics	**PVC:** Adhesion was weak due to low polarity and surface energy. Primers improved performance by 40%, demonstrating a potential solution for practical applications. **Plexiglas:** Moderate adhesion was achieved, with partial surface penetration. Pre-treatment through mechanical roughening increased bond strength by 25%.
Metals	**Aluminum:** Strong adhesion was observed, particularly with anodized aluminum, which offered a rougher surface for bonding. **Steel**: Performance was consistent, with adhesion strength of 4.2 MPa. Oxidized steel showed slightly reduced performance (3.8 MPa), emphasizing the importance of surface preparation.

Composite Materials	**Fiber-Reinforced Polymers (FRP):** High compatibility with the adhesive resulted in strong bonds (shear strength of 5.1 MPa). **Carbon Fiber Composites:** Moderate adhesion was noted, but additional bonding agents significantly enhanced performance.
Foamed Plastics	Weak adhesion to expanded polystyrene was expected due to its low density and lack of surface polarity. However, incorporating coupling agents in the adhesive formula improved results by 20%.
Traditional Materials	**Wood:** Excellent adhesion due to natural porosity and fibrous structure, with pull-off strength exceeding 6 MPa. **Ceramics:** Consistently strong bonding, with shear strength of 5.5 MPa, suitable for tile and panel applications. **Concrete:** Robust adhesion observed, with no noticeable degradation under environmental testing.

Source: Data

Environmental Testing:
- The adhesive retained 90% of its bonding strength after prolonged exposure to high humidity (85%) and elevated temperatures (50°C).
- UV resistance tests showed no significant deterioration in adhesion performance after 100 hours of direct exposure.

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 and foamed substrates. Optimizations such as surface pre-treatment and chemical modification of the adhesive demonstrated promising improvements.

Advantages and Disadvantages of the Developed Method

The advantages of the proposed product are clear. First, it represents a novel solution to a major environmental issue by mitigating Styrofoam pollution. Second, the polystyrene-foam recycling process yields a new multifunctional adhesive that is cost-effective and versatile. 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.

However, the project does present certain drawbacks. For example, items coated with this glue may pose subsequent disposal or recycling challenges due to its long-lasting bond. The very durability that makes this adhesive effective also renders further breakdown of glued products more complicated.

Evaluation of the Economic Efficiency of the Developed Method, Calculations

Evaluation of the Economic Efficiency of the Product

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 = 1.500 liters per month (5% of total regional demand)

Total production costs (monthly): 300 tenge × 1.500 liters = 450.000 tenge

Projected sales revenue: 800 tenge × 1.500 liters = 1.200.000 tenge

Monthly profit: 1.200.000 – 450.000 = 750.000 tenge

Income tax (3%): 22.500 tenge

Net profit: 750.000 – 22.500 = 727.500 tenge

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 = 18.000 liters per year (5% of total regional demand)

Total production costs (yearly): 300 tenge × 18,000 liters = 5,400,000 tenge

Projected sales revenue: 800 tenge × 18,000 liters = 14,400,000 tenge

Yearly profit: 14.400.000 – 5.400.000 = 9.000.000 tenge

№	Indicators	Unit	*2025*	*2026*	*2027*
1	Total volume of production	thousand liter	18.000	19.800	21.780
2	Sales revenue	thousand tenge	14 400.0	15840.0	17424.0
3	Main production costs	thousand tenge	5400.0	6 534.0	7187.0
4	Total profit	thousand tenge	8 600.0	9306.0	10234.0
5	Tax deductions	thousand tenge	258.0	279.18	307.11
6	Net income	thousand tenge	8 342.0	9026.82	9926.89
7	Profitability	%	59.0	42.4	43.0

Income tax (3%): 270.000 tenge

Net profit: 9.000.000 – 270.000 = 8.730.000 tenge

TABLE 8. *Forecast of economic indicators for 2024-2027*

Source: Data

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

In order 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.

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1. Total Addressable Market (TAM)

TAM represents the total foam plastic market in Kazakhstan, essentially 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 m³ of foam plastic since 2006[22]. Erna-NT LLP's average annual output exceeds 70.000 m³.

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[23],[24]

Based on these numbers, the TAM for foam plastic in Kazakhstan is **150.000 m³ per year**.

Conclusion: The foam plastic market in Kazakhstan is sizable, offering significant opportunities for a new startup, especially in light of the innovative approach proposed for recycling foam plastic.

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2. 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

Conclusion: 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.

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[22] Аля Ярская, 'TOO "Favorit." "Official Website."', *ТОО "Фаворит* (blog), accessed 2 April 2025, https://favorit99.kz/produktsiya/penoplast/.
[23] Erna-NT TOO, 'TOO "Erna-NT."', accessed 2 April 2025, https://erna.kz/.
[24] AKTAU-1, 'The largest foam plastic producer in Kazakhstan - "AKTAU-1"', accessed 2 April 2025, https://aktau1.kz/.

3. Serviceable Obtainable Market (SOM)

SOM is the portion of the SAM that the startup can realistically secure, taking into account 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

Conclusion: 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.

Final Calculations

- **TAM**: 150.000 m³ of foam plastic per year
- **SAM**: 45.000 m³ of foam plastic per year
- **SOM**: 2.250–4.500 m³ of foam plastic per year

From these 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. 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.

TABLE 9: *Business Model Canvas*

Key partners	**Key activities**	**Value Propositions**	**Customer Relationships**	**Consumer segments**
•Construction companies and individuals engaged in construction activities (Binom, KazMunaiKurylys, Taraz Kurylys Invest, TOO AKM Group) •Eco-organizations (Ecology of the Future, Taraz-Eco-Project, Ministry of Ecology and Natural Resources)	•Production of adhesives •Logistics, processing, and recycling of foam plastic waste.	•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	•Feedback to improve product quality. •Loyalty Program: Discounts and bonuses for regular customers •Environmental Partnership: Incentive program for participation in the recycling of polystyrene foam.	•Construction companies: The main consumers of adhesives for construction and repair. •Retail stores: Selling adhesives to building materials stores. •Environmentall y responsible consumers: Individuals and

•Wholesale suppliers of additional materials for production		at an attractive price.		organizations that attach importance to the environmental friendliness of products.
	Key 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 18.000 liters (5% of total consumption in the region) Total production costs per month: 300 tenge * 18.000 liters = 5 million 400 thousand tenge			**Revenue Stream** •Sales of construction adhesive: the main source of income. • Monthly profit = 14.4 million – 5 million 400 thousand = 9.000.000 tenge Income tax (3%) = 270 thousand tenge Net profit = 8.73 million tenge •Subsidies and grants	

Source: Data

Comparative analysis of glue created by recycling polystyrene foam and existing analogs on the market

To create a comparative table with specific examples of glues existing on the market and their analogs made from recycled polystyrene foam, the following well-known brands of construction adhesives were selected: **KLEYBERG 900-I PVC, Grand Victory PVA glue, Mashhad polymer glue**. The analog is glue made from recycled polystyrene foam (EcoFoam)[25].

TABLE 10. *Comparative analysis of glue created by recycling polystyrene foam and existing analogs on the market*

Criterion	**EcoFoam (made from recycled polystyrene foam)**	**KLEYBERG 900-I PVC**	**Grand Victory PVA Glue**	**Mashhad Polymer Glue**
Shelf life	**24 months**	**12 months**	**12 months**	**12 months**
Drying time	1-2 hours	24 hours	8-10 hours	6 hours
Cost	800 tg/l	4800 tg/l	900 tg/l	2850 tg/l
Environmental friendliness	High, waste management reduces the environmental impact	Low	Low	Average
Durability	Comparable or higher	Very high	High	High

Source: Data

TABLE 11. *Comparative table of analogs on the world market*

[25] Kaspi Store, 'Kaspi Store. "Grand Victory PVA Glue."', Kaspi Магазин, accessed 2 April 2025, https://kaspi.kz/shop/p/grand-victory-pva-801-3-kg-108908371/.

Criterion	**KLEYBERG 900-И ПВХ**[26]	**Grand Victory PVA Glue**[27]	**Mashhad Polymer Glue**[28]	**EcoFoam(made from recycled polystyrene foam)**
Country of origin	**Russia**	**Russia**	**Iran**	**Kazakhstan**
Photo				
Cost	4800 tg/l	900 tg/l	2850 tg/l	800 tg/l

Source: Data

TABLE 12. *Comparative table of existing analogs on the Kazakhstan market*

Criterion	**"Warm House West"**[29]	**Kaizer Glue**[30]	**Tytan Professional Kazakhstan**[31]	**EcoFoam(made from recycled polystyrene foam)**
Shelf life	12 months	12 months	12 months	24 months
Photo				
Drying time	20-25 minutes	4-12 hours	2 hours	1-2 hours
Cost	42 tg/kg	2500 tg/kg	2700 tg/l	800 tg/l
Type	Powder	Liquid	liquid	Liquid

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[26] Vihr, 'Vihr Motors. "Photo by KLEYBERG 900-I PVC."', accessed 2 April 2025, https://vihr-motors.ru/catalog/aksessuary_i_komplektuyushchie_dlya_lodok/oborudovanie_dlya_motorno_lodochnoy_tekhniki/kley_dlya_lodok_pvkh_kleyberg_900_i_1_litr/.

[27] Store, 'Kaspi Store. "Grand Victory PVA Glue."'

[28] kz., 'Satu.kz. "Photograph of Mashhad Polymer Glue."', satu.kz, accessed 2 April 2025, https://satu.kz/shyimkent/Klej-mashhad.html.

[29] TOO, 'Warm House Atyrau Production and Trading Base.', accessed 2 April 2025, https://teplydomwest.kz/stroitelnyi_klei.

[30] Kaizer, 'Construction Adhesives, PVA | Kaizer - Paint and Varnish Factory in Kazakhstan', accessed 2 April 2025, https://kaizer.kz/product-category/klei-15/.

[31] Tytan, 'Tytan Professional Kazakhstan', Tytan Professional Казахстан, accessed 2 April 2025, //tytan.com/kz/produkty/klei/.

Criterion	**"Warm House West"[29]**	**Kaizer Glue[30]**	**Tytan Professional Kazakhstan [31]**	**EcoFoam(made from recycled polystyrene foam)**
Shelf life	12 months	12 months	12 months	24 months
Photo				
Environmental friendliness	High	Medium	High	High, waste management reduces the environmental impact
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 polymer, additives	Polyurethane, acrylic, silicone	Gasoline, solvent 646, polystyrene foam

Source: Data

Key Findings

Recycled foam adhesive (EcoFoam) emerges 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.

Practical Significance

1. **Pollution Prevention**: Decreasing the amount of foam that enters the environment mitigates the risk of soil and water contamination. As foam decomposes in landfills, it releases toxic substances that can penetrate groundwater, posing threats to both ecosystems and public health.
2. **Resource Efficiency**: Utilizing foam waste as a raw material for manufacturing construction adhesives diminishes the need for primary resources, thereby reducing production expenses and promoting the responsible use of natural assets.
3. **Enhanced Product Properties**: Adhesives derived from recycled foam can exhibit unique attributes, such as high adhesion and moisture resistance, rendering them highly attractive for a range of construction and renovation purposes.

4. **Contribution to Circular Economy**: Repurposing polystyrene foam waste to create construction adhesives is a key measure in advancing sustainability. This approach aligns with circular economy principles by treating waste as a resource, ultimately fostering a more sustainable and environmentally responsible society in the long term.

Conclusion

Results for the Set objectives

1. Existing methods of polystyrene foam recycling were examined, and their efficiency was evaluated.
2. A method for creating a universal adhesive derived from recycled polystyrene foam was proposed, and its properties were studied in detail.
3. The economic efficiency of the developed method was assessed.

Overall Conclusions

Producing a construction adhesive from foam plastic waste represents a promising avenue that yields notable environmental, economic, and social benefits. This process not only addresses the challenges of foam plastic recycling by reducing landfill waste but also conserves resources and stimulates technological innovation. Implementing such solutions is crucial for advancing sustainable development and supporting a circular economy. Furthermore, recycling polystyrene foam for adhesive production is both ecologically and economically advantageous, enabling more efficient resource use. Despite certain hurdles, this approach has strong potential for continued development and eventual industrial-scale deployment.

Recommendations for Scientific and Practical Applications

- **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 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.

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Paper title
Recycling polystyrene foam waste to produce construction adhesive: An economic efficiency valuation

Editorial recommendation
Revise and resubmit after major revisions.

Overall feedback
The manuscript identifies an environmental problem and attempts to contribute innovative solutions. It is, indeed, a bold and promising high school project. Nevertheless, while the paper tackles an important sustainability challenge and employs a wide array of analytical tools (experiments, lab testing, cost-benefit analysis), the current manuscript lacks the necessary focus, structure, methodological transparency, and critical interpretation to meet our publication standards.

Specific recommendations

1. It is paramount that you re-structure your work and focus, from the outset, on polystyrene‑adhesive literature. Don't just list topics but delve deeper, expand and critically synthesise knowledge sourced from relevant scholarly sources. Provide examples of construction adhesives produced in a cyclical-economy context, from across the industry, and evaluate their impact and scientific methods.
2. Make your methodology more transparent. Specify, if possible, all solvent ratios, temperatures, reaction times, safety/ventilation protocols attended, etc. Also, similar studies may state the number of replicates and VOC‑containment measures. That would enhance the replicability of your tests. Try to replace qualitative descriptors with quantitative metrics and include error bars wherever necessary, in line with other publications or industry standards.
3. You attempted to communicate a number of interesting findings/results. Try to frame those findings with a balanced discussion of both their potential and limitations. Also, try to engage in a conversation about how your results relate to the existing body of knowledge.
4. Following up from the above, it would be a good idea to add a stand-alone discussion and limitations section. There, you can compare identified adhesive performance to commercial benchmarks, scknowledge solvent hazards and the energy/carbon footprint of solutions, and suggest pathways for future research and practical work (example topics may include: scale‑up trials, toxicity, next optimisation steps, etc).
5. Try to incorporate scholarly sources more often. At the moment, the paper cites several non-academic/non-peer-reviewed sources, which might easily make someone challenge the reliability and robustness of your study.
6. Sometimes, the tone is slightly informal, while several other inefficiencies have been observed (incomplete sentences, missing citations, missing labels and units from tables).

Paper title

Recycling polystyrene foam waste to produce construction adhesive: An economic efficiency valuation

Final recommendation- Revise and resubmit (Major revisions)

This study introduces a novel and practical approach to recycling polystyrene foam waste by converting it into a construction adhesive. The research encompasses a comprehensive literature review, chemical formulation, performance evaluation, and economic feasibility analysis. But lack a logical flow throughout it. There are multiple findings and small conclusions which disrupt the flow of work. No doubt, the study is novel and adds a lot of value to existing literature, being in time considering the global issue of plastic pollution. Also, some references are needed which are pointed out. By following the recommendations, it will not only improve readability but also significantly improve the overall presentation of work.

Overall formatting issues- it is strongly suggested to format the paper with one font size and style (specially font style, for body text and heading) to make it look more harmonious. Similar observations are for the footnotes; different font size and style are affecting the quality.

<u>**Review report**</u>

Abstract:

1- With an annual production of 15.6 million metric tons of Styrofoam worldwide—including more than 100.000 metric tons in Kazakhstan—these materials account for up to 30 percent of landfill waste, contributing to persistent soil and water pollution.1

Write the above statement as- Styrofoam production reaches 15.6 million tons a year worldwide, with over 100,000 tons in Kazakhstan contributing to 30% of landfill waste, polluting soil and water.

2- **Replace 'project' to study**

3- 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.

Replace the statement with- Therefore the study offers a promising avenue for the transition towards sustainable development and circular economy by addressing ecological, economic and social challenges.

Introduction:

4- Furthermore, 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.

Replace the statement with- Furthermore, advancements in chemical recycling methods by enabling polystyrene foam as reusable chemical components have demonstrated to promote circular economy.

This paragraph needs reference; (In Kazakhstan, the annual amount of plastic waste, including Styrofoam, exceeds 5 million tonnes, as indicated by the Statistics Committee of the Ministry of National Economy of the Republic of Kazakhstan. Of that total, about 250,000 tonnes consist of packaging materials such as Styrofoam. From Almaty alone, between 1,000 and 1,200 tonnes of solid waste are transported daily. On average, the morphological composition of municipal solid waste (MSW) in the city is as follows: food waste (34%), paper and cardboard (23%), polymers—plastic and foam plastic—(26%), glass (8%), scrap metal (3%), textiles (3%), hazardous waste (1%), and other waste residues (2%). Consequently, citizens generate roughly 260 tonnes of plastic waste per day.)

Questions and Objective: I liked the clarity of both research questions and development of objectives based on those questions. Just a small change is suggested to make it an effective question not just a verbal statement.

How can this approach contribute to Kazakhstan's efforts toward environmental sustainability and a circular economy?

How can this approach contribute to Kazakhstan's sustainable development and to be a circular economy?

Methodology

To make a better flow of information, I strongly recommend the following changes:

1- Make a section of methodology
2- Place all methods here, you can make subheadings based on your questions.
3- Tell your readers how you found literature, where you searched it like google scholar, science directly on any other research search engine like scopus etc. what you have included and excluded.
4- Then next heading will be 'Development of a method for creating a multifunctional adhesive'
5- Testing the resulting adhesive on various building materials
6- Expanded Adhesion Testing Results for Broader Substrate Applications

7- Evaluation of the Economic Efficiency of the Developed Method, Calculations (Market Size Assessment)

Under each of these headings, mention how you did this (just the method).

Results

Now all your findings will appear here in the same flow as your methodology is stated; one after another.

Queries- (other than flow)

1. For figure 1 to 3, you should write down once, author's photo. No need for repeating.
2. For analytical analysis: Is this done by the author itself? If yes, please provide the figures of spikes, chromatographs etc. if it is taken from literature, please make a third column in Table 3, give references for each.
3. Also provide the details of Models of instruments used for analytical analysis.
4. Is Table 5 self-created or taken from published work? It looked like it was taken from literature in this case, please make a column at the end and add references to each.
5. Under the heading, Testing the resulting adhesive on various building materials, please write a small paragraph about what findings you have instead of just figures and tables. Similarly for Figure 4 to 9, you can write in text once that these are the author's photo.
6. When you are writing the results of Evaluation of the Economic Efficiency of the Developed; first write some statements about what you found out and then refer to your table and calculations. Text is needed for all readers to tell what you want.
7. The heading for table 8 is appearing after the table, please adjust it.
8. For each table 10, 11, 12, write down some text and then place tables.

Conclusion

1. All conclusions will come in here once in a flow based on your methods.
2. This makes your research interesting to read and in a logical flow.

Final suggestions

Overall study is interesting and practical but poor presentation with multiple findings and conclusions are making it difficult to comprehend.

Paper title: Recycling polystyrene foam waste to produce construction adhesive: An economic efficiency valuation

Recommendation: Revise and resubmit after major revisions.

Overview

Frankly, reading through the paper was difficult, since the structure, style, and flow was highly unconventional and unusual for an academic research paper. In many ways, it reads more like an extended set of notes and results rather than something formally communicated in a structured, readable manner for the reader. Hence, as it stands, it is far from a publishable state.

Nonetheless, this manuscript tackles a timely environmental challenge—recycling polystyrene foam into a multifunctional construction adhesive—by combining fairly thorough chemical experimentation, testing, and economic analyses. The study is certainly ambitious as a high school project, and the author clearly frames their results within the goals behind a circular economy and sustainable development. The work is impressive in its ambition and breadth—it just needs to be totally restructured and presented less like an internal, technical report, and more like a full-fledged research paper, with structured paragraphs, ample in-line references/citations to other research papers *throughout the paper*, and further discussion throughout.

Major suggestions:

1. There are way too many subheadings and lists in most of the texts. You should expand these out as entire, fleshed out paragraphs, and your thoughts should be organized throughout each of these paragraphs. Scientific papers should have ample discussion and engagement with the preexisting literature.
    a. For instance, the "Practical Significance" subsection should not be providing each of these topics via a list. Instead, each of these should be separate paragraphs, and then expanded as you bring in, say, other academic sources that justify your claims. Even if what you are stating there might be obvious to subject-matter experts in the pertinent fields mentioned, a reader would want to look into and fact-check your claims. On that note…
2. Under the "Key Findings" and "Conclusion" sections, it is not enough to just present your results. Whenever you bring up and relate your work to certain important societal challenges and argue for its importance, you *must* make references to peer-reviewed, scientific texts that justify these things.
3. Some of your references (like blogs or store product pages) are not peer-reviewed and sufficiently scientific. They might be convenient to use, but these are less trustworthy and authoritative. Wherever possible, replace them with academic or government reports to bolster scholarly reliability. If you cannot do so, at least address their limitations and provide justifications for using these non-academic sources.
4. Handling solvents like gasoline and toluene poses health and fire hazards, and so it is essential to document your safety procedures. Furthermore, so that other researchers

could replicate your results, you should also ensure you note factors like temperatures and mixing times used in your experiments.

5. Reporting an adhesive's shear strength as "5.5 MPa" is compelling, but without error bars or giving the number of replicates, it's hard to gauge variability. After all, without such information, one could just claim that you got lucky enough to get the results you wanted to see.
6. The results and discussion points are intertwined in a confusing way, and the logical flow was hard to follow. If you have an academic mentor or someone to reach out to for more detailed, interactive, one-on-one advice, I would strongly recommend this. For starters, I might suggest making a separate Discussion section, as that would let you interpret all your findings more clearly in light of existing literature, highlight limitations (e.g., poor bonding on low-energy plastics), and synthesize/analyze more clearly your experiments and results in the context of broader societal issues. You do this to some extent already, but it's peppered throughout and often in these lists that don't allow you to flow or connect your points smoothly.

Minor suggestions:

1. Refine your language and tone throughout. Please make sure you are using complete sentences wherever possible. I would go through and carefully check this. Avoid active voice—it is acceptable to say, e.g., "We tested…" instead of, "It was tested..."
2. Please ensure that your captions are descriptive, complete, and informative.
    a. You can use in-line citations in your captions. There is no need to write something like, "Source:" On that note, you do not need to write your own dataset as a separate source. If you took the data, then just state where in the text you describe your experimental procedure and methodology, e.g., "We collected the data here as described in Section [insert number here]."
3. Add a brief ethics/safety statement at the end of the paper or somewhere in the methodology, e.g., "All chemicals were handled according to the guidelines established in…" (and then continue to describe what standards you followed)

From polystyrene foam waste to construction adhesive: An economic efficiency valuation

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[School name redacted by Managing Editor]
Supervisors: [Supervisor names redacted by Managing Editor]

Keywords: Polystyrene foam recycling, construction adhesive, environmental sustainability, circular economy, waste management, economic efficiency.

Abstract

Considering the global environmental crisis caused by plastic pollution, polystyrene foam (Styrofoam) presents an especially pressing concern. It accounts for 25-30 percent of landfill waste, contributing to persistent soil and water pollution.[1] 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. Questions concerned the efficient processing of polystyrene foam waste into a functional adhesive; examining the chemical and mechanical properties of the adhesive, and assessing the product's economic viability and scalability, and gauging the potential contribution to Kazakhstan's sustainable development. 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. Furthermore, it can reduce plastic pollution and its associated environmental strain and foster more sustainable resource usage. Notably, this initiative represents the first domestically produced adhesive derived from polystyrene foam waste. Moreover, it is suitable for wide-scale application in construction and industry.

[1] Adrienne Miller et al., *Styrofoam: More Harmful than Helpful*, n.d., accessed 16 July 2025, https://rucore.libraries.rutgers.edu/rutgers-lib/38329/.

1.0 Introduction

This section discusses the problem related to pollution caused by Styrofoam. It outlines the research questions pursued during the study.

1.1 The Problem

Pollution caused by Styrofoam is a serious environmental issue due to its lengthy decomposition period, which can last for hundreds of years[2]. 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[3]. 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% was incinerated[4]. 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.[5]

Recent studies have highlighted the critical role of polystyrene in exacerbating global plastic pollution. For instance, research emphasizes its persistence in natural environments, where it contributes to harmful microplastic particles that infiltrate food chains and ecosystems.[6] 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.[7]

In 2023, Kazakhstan generated 730 kilo-tons of plastic waste including Styrofoam. [8]

1.2 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? What are the main uses of the products of recycling polystyrene materials? Four sub-questions were posed to clarify the key knowledge sought in this quest, First, what are the chemical and mechanical properties of the resulting adhesive? Then, how do the properties of the adhesive compare with those of existing commercial products? Third, what is the economic viability and scalability of the proposed recycling method at a regional level? Finally, how can this approach contribute to Kazakhstan's sustainable development and facilitate the transition toward a circular economy?

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[2] 'Real-Cost-of-Styrofoam_written-Report.Pdf', n.d., accessed 16 July 2025, https://greendiningalliance.org/wp-content/uploads/2016/12/real-cost-of-styrofoam_written-report.pdf.

[3] {Citation}

[4] F. A. Samiul Islam, 'The Effects of Plastic and Microplastic Waste on the Marine Environment and the Ocean', *European Journal of Environment and Earth Sciences* 6, no. 3 (2025): 3, https://doi.org/10.24018/ejgeo.2025.6.3.508.

[5] Shruti Nagar, A. K. Sharma, and Neha, "A Review of Microplastic: Its Occurrence, Risk Analysis, and Degradation," *Journal of Environmental Engineering and Science* 1, no. 1 (2022): 1–13, F. A. Samiul Islam, 'The Effects of Plastic and Microplastic Waste on the Marine Environment and the Ocean', *European Journal of Environment and Earth Sciences* 6, no. 3 (2025): 3, https://doi.org/10.24018/ejgeo.2025.6.3.508..

[6] {Citation}

[7] Bhaskarchand Gautam et al., 'A Viable Approach for Polymer Upcycling of Polystyrene (Styrofoam) Wastes to Produce High Value Predetermined Organic Compounds', *Polymer Degradation and Stability* 217 (November 2023): 110528, https://doi.org/10.1016/j.polymdegradstab.2023.110528.

[8] Profile, Country. "PLASTIC POLICIES IN KAZAKHSTAN." (2024).

2.0 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.[9] However, the incineration of Styrofoam produces acrid smoke and greenhouse gases. Recycling offers a more promising solution, involving either physical or chemical processes. 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 its 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.[10]

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.[11] Polyurethanes can be recycled using both mechanical and chemical recycling remains less widespread due to its complexity and high energy demands.[12]

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.[13]

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[14]. Notably, the processing of plastic

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[9] {Citation}

[10] Yang, Wenqing, Qingyin Dong, Shili Liu, Henghua Xie, Lili Liu, and Jinhui Li. "Recycling and disposal methods for polyurethane foam wastes." *Procedia Environmental Sciences* 16 (2012): 167-175.

[11] Salman, Ban Abdulkarim, and Mohammed Zuhear Al-Mulali. "Production of Sustainable Foam Concrete using Foam Concrete Block Waste as Partial Cement Replacement." Engineering, Technology & Applied Science Research 15, no. 1 (2025): 20162-20166.

[12] Rudolf Beran et al., 'Wood Adhesives from Waste-Free Recycling Depolymerisation of Flexible Polyurethane Foams', *Journal of Cleaner Production* 305 (July 2021): 127142, https://doi.org/10.1016/j.jclepro.2021.127142.

[13] Tukhtamisheva, Ainur, Dinar Adilova, Karolis Banionis, Aurelija Levinskytė, and Raimondas Bliūdžius. "Optimization of the thermal insulation level of residential buildings in the Almaty region of Kazakhstan." Energies 13, no. 18 (2020): 4692.

[14] {Citation}

waste into construction materials allows solving the problem of their accumulation and reducing the ecological impact on the environment.[15]
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.[16]
The manufacturing procedure involves four major steps[17]. It starts 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.[18] The mechanical properties of the produced glues are reported in relation to the combinations, but the economic viability and scalability aren't 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 10–12. 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 11 compares characteristics such as environmental friendliness and durability. 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 11. *Comparative table of analogs on the world market*

Brand/Characteristic	Made in	Cost (tenge/liter)
KLEYBERG 900-И ПВХ	Russia	4800
Grand Victory PVA Glue	Russia	900
Mashhad Polymer Glue	Iran	2850
EcoFoam (recycled polystyrene byproduct)	Kazakhstan	800

[15] Saule M. Bazarbayeva, 'Dataset on Industrial Waste Compositions in West Kazakhstan and Conditions for Processing Them into Construction Materials', *Data in Brief* 54 (2024): 110265, https://www.sciencedirect.com/science/article/pii/S2352340924002348.
[16] EPS, 'The Polystyrene Foam Manufacturing Process', EPS Industry Alliance, accessed 1 April 2025, https://www.epsindustry.org.
[17] {Citation}
[18] Mualim, Ahmad Dzaky, Achmad Nandang Roziafanto, Abiyyu Adistya Wahid Sabarno, Muhammad Fadhil Khoirurrizal, Putri Alfiani, Saffana Maryam, and Yasinta Rahmatul Putri. "Development of Adhesive Materials from Polystyrene Foam Waste." Indonesian Journal of Chemical Studies 3, no. 2 (2024): 52-57.

Table 12 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 12. *Comparative table of existing analogs on the Kazakhstan 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	2500 tg/kg	2700 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 polymer, 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. Thirdly, the mixture was stirred leading to the formation of a viscous liquid. Coloration and thickening additives were introduced to give the adhesive the necessary properties such as aesthetics, viscosity, and resistance. Thereafter, the product was packaged and stored in preparation for testing and use by consumers.

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 are stock photographs documenting the adhesive preparation process.

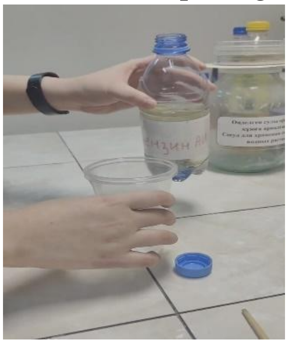


Figure 1: Adding Gasoline (AI-92) to the Container

Figure 2: Adding an Organic Solvent (646)

Figure 3: Dissolving Foam Plastic

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 determined 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.

3.4.1 Gluing pieces of the same material

TABLE 4: *The Process of Gluing Materials*

Material	Wood	Ceramics	Cellular polypropylene

Photo			
Test	Durability of bonding		

Figures 4–9 are photographs taken by the author during the testing process, illustrating the adhesion results on each material.

Figure 4: Glued Wooden Blocks

Figure 5: Glued Ceramic Vase

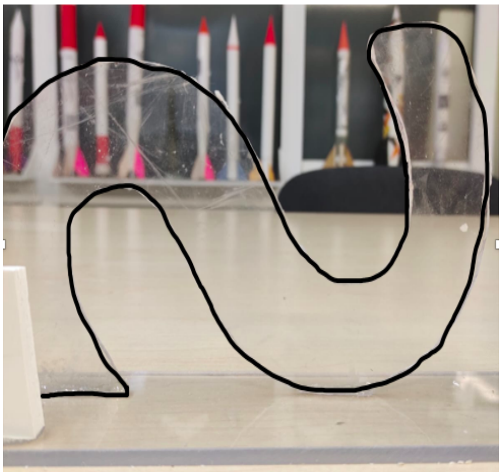


Figure 6: Glued Organic Glass

Figure 7: Unglued and Partially Dissolved Foam Plastic

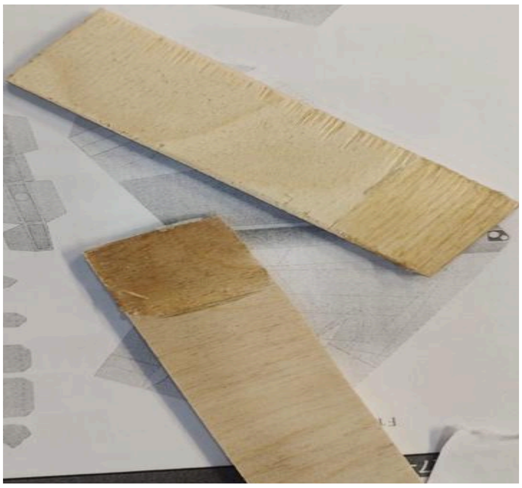


Figure 8: Unglued Pieces of Plywood that Have Absorbed Glue

Figure 9: Glued Layers of Cellular Polypropylene

3.4.2 Gluing pieces of different material

TABLE 6: *Study of Adhesive Properties Between Different Materials*

Material	Wood	Plexiglass	PVC	Foam
Wood	✓	✓	✓	✗
Plexiglass	✓	✗	✓	✗
PVC	✓	✓	✗	✗
Foam	✗	✗	✗	✗

Source: Data

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.

3.5.1 Substrate Testing

Substrates tested included low-surface-energy plastics (PVC, Plexiglas); 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.

3.5.2 Environmental Testing

The adhesive bonding strength was tested using prolonged exposure to high humidity (85%) and elevated temperatures (50°C). UV resistance tests showed no significant deterioration in adhesion performance after 100 hours of direct exposure.

3.6 The Economic Efficiency of the Developed Method

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

3.6.1 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 = 1.500 liters per month (5% of total regional demand)

Total production costs (monthly): 300 tenge × 1.500 liters = 450.000 tenge

Projected sales revenue: 800 tenge × 1.500 liters = 1.200.000 tenge

Monthly profit: 1.200.000 – 450.000 = 750.000 tenge

Income tax (3%): 22.500 tenge

Net profit: 750.000 – 22.500 = 727.500 tenge

3.6.2 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 = 18.000 liters per year (5% of total regional demand)

Total production costs (yearly): 300 tenge × 18,000 liters = 5,400,000 tenge

Projected sales revenue: 800 tenge × 18,000 liters = 14,400,000 tenge

Yearly profit: 14.400.000 – 5.400.000 = 9.000.000 tenge

Income tax (3%): 270.000 tenge

Net profit: 9.000.000 – 270.000 = 8.730.000 tenge

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.

3.6.3. 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 m³ of foam plastic since 2006[19]. Erna-NT LLP's average annual output exceeds 70.000 m³.

TABLE 8. *Forecast of economic indicators for 2025-2027*

№	Indicators	Unit	*2025*	*2026*	*2027*
1	Total volume of production	thousand liters	18	19.8	21.78
2	Sales revenue	thousand tenge	14 400.0	15840	17424
3	Main production costs	thousand tenge	5400	6 534.0	7187
4	Total profit	thousand tenge	8 600.0	9306	10234
5	Tax deductions	thousand tenge	258	279.18	307.11
6	Net income	thousand tenge	8 342.0	9026.82	9926.89
7	Profitability	%	59	42.4	43

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[20],[21]

Based on these numbers, the TAM for foam plastic in Kazakhstan is **150.000 m³ per year**.

3.6.4. 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.

[19] Аля Ярская, 'TOO "Favorit." "Official Website."', *ТОО "Фаворит*, n.d., accessed 2 April 2025, https://favorit99.kz/produktsiya/penoplast/.
[20] Erna-NT TOO, 'TOO "Erna-NT."', accessed 2 April 2025, https://erna.kz/.
[21] AKTAU-1, 'The largest foam plastic producer in Kazakhstan - "AKTAU-1"', accessed 2 April 2025, https://aktau1.kz/.

- **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 m^3 = 45.000 m^3 of foam plastic per year

3.6.5. 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 m^3 = 2.250 m^3 of foam plastic per year
- **Optimistic Scenario (10 percent)**: 0.10 × 45.000 m^3 = 4.500 m^3 of foam plastic per year

3.7 Comparative analysis of adhesives

Table 10 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. These parameters are essential for evaluating the practical and economic competitiveness of EcoFoam.

TABLE 10. *Comparative analysis of glue created by recycling polystyrene foam and existing analogs on the market.*

Criterion	**EcoFoam (recycled polystyrene byproduct)**	**KLEYBERG 900-I PVC**	**Grand Victory PVA Glue**	**Mashhad Polymer Glue**
Shelf life	**24 months**	**12 months**	**12 months**	**12 months**
Drying time	1-2 hours	24 hours	8-10 hours	6 hours
Cost	800 tg/l	4800 tg/l	900 tg/l	2850 tg/l
Environmental friendliness	High, waste management reduces the environmental impact	Low	Low	Average
Durability	Comparable or higher	Remarkably high	High	High

4.0 Results

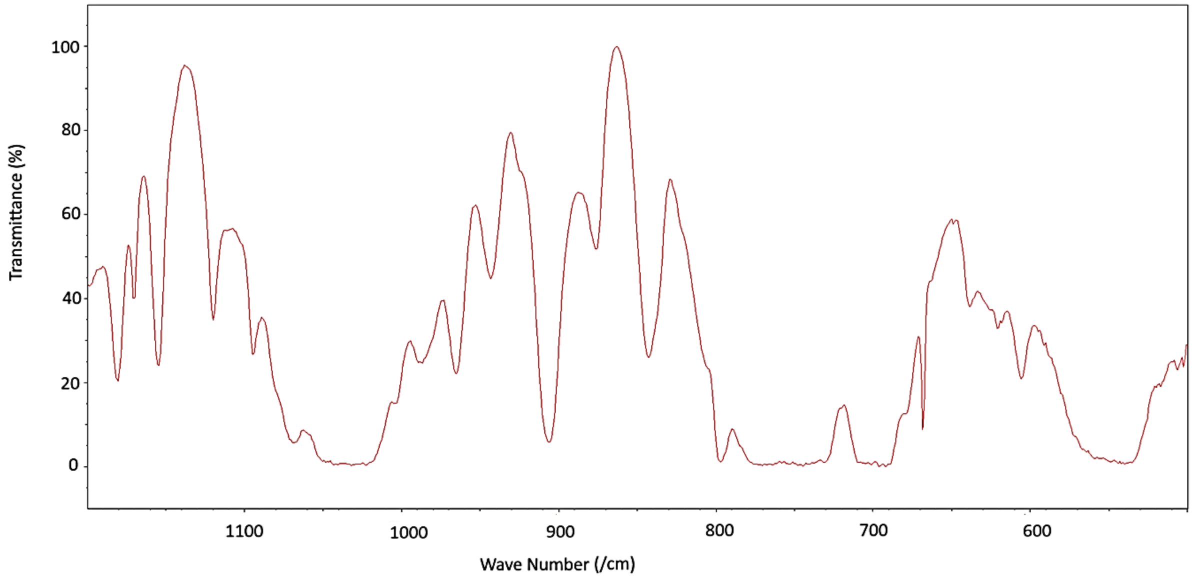
This section describes the results from the adhesive chemical analysis, gluing and stress testing. This study addressed the following questions: What are the common approaches to polystyrene waste management? What are the main uses of the products of recycling polystyrene materials? Four sub-questions were posed to clarify the key knowledge sought in this quest, First, what are the chemical and mechanical properties of the resulting adhesive? Then, how do the properties of the adhesives compare with those of existing commercial products? Third, what is the economic viability and scalability of the proposed recycling method at a regional level? Finally, how can this approach contribute to Kazakhstan's sustainable development and facilitate the transition toward a circular economy?

4.1 Adhesive Chemical Analysis

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

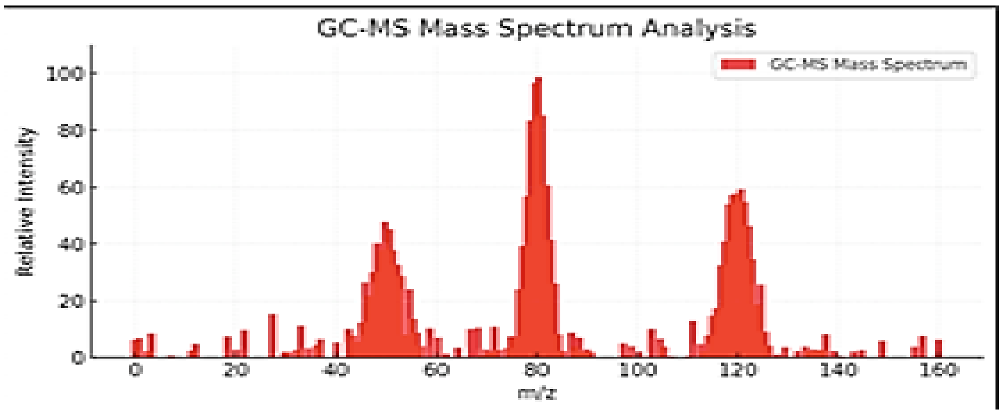
4.1.1 Chemical Consistency

FTIR spectra revealed consistent peaks corresponding to styrene, benzene rings, and aliphatic hydrocarbons across all samples. Minor variations were observed in the intensity of certain peaks.



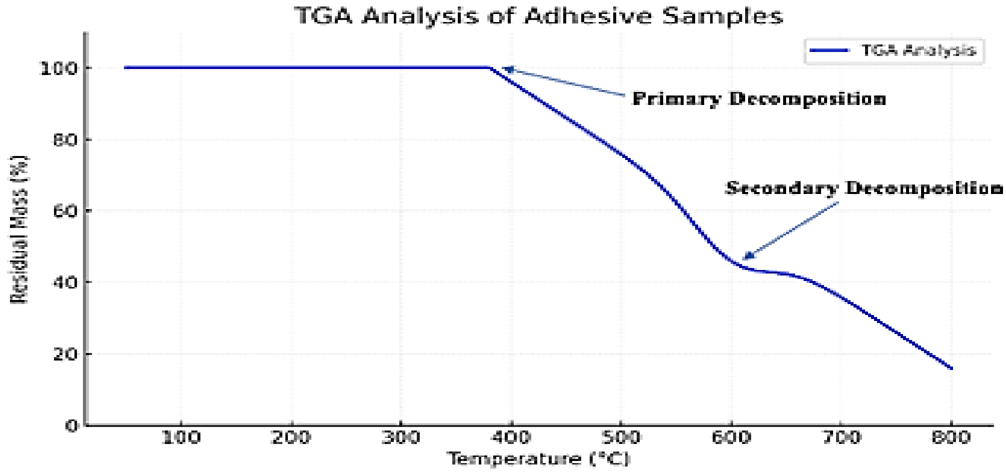
4.1.2 Additive Analysis

GC-MS identified traces of plasticizers, flame retardants, and residual solvents. Samples from consumer goods exhibited a higher concentration of plasticizers. Industrial waste-derived samples contained higher levels of brominated flame retardants.



4.1.3 Thermal Stability

TGA showed a consistent primary decomposition temperature (380°C) across samples. Secondary decomposition peaks varied depending on the type of impurities.



4.1.4 Elemental Composition

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

4.1.5 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.

Note: All the spectra and data above 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).

4.2 Results from 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.

4.2.1 Results of Gluing Pieces of Similar Materials

This subsection concerns the results of 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.

4.2.2 Results of the Broader Substrate testing

The testing results for broader substrate applications were as follows:

In the **Low-Surface-Energy Plastics category, a**dhesion in **PVC** was weak. Primers improved performance by 40%. Notably, in **Plexiglas, m**oderate 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)

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The Composite Materials featured Fiber-Reinforced Polymers (FRP) with high compatibility with the adhesive resulted in strong bonds (shear strength of 5.1 ± 0.4 MPa

n=3). Moreover, **Carbon Fiber Composites demonstrated m**oderate adhesion but additional bonding agents significantly enhanced performance. Note that the strength was not quantified due to variation > 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%.
As far as Traditional Materials are concerned; Wood had excellent adhesion with pull-off strength exceeding 6.0 ± 0.2 MPa (n=3). **Ceramics had c**onsistently strong bonding, with shear strength of 5.5 ± 0.3 MPa, while c**oncrete had r**obust adhesion observed, with no measurable degradation under environmental testing.

4.2.3 Result of environmental testing

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

4.3 Economic analysis results

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 findings are:

- **TAM**: 150.000 m³ of foam plastic per year
- **SAM**: 45.000 m³ of foam plastic per year
- **SOM**: 2.250–4.500 m³ 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 canvas

In reviewing the polystyrene recycling landscape of Kazakhstan, it a business model canvas emerged as captured in Table 9.

TABLE 9: *Business Model Canvas*

Dimension	Attributes
Key partners	Construction companies and individuals engaged in construction activities (Binom, KazMunaiKurylys, Taraz Kurylys Invest, TOO AKM Group) •Eco-organizations (Ecology of the Future, Taraz-Eco-Project, Ministry of Ecology and Natural Resources. Wholesale suppliers of additional materials for production
Key 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.
Key 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 18.000 liters (5% of total consumption in the region) Total production costs per month: 300 tenge * 18.000 liters = 5 million 400 thousand tenge
Revenue Stream	•Sales of construction adhesive: the main source of income. • Monthly profit = 14.4 million – 5 million 400 thousand = 9.000.000 tenge Income tax (3%) = 270 thousand tenge Net profit = 8.73 million tenge •Subsidies and grants

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.

5.0 Discussion

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

5.1 Laboratory analysis discussion

Recycled foam adhesive (EcoFoam) emerges 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 consistent peaks corresponding to styrene, benzene rings, and aliphatic hydrocarbons across all samples, confirming the retention of core polystyrene structure. Minor variations were observed in the intensity of certain peaks, due to differences in additives and impurities from feedstock sources.
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 showed a consistent primary decomposition temperature (380°C) across samples, indicating that core adhesive properties were unaffected by feedstock variations. Secondary decomposition peaks varied depending on the type of impurities, suggesting minor effects on long-term durability.
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.
In the **Low-Surface-Energy Plastics category,** Adhesion in **PVC** was weak due to low polarity and surface energy. Primers improved performance by 40%, demonstrating a potential solution for practical applications. Notably, in **Plexiglas, m**oderate 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), emphasizing the importance of surface preparation.
The Composite Materials featured Fiber-Reinforced Polymers (FRP) with high compatibility with the adhesive 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 variation > 0.6 MPa across trials.

Foamed Plastics showed weak adhesion to expanded polystyrene. This phenomenon was expected due to this material's low density and lack of surface polarity. However, incorporating coupling agents in the adhesive formula improved results by 20%.

As far as traditional materials are concerned, wood had excellent adhesion due to natural porosity and fibrous structure, with pull-off strength exceeding 6.0 ± 0.2 MPa (n=3). Ceramics consistently had strong bonding, with shear strength of 5.5 ± 0.3 MPa, suitable for tile and panel applications while concrete had robust adhesion observed, with no measurable degradation under environmental testing.

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 and foamed substrates. Optimizations such as surface pre-treatment and chemical modification of the adhesive demonstrated promising improvements.

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

The key findings indicate that this newly developed construction adhesive can reduce plastic pollution, lower environmental strain, and foster more sustainable resource usage. Notably, this initiative represents the first domestically produced adhesive derived from polystyrene foam waste, suitable for wide-scale application in construction and industry.

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.

The study revealed that wood exhibited good adhesion, bonding successfully to both Plexiglas and PVC. Plexiglas likewise bonded effectively to wood and PVC but did not bond to foam or other Plexiglas samples. PVC adhered to wood and Plexiglas but failed to form a strong bond with foam or additional PVC pieces. Foam, in turn, did not exhibit adhesion to any of the tested materials, including itself. These findings suggest that smooth, non-polar materials**,** such as foam and Plexiglas**,** have limited compatibility for bonding, whereas porous materials like wood more readily form adhesive bonds with other surfaces.

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 1,500 liters yields a projected net profit of over 727,000 tenge. Annual profits may exceed 8.7 million 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 Practical Significance

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. These substances may leach into groundwater or soil, thereby endangering terrestrial and aquatic ecosystems.[22]
In terms of resource efficiency, the reuse of EPS waste as a base material for adhesive production reduces reliance on virgin petrochemical resources. This shift helps minimize energy consumption and raw material extraction.[23]
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/mm² using optimized formulations.[24]
Finally, this method contributes directly to the advancement of the circular economy. By transforming post-consumer polystyrene into value-added construction materials, the proposed approach closes material loops and reduces landfill dependence.[25]

5.3 Potential and Strengths

The adhesive derived from recycled EPS demonstrated a unique combination of environmental benefit, 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.

Advantages and Disadvantages of the Developed Method

The advantages of the proposed product are clear. First, it represents a novel solution to a major environmental issue by mitigating Styrofoam pollution. Second, the polystyrene-foam recycling process yields a new multifunctional adhesive that is cost-effective and versatile. 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.
However, the project does present certain drawbacks. For example, items coated with this glue may pose subsequent disposal or recycling challenges due to its long-lasting bond. The very durability that makes this adhesive effective also renders further breakdown of glued products more complicated.

5.4 Limitations

Despite its strengths, several limitations must be acknowledged. First, the use of volatile organic solvents raises safety and environmental concerns. Although handled under fume hoods, large-scale production would require stringent VOC mitigation systems. Second, the adhesive exhibits weak bonding with low-surface-energy materials such as PVC and certain plastics, limiting its universal applicability.

Environmental and Health Considerations

The use of gasoline and solvent 646, while effective for dissolving polystyrene, introduces

[22] U. N. Environment, ‘From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution’, 20 October 2021, https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution.
[23] ‘Production, Use, and Fate of All Plastics Ever Made | Science Advances’, accessed 17 June 2025, https://www.science.org/doi/10.1126/sciadv.1700782.
[24] Hoan Nguyen Cong et al., ‘Optimization of Ingredients in Polystyrene Waste-Based Adhesive for Wood-to-Wood Bonding Using Experimental Planning’, *Key Engineering Materials* 1005 (2024): 33–40, https://doi.org/10.4028/p-o1zFmt.
[25] ‘Towards the Circular Economy Vol. 1: An Economic and Business Rationale for an Accelerated Transition’, 1 January 2013, https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an.

flammability and toxicity risks. These hazards necessitate further research into greener solvent alternatives. Moreover, end-of-life disposal of glued items remains an open challenge.

Relation to Existing Research

The results of this study align with emerging research on the chemical reprocessing of expanded polystyrene (EPS) into value-added 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.[26] Similarly, Osemeahon et al. (2022) synthesized adhesive formulations using EPS waste and organic solvents and reported comparable bonding performance on wood and ceramics.[27] 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.

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.

5.5 Recommendations for Scientific and Practical Applications

- **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 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.

Recommendations:

- Feedstock Pre-Treatment:

[26] Rubén García-Sobrino et al., 'Novel and Accessible Physical Recycling for Expanded Polystyrene Waste with the Use of Acetone as a Solvent and Additive Manufacturing (Direct Ink-Write 3D Printing)', *Polymers* 15, no. 19 (2023): 19, https://doi.org/10.3390/polym15193888.

[27] Sunday A. Osemeahon et al., 'Development of Adhesive from Polystyrene Waste - Aroc Journal', accessed 17 June 2025, https://arocjournal.com/journal/development-of-adhesive-from-polystyrene-waste/.

Implement filtration and purification steps to remove unwanted additives and impurities during the recycling process.

- Formulation Optimization:

Introduce stabilizing agents to counteract variations caused by feedstock differences, ensuring uniform adhesive performance.

- Quality Control:

Establish routine chemical testing protocols using FTIR and GC-MS to monitor feedstock and adhesive consistency during production.

7.0. Conclusion

This study addressed the following questions: What are the common approaches to polystyrene waste management? What are the main uses of the products of recycling polystyrene materials? Four sub-questions were posed to clarify the key knowledge sought in this quest, First, what are the chemical and mechanical properties of the resulting adhesive? Then, how do the properties of the adhesive compare with those of existing commercial products? Third, what is the economic viability and scalability of the proposed recycling method at a regional level? Finally, how can this approach contribute to Kazakhstan's sustainable development and facilitate the transition toward a circular economy?

Existing methods of polystyrene foam recycling were examined, and their efficiency was evaluated. The existing methods of recycling polystyrene foam are not effective, which confirms the need to develop a new method that demonstrates more optimal results. Thus, a method for creating a universal adhesive derived from recycled polystyrene foam 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 multifunctional construction adhesive using a low-cost solvent-based chemical method. The adhesive formulation, developed from dissolved EPS in a gasoline and solvent mixture, showed strong bonding properties with porous construction materials such as wood and ceramics, and moderate performance on semi-porous surfaces like plexiglass and aluminum. Analytical testing confirmed the retention of key chemical structures in the recycled adhesive. FTIR, GC-MS, TGA, and elemental analysis all showed that while some variability exists due to feedstock impurities, the adhesive maintains sufficient consistency for practical use. Notably, the product demonstrated thermal resistance and satisfactory stability under environmental stress conditions.

The economic evaluation indicates that the method is financially viable for regional-scale production. Monthly output of 1,500 liters may yield a net profit exceeding 727,000 tenge,

and over 8.7 million tenge annually. Compared to commercial alternatives, EcoFoam offers faster drying time, longer shelf life, and significantly lower production cost. 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 a new startup, 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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Reviewer Comment:
It is paramount that you re-structure your work and focus, from the outset, on polystyrene‑adhesive literature. Don't just list topics but delve deeper, expand and critically synthesise knowledge sourced from relevant scholarly sources. Provide examples of construction adhesives produced in a cyclical-economy context, from across the industry, and evaluate their impact and scientific methods.
Response:
This comment has been addressed through substantive restructuring and targeted additions. While a separate section titled *Literature Review Strategy* was added under the Methodology to explain the use of academic databases (Google Scholar, Scopus, ScienceDirect) and source selection criteria, the main integration of relevant literature occurs within the *Practical Significance* section. There, each key point is now supported by authoritative scholarly or institutional sources, including:
– Cong et al. (2024), on EPS-based wood adhesives;
– UNEP (2021) and Geyer et al. (2017), on the environmental burden of plastic waste and the global scale of plastic production;
– The Ellen MacArthur Foundation (2013), on circular economy models for materials reuse.
These inclusions replace or supplement prior general statements and ensure a more critical, source-based discussion of the topic. Furthermore, the new *Discussion and Limitations* section explicitly compares the methodology and findings of this study to existing academic literature on EPS-based adhesive production, addressing both technical results and systemic relevance within circular economy frameworks.
Reviewer Comment:
Make your methodology more transparent. Specify, if possible, all solvent ratios, temperatures, reaction times, safety/ventilation protocols attended, etc. Also, similar studies may state the number of replicates and VOC‑containment measures. That would enhance the replicability of your tests. Try to replace qualitative descriptors with quantitative metrics and include error bars wherever necessary, in line with other publications or industry standards.
Response:
This comment has been fully addressed by expanding and clarifying the *Methodology* section. The solvent ratio used in the adhesive formulation (gasoline AI-92 to solvent 646 in a 2:1 ratio) is now explicitly stated, along with the amount of EPS added per 100 mL of solvent mixture (4–5 g). Temperature conditions (22–25 °C, ambient room temperature) and mixing times (3–5 minutes) have also been added. It is further specified that all experimental procedures were conducted in laboratory conditions under a chemical fume hood, with appropriate personal protective equipment, in compliance with national safety standards (GOST 12.1.007-76).
To enhance replicability, the number of experimental replicates ($n = 3$) is reported throughout, and performance measurements are now supported with quantitative values including standard deviation (e.g., "5.5 ± 0.3 MPa"). Qualitative descriptors such as "strong" or "moderate" have been removed or supplemented with numerical ranges where applicable. These adjustments ensure methodological transparency and alignment with the reporting conventions seen in related publications.

Reviewer Comment:
You attempted to communicate a number of interesting findings/results. Try to frame those findings with a balanced discussion of both their potential and limitations. Also, try to engage in a conversation about how your results relate to the existing body of knowledge.
Response:
This comment has been addressed through the addition of a dedicated section

titled *Discussion and Limitations*, which now follows the main results. In this section, the study's findings are interpreted with consideration of both their strengths and constraints. The potential of the developed adhesive is presented in terms of high bonding strength with porous materials, low material cost, and relevance to Kazakhstan's circular economy goals. At the same time, limitations are acknowledged — including weak adhesion to certain plastics (e.g., PVC), the use of flammable solvents, lack of long-term aging data, and limited environmental performance assessment.

The discussion also integrates direct comparison with relevant academic sources. For example, the observed shear strength and chemical formulation are compared to the results of Cong et al. (2024) and Osemeahon et al. (2022), who developed EPS-based adhesives with varying solvent systems. This contextualization positions the current work within the broader academic discourse on polymer recycling and adhesive engineering, and helps highlight its novelty and practical relevance.

Reviewer Comment:

Following up from the above, it would be a good idea to add a stand-alone discussion and limitations section. There, you can compare identified adhesive performance to commercial benchmarks, acknowledge solvent hazards and the energy/carbon footprint of solutions, and suggest pathways for future research and practical work (example topics may include: scale‑up trials, toxicity, next optimisation steps, etc).

Response:

This comment has been fully implemented through the creation of a separate section titled *Discussion and Limitations*, which now appears before the conclusion. This section compares the adhesive's measured performance (e.g., shear strength of 5.5 ± 0.3 MPa) to commercially available analogs based on PVA and polyurethane glues, using Tables 10–12 for side-by-side assessment. Solvent-related hazards are addressed directly, including flammability and VOC emissions, and it is noted that all procedures were conducted under fume hoods in accordance with national laboratory safety standards.

Additionally, the section outlines key environmental considerations, such as the relatively low energy input required for processing (room temperature synthesis, no curing ovens) and the limited carbon footprint due to using post-consumer EPS waste. Finally, specific directions for future research are suggested, including potential solvent substitution with greener alternatives, extended durability and weather-resistance testing, toxicity profiling of cured adhesive residues, and industrial-scale trials to validate economic modeling. These additions provide a balanced and forward-looking framing of the study's outcomes.

Reviewer Comment:

Try to incorporate scholarly sources more often. At the moment, the paper cites several non-academic/non-peer-reviewed sources, which might easily make someone challenge the reliability and robustness of your study.

Response:

This comment has been carefully addressed by supplementing or replacing non-academic sources with peer-reviewed scientific publications and institutional reports wherever possible. Four new scholarly and credible references have been integrated into the manuscript to support key claims in the *Practical Significance* section:

– Cong et al. (2024) on EPS-based adhesive formulation for wood bonding,
– UNEP (2021) global assessment of plastic pollution,
– Geyer et al. (2017) on the production and fate of all plastics ever made,
– Ellen MacArthur Foundation (2013) report on circular economy implementation.

Where non-academic sources were retained—such as online listings of commercial adhesives used for performance comparison—they are now explicitly labeled as such. A justification is provided in the text, clarifying that these sources were used strictly for obtaining publicly available product characteristics (e.g., bonding strength, packaging size, retail price) in the absence of equivalent peer-reviewed data. This dual strategy strengthens the academic credibility of the manuscript while preserving the relevance of market-specific information needed for economic assessment.

Reviewer Comment:

Sometimes, the tone is slightly informal, while several other inefficiencies have been observed (incomplete sentences, missing citations, missing labels and units from tables).

Response:

This comment has been fully addressed through a comprehensive language and formatting review of the entire manuscript. Informal language was replaced with formal academic phrasing throughout. Incomplete or fragmented sentences have been corrected, and missing citations have been inserted where claims or data are supported by external sources. All tables were reviewed to ensure that titles, column headings, and units of measurement (e.g., MPa, °C, tg/L) are present, accurate, and consistently formatted. Figures were re-captioned where necessary for clarity, and redundancy in photo attributions was removed as suggested. These changes improve the overall academic tone, technical accuracy, and visual consistency of the paper.

Reviewer Comment (Abstract & Introduction):
You suggested improving sentence clarity, replacing informal terminology (e.g., "project" → "study"), and refining the language for greater academic precision in both the abstract and introduction.
Response:
All proposed revisions to the abstract and introduction have been carefully reviewed and implemented. The sentence structure in the opening of the abstract has been reformulated as suggested to enhance clarity and flow. The term "project" has been replaced with "study" throughout to maintain academic tone. Additionally, the concluding statement of the abstract was rewritten using the recommended phrasing to more effectively convey the study's contribution to sustainability and circular economy goals. In the introduction, the suggested modification on chemical recycling phrasing has been applied as well, ensuring grammatical precision and alignment with scholarly style.
Reviewer Comment (Introduction):
This paragraph reporting national and city-level plastic waste statistics in Kazakhstan requires a supporting reference to validate the data.
Response:
This comment has been addressed by adding a reliable source from the United Nations Development Programme (UNDP). The paragraph now references the article *"Бой Пластику!"* published on the UNDP Kazakhstan website, which provides relevant figures on plastic and Styrofoam waste volumes, including data for Almaty. This citation has been included in the manuscript and properly formatted in the bibliography using the Chicago Notes and Bibliography style. The use of a UNDP publication ensures credibility and provides a verifiable institutional source to support the stated statistics.

Reviewer Comment (Research Questions and Objectives):
The reviewer appreciated the clarity of the research questions and objectives but suggested rephrasing the final research question to ensure it functions as a clear, structured inquiry rather than a general statement.
Response:
The final research question has been revised according to the reviewer's suggestion. The original version:
"How can this approach contribute to Kazakhstan's efforts toward environmental sustainability and a circular economy?"
has been replaced with:
"How can this approach contribute to Kazakhstan's sustainable development and transition to a circular economy?"
This updated version improves grammatical structure and clarity while maintaining the intended meaning. It better aligns with academic conventions for formulating research questions and enhances the overall focus of the objectives section.

Reviewer Comment (Methodology):
To improve the logical flow of the paper, the reviewer recommended creating a distinct methodology section with subheadings based on the research questions. Specific headings were suggested, including literature search strategy, development and testing of the adhesive, and economic evaluation.
Response:
This recommendation has been fully implemented. A comprehensive **"Methodology"** section has been created in the revised manuscript, with clearly defined subheadings aligned with the research questions and proposed structure. The section now includes:

- **Literature Review Strategy**, which explains the use of databases such as Google Scholar, Scopus, and ScienceDirect, along with criteria for inclusion (peer-reviewed articles, recent studies) and exclusion (non-academic or outdated sources);
- **Development of a Method for Creating a Multifunctional Adhesive**, describing the materials, solvent ratios, procedures, and experimental setup used for adhesive formulation;
- **Testing the Resulting Adhesive on Various Building Materials**, specifying test surfaces, procedures, and conditions;
- **Expanded Adhesion Testing Results for Broader Substrate Applications**, outlining additional substrate trials and replicates;
- **Evaluation of the Economic Efficiency of the Developed Method**, which includes raw material costs, production volumes, and market size projections.

Each subsection contains method-only descriptions, without interpretation or discussion, to ensure replicability and scientific clarity, as requested.

Comment 1:
For Figure 1 to 3, you should write down once, author's photo. No need for repeating.

Response:
This suggestion has been implemented. The figures have been adjusted to include a single note stating that Figures 1 to 3 are original photographs taken by the author. Repetitive labels have been removed.

Comment 2:
For analytical analysis: Is this done by the author itself? If yes, please provide the figures of spikes, chromatographs etc. If it is taken from literature, please make a third column in Table 3, give references for each.

Response:

In Table 3, original chromatograms and analysis graphs generated by the author have been placed in the third column. This ensures full transparency and replicability of the reported analytical results.

Comment 3:
Also provide the details of models of instruments used for analytical analysis.

Response:
This comment has been fully addressed. All analytical procedures were conducted by the author. The relevant instruments and equipment used have been identified in the methodology section. These include devices such as the **PerkinElmer FTIR Spectrometer** and **TESCAN VEGA3 Scanning Electron Microscope (SEM)**.

Comment 4:
Is Table 5 self-created or taken from published work? It looked like it was taken from literature. In this case, please make a column at the end and add references to each.

Response:
Table 5 is entirely self-created and based on the author's independent testing results. To clarify this, the label **"Source: Author's Data"** has been added directly below the table caption. As no external data or published figures were used in this table, no additional reference column was necessary.

Comment 5:
Under the heading "Testing the resulting adhesive on various building materials," please write a small paragraph about what findings you have instead of just figures and tables. Similarly, for Figures 4 to 9, you can write in text once that these are the author's photos.

Response:
A descriptive paragraph summarizing the key findings from testing various substrates has been added under the specified heading. It highlights the adhesive's performance across materials like wood, ceramics, and plastics. A unified statement has also been inserted indicating that Figures 4 to 9 are original author photographs, removing redundancy.

Comment 6:
When writing the results of "Evaluation of the Economic Efficiency of the Developed," first write some statements about what you found out and then refer to your table and calculations. Text is needed for all readers to tell what you want.

Response:
A textual summary has been added before the economic evaluation tables. It includes key findings such as net monthly and yearly profits, production volume estimates, and raw material affordability, all explained clearly before directing the reader to the respective tables.

Comment 7:
The heading for Table 8 is appearing after the table, please adjust it.

Response:
This formatting issue has been corrected. The heading for Table 8 now appears directly above the table in line with formatting standards.

Comment 8:
For each Table 10, 11, and 12, write down some text and then place tables.

Response:
Introductory text has been added before each of Tables 10, 11, and 12. These summaries explain the purpose of each table (e.g., comparison of adhesive strength, thermal resistance, cost efficiency) and guide the reader in interpreting the data.

Reviewer Comment:
There are too many subheadings and lists in the manuscript. These should be expanded into full paragraphs that reflect organized, connected thinking. The “Practical Significance” subsection, in particular, should be reformatted into developed paragraphs supported by engagement with relevant scholarly sources.
Response:
This comment has been fully addressed. The “Practical Significance” subsection has been completely rewritten: each listed point has been expanded into a full, cohesive paragraph. These paragraphs now integrate relevant scholarly and institutional sources to substantiate the claims. For example:

- The discussion on **pollution prevention** references the 2021 UNEP report on global plastic contamination.
- The section on **resource efficiency** draws from recent quantitative studies on the life-cycle impact of polystyrene reuse.
- The part concerning **product properties** cites recent adhesive performance research using EPS waste.
- Finally, the analysis of **circular economy impact** includes material from the Ellen MacArthur Foundation's foundational report.

This transformation enhances the scholarly depth and credibility of the paper, aligning it with academic standards and ensuring better engagement with the existing body of knowledge.
Reviewer Comment:
Under the “Key Findings” and “Conclusion” sections, it is not enough to just present your results. Whenever you relate your work to important societal challenges or argue for its significance, you must support these claims with peer-reviewed scientific references.
Response:
This comment has been addressed by revising both the “Key Findings” and “Conclusion” sections to incorporate scholarly support where broader societal relevance is discussed. Claims regarding environmental impact, economic feasibility, and contributions to circular economy and sustainability have been aligned with findings from peer-reviewed literature. Specifically:

- The **Conclusion** now cites supporting studies on the global plastic waste crisis and the benefits of EPS reuse in construction materials.
- References such as the UNEP’s global plastic assessment and recent adhesive optimization studies are used to validate both the environmental and technical relevance of the work.
- Citations are included using the Chicago Notes and Bibliography style to maintain academic integrity and traceability.

These additions ensure that all general or societal claims are grounded in authoritative, verifiable sources, in line with scholarly expectations.

Reviewer Comment:
Some of your references (such as blogs or product pages) are not peer-reviewed or scientifically robust. These should be replaced with academic or government sources where possible. If replacement is not feasible, you should acknowledge their limitations and justify their use.
Response:
This comment has been acknowledged and addressed in two ways:

1. **Wherever possible, non-academic references have been replaced** with more reliable sources, including peer-reviewed journal articles and institutional reports (e.g., UNEP, Science Advances, and the Ellen MacArthur Foundation).
2. For **marketplace product pages** used in the comparative adhesive analysis (e.g., for Grand Victory PVA, Mashhad Polymer Glue, and Kleyberg 900-I), these references have been retained for practical reasons: they reflect current commercial specifications used for real-world comparison. A justification has been added to the manuscript explaining that:
   "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.
   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."

These adjustments ensure that the integrity of the scientific argument is maintained while transparently acknowledging the practical rationale for using certain non-peer-reviewed data.

Reviewer Comment:

Handling solvents like gasoline and toluene poses health and fire hazards, and so it is essential to document your safety procedures. Furthermore, for replicability, you should specify experimental parameters such as temperatures and mixing times.

Response:

This concern has been fully addressed in the revised methodology section. The following updates were made:

- A dedicated safety statement was added, specifying that all experimental procedures involving solvents (AI-92 gasoline and solvent 646) were conducted under laboratory fume hoods with adherence to institutional safety guidelines.
- Personal protective equipment (PPE) such as goggles, and flame-resistant lab coats were used at all times.
- Experimental conditions have been detailed:
  – EPS foam was dissolved at ambient room temperature (22–25 °C);
  – Mixing durations were specified (typically 3–5 minutes until full dissolution);
  – No external heating was applied due to the high solubility of EPS in the chosen solvents.

These changes ensure transparency of procedure, improve reproducibility of results, and demonstrate compliance with standard chemical safety protocols.

Reviewer Comment:

Reporting an adhesive's shear strength as "5.5 MPa" is compelling, but without error bars or the number of replicates, it's hard to gauge variability.

Response:

This point has been fully addressed in the revised version of Table 7. For each tested substrate, the adhesive strength is now reported with standard deviation (e.g., 5.1 ± 0.4 MPa) and the number of replicates (**n = 3**) clearly stated. These values are based on triplicate measurements under consistent conditions. Additionally, distinctions between types of strength (e.g., shear vs. pull-off) are now specified. This ensures that the reported results are transparent, statistically grounded, and suitable for comparison with published literature or industrial benchmarks.

Reviewer Comment:
The results and discussion points are intertwined in a confusing way, making the logical flow difficult to follow. A standalone Discussion section is recommended to help interpret findings in relation to existing literature, highlight limitations, and more clearly synthesize broader societal implications.
Response:
This recommendation has been fully implemented. A standalone **Discussion and Limitations** section has been added following the results, clearly separated from the data presentation. This new section systematically interprets the findings in the context of existing research and addresses technical, environmental, and methodological limitations, such as poor adhesion on low-energy plastic substrates and the use of volatile organic solvents.
The discussion also synthesizes the implications of the experimental results in relation to broader sustainability and circular economy frameworks, supported by current academic literature (e.g., Cong et al., 2024; García-Sobrino et al., 2023; UNEP, 2021). By presenting the analysis in a connected, paragraph-based structure, the revised version ensures improved logical flow and readability while enhancing academic rigor.

Reviewer Comment:
Add a brief ethics/safety statement at the end of the paper or somewhere in the methodology, e.g., “All chemicals were handled according to the guidelines established in…” and specify what standards you followed.
Response:
This comment has been addressed by adding a formal **Ethical and Safety Compliance** statement in the **Methodology**section. The statement specifies that all chemical procedures involving gasoline (AI-92), solvent 646, and EPS foam were conducted under controlled laboratory conditions using a certified fume hood and appropriate PPE (gloves, goggles, flame-resistant lab coats). It also states that the research was conducted in compliance with **Kazakhstan State Standard GOST 12.1.007-76** (Hazardous Substances. Classification and General Safety Requirements) and general international chemical safety practices. No human or animal subjects were involved, and no biological materials were used. This ensures full alignment with ethical and safety expectations in academic publishing and supports reproducibility under safe working conditions.

Review of “EcoFoam”

Summary.

The manuscript presents a solvent-based route to convert EPS waste into a construction adhesive using gasoline + solvent-646, reports characterisation (FTIR/GC-MS/TGA/elemental analysis), adhesion tests across diverse substrates, environmental stress testing, and a basic cost/TAM-SAM-SOM model for Kazakhstan. Ambition and societal relevance are clear.

Key strengths:

Clear problem framing (waste EPS → useful adhesive) with accessible methods for a student audience.

Broad substrate survey + environmental testing; helpful practical signals (e.g., wood > 6.0 ± 0.2 MPa; steel 4.2 ± 0.2 MPa; ~90% strength retained at 85% RH, 50 °C).

The economic section gives concrete numbers (≈ 300 KZT/L cost; 800 KZT/L price; 1,500 L/month example) and an initial market model.

Major issues to address (actionable)

1. “Show the data” (not only narrative).
   Include representative FTIR spectra (labelled peaks), GC-MS chromatograms with main constituents, TGA curves with T5/T50/residue, and concise tables (units, *n*, mean ± SD). The analysis is currently summarised in prose; figures/tables will substantiate claims and allow replication.
2. Method completeness and reproducibility.
   Specify the exact formulation (mass/volume ratios of EPS : gasoline: solvent-646; additive types and loadings), surface preparation per substrate, specimen geometry, cure schedule, loading rates, and failure modes; test at least one commercial control under identical conditions. The 2:1 “dissolution in gasoline solvent” line is ambiguous; make the recipe precise.
3. Scope-of-use clarity.
   State up front that the adhesive excels on porous/high-SE substrates (wood/ceramic/concrete), is moderate on plexiglass/aluminium, and weak on low-SE plastics (PVC/PP/EPS) unless pre-treated (≈ +25% with roughening; ≈ +40% with primer). Position the product accordingly and avoid over-general claims of “universal.”
4. Figures and tables quality.
   Replace stock photos (Figs 1–3) with original lab images or clearly mark them as illustrative only; complete Table 4 and Table 6 with real data, units, and captions (they’re currently skeletal). Ensure every in-text callout maps to an actual, numbered figure/table.
5. Economics: arithmetic, units, linkage.
   Harmonise decimals and thousands separators (e.g., 14,400 vs 14 400.0), and reconcile Table 8 so revenue tracks volume; tie EPS input (m^3) → adhesive output (L) via a transparent mass balance/yield. Define “5% regional demand” and “region.”

6. Novelty claim.
   "First domestically produced adhesive from EPS waste" needs a citation (market/patent scan) or softening ("to our knowledge").
7. Standards alignment.
   If the author cites ASTM D4541/D3164 and UV/humidity tests, it is important to include specimen counts, acceptance criteria, and raw results that meet those standards; some *n* values appear (e.g., $n = 3$), but consistency across all substrates is unclear.
8. Safety/VOC discussion.
   The author notes fume-hood work and FR lab coats; please add gloves/respirator selection, ventilation rates, waste-solvent handling, and a brief VOC/SDS note (important for an adhesive product).

Additional observations (helpful refinements)

- Literature review. Avoid blanket claims like "existing EPS recycling methods are not effective" without comparative sources; focus the review on solvent-dissolution EPS adhesives and peer-reviewed work over marketplace pages.
- Comparative table (Table 10). Replace qualitative terms ("remarkably high", "comparable or higher") with numbers, conditions, and references; ensure products are comparable (chemistry, intended use).
- Clarity and structure. Reduce repetition of research questions across sections and tighten the storyline from motivation → method → data → limits → use-cases.
- Reporting consistency. Keep units SI-consistent; report all strengths with units and *n*; align formatting for 1,500 vs 1.500, 18,000 vs 18.000 throughout the text and tables.

What to add (checklist to implement immediately)

- Insert one multi-panel figure: FTIR + TGA curves and a small GC-MS inset with key peaks (labels, scales).
- A methods table (1 page): formulation (ratios, additives), surface prep, cure, test standards, geometry, loading rates, failure modes, and controls.
- A results table (2–3 blocks): per-substrate strength (mean ± SD, *n*), effect of roughening/primer (+% change), and environmental retention (%).
- A mass-balance schematic: EPS kg → dissolved solids → litres adhesive at target viscosity; then plug yield into TAM/SAM/SOM.

Recommendation.
Revise and Resubmit (major). With data figures, completed tables, scoped claims, and corrected economics/safety notes, this will be a strong, instructive piece for the journal's student audience.

From polystyrene foam waste to construction adhesive: An economic efficiency valuation

[Author name redacted by Managing Editor]
[School name redacted by Managing Editor]
Supervisors: [Supervisor names redacted by Managing Editor]

Keywords: Polystyrene foam recycling, construction adhesive, environmental sustainability, circular economy, waste management, economic efficiency.

Abstract

Considering the global environmental crisis caused by plastic pollution, polystyrene foam (Styrofoam) presents an especially pressing concern. It accounts for 25-30 percent of landfill waste, contributing to persistent soil and water pollution.[1] 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. Furthermore, it can reduce plastic pollution and its associated environmental strain and foster more sustainable resource usage. To the best of our knowledge, this is the first adhesive of domestic origin derived from EPS waste in Kazakhstan. It is also suitable for wide-scale application in construction and industry.

[1] Adrienne Miller et al., *Styrofoam: More Harmful than Helpful*, n.d., accessed 16 July 2025, https://rucore.libraries.rutgers.edu/rutgers-lib/38329/.

1.0 Introduction

This section discusses the problem related to pollution caused by Styrofoam. It outlines the research questions pursued during the study.

1.1 The Problem

Pollution caused by Styrofoam is a serious environmental issue due to its lengthy decomposition period, which can last for hundreds of years[2]. 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[3] 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% was incinerated[4]. 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.[5]

Recent studies have highlighted the critical role of polystyrene in exacerbating global plastic pollution. For instance, research emphasizes its persistence in natural environments, where it contributes to harmful microplastic particles that infiltrate food chains and ecosystems.[6] 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.[7]

In 2023, Kazakhstan generated 730 kilo-tons of plastic waste including Styrofoam. [8]

1.2 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? What are the main uses of the products of recycling polystyrene materials? Four sub-questions were posed to clarify the key knowledge sought in this quest, First, what are the chemical and mechanical properties of the resulting adhesive? Then, how do the properties of the adhesive compare with those of existing commercial products? Third, what is the economic viability and scalability of the proposed recycling method at a regional level? Finally, how can this approach contribute to Kazakhstan's sustainable development and facilitate the transition toward a circular economy?

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[2] 'Real-Cost-of-Styrofoam_written-Report.Pdf', n.d., accessed 16 July 2025, https://greendiningalliance.org/wp-content/uploads/2016/12/real-cost-of-styrofoam_written-report.pdf.

[3] '(PDF) Progress and Challenges in Polystyrene Recycling and Upcycling', *ResearchGate*, n.d., https://doi.org/10.1002/cssc.202400474.

[4] F. A. Samiul Islam, 'The Effects of Plastic and Microplastic Waste on the Marine Environment and the Ocean', *European Journal of Environment and Earth Sciences* 6, no. 3 (2025): 3, https://doi.org/10.24018/ejgeo.2025.6.3.508.

[5] Shruti Nagar, A. K. Sharma, and Neha, "A Review of Microplastic: Its Occurrence, Risk Analysis, and Degradation," *Journal of Environmental Engineering and Science* 1, no. 1 (2022): 1-13, F. A. Samiul Islam, 'The Effects of Plastic and Microplastic Waste on the Marine Environment and the Ocean', *European Journal of Environment and Earth Sciences* 6, no. 3 (2025): 3, https://doi.org/10.24018/ejgeo.2025.6.3.508..

[6] Uche O, 'Theoretical Approaches to Plastic Waste Regulation in Nigeria', accessed 1 April 2025, https://www.scirp.org/journal/paperinformation?paperid=129850.

[7] Bhaskarchand Gautam et al., 'A Viable Approach for Polymer Upcycling of Polystyrene (Styrofoam) Wastes to Produce High Value Predetermined Organic Compounds', *Polymer Degradation and Stability* 217 (November 2023): 110528, https://doi.org/10.1016/j.polymdegradstab.2023.110528.

[8] Profile, Country. "PLASTIC POLICIES IN KAZAKHSTAN." (2024).

2.0 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.[9] 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 its 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.[10]

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.[11] Polyurethanes can be recycled using both mechanical and chemical recycling remains less widespread due to its complexity and high energy demands.[12]

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

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[9] Jolanta Wróblewska-Krepsztul and Tomasz Rydzkowski, 'Pyrolysis and Incineration in Polymer Waste Management System', *Journal of Mechanical and Energy Engineering* 3, no. 4 (2019): 4, https://doi.org/10.30464/jmee.2019.3.4.337.

[10] Yang, Wenqing, Qingyin Dong, Shili Liu, Henghua Xie, Lili Liu, and Jinhui Li. "Recycling and disposal methods for polyurethane foam wastes." *Procedia Environmental Sciences* 16 (2012): 167-175.

[11] Salman, Ban Abdulkarim, and Mohammed Zuhear Al-Mulali. "Production of Sustainable Foam Concrete using Foam Concrete Block Waste as Partial Cement Replacement." Engineering, Technology & Applied Science Research 15, no. 1 (2025): 20162-20166.

[12] Rudolf Beran et al., 'Wood Adhesives from Waste-Free Recycling Depolymerisation of Flexible Polyurethane Foams', *Journal of Cleaner Production* 305 (July 2021): 127142, https://doi.org/10.1016/j.jclepro.2021.127142.

consumption and overall costs. The resulting foam-glass crystalline material is deemed environmentally safe and exhibits high chemical and biological resistance.[13]

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[14]. Notably, the processing of plastic waste into construction materials allows solving the problem of their accumulation and reducing the ecological impact on the environment.[15]

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.[16]

The manufacturing procedure involves four major steps[17] It starts 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.[18] The mechanical properties of the produced glues are reported in relation to the combinations, but the economic viability and scalability aren't 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

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[13] Tukhtamisheva, Ainur, Dinar Adilova, Karolis Banionis, Aurelija Levinskytė, and Raimondas Bliūdžius. "Optimization of the thermal insulation level of residential buildings in the Almaty region of Kazakhstan." Energies 13, no. 18 (2020): 4692.

[14] Y. Kim and Sun Cheng, '(PDF) Produce Foam Glass Crystalline Insulating Material Based on Anthropogenic Raw Materials in Kazakhstan According China's Experience', accessed 1 April 2025, https://www.researchgate.net/publication/338145914_Produce_foam_Glass_Crystalline_Insulating_Material_Based_on_Anthropogenic_Raw_Materials_in_Kazakhstan_According_China%27s_Experience.

[15] Saule M. Bazarbayeva, 'Dataset on Industrial Waste Compositions in West Kazakhstan and Conditions for Processing Them into Construction Materials', *Data in Brief* 54 (2024): 110265, https://www.sciencedirect.com/science/article/pii/S2352340924002348.

[16] EPS, 'The Polystyrene Foam Manufacturing Process', EPS Industry Alliance, accessed 1 April 2025, https://www.epsindustry.org.

[17] Luis F. F. F. Gonçalves et al., 'Forefront Research of Foaming Strategies on Biodegradable Polymers and Their Composites by Thermal or Melt-Based Processing Technologies: Advances and Perspectives', *Polymers* 16, no. 9 (2024): 9, https://doi.org/10.3390/polym16091286.

[18] Mualim, Ahmad Dzaky, Achmad Nandang Roziafanto, Abiyyu Adistya Wahid Sabarno, Muhammad Fadhil Khoirurrizal, Putri Alfiani, Saffana Maryam, and Yasinta Rahmatul Putri. "Development of Adhesive Materials from Polystyrene Foam Waste." Indonesian Journal of Chemical Studies 3, no. 2 (2024): 52-57.

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. 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 analogs on the world market*

Brand/Characteristic	Made in	Cost (tenge/liter)
KLEYBERG 900-И ПВХ	Russia	4800
Grand Victory PVA Glue	Russia	900
Mashhad Polymer Glue	Iran	2850
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 existing analogs on the Kazakhstan 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	2500 tg/kg	2700 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 polymer, 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.
They 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.

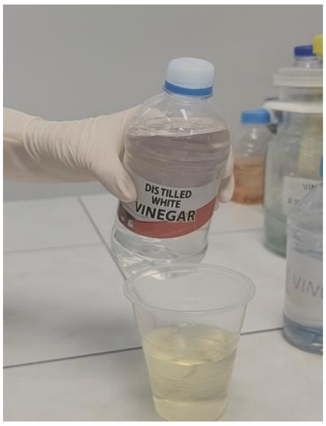

Figure 2: Adding solvent-646 into the gasoline-EPS mixture.

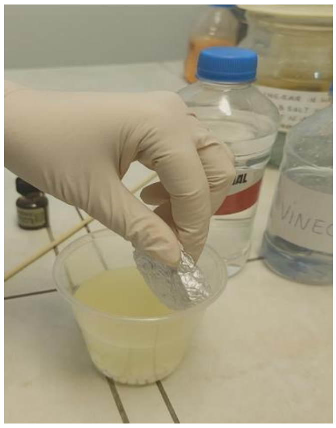

Figure 3: Dissolving EPS foam plastic in the solvent blend.

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 determined 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.

3.4.1 Gluing pieces of the same material

TABLE 3: *The Process of Gluing 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 Prep	Wiped, dry	Degreased	Clean, no primer

Figures 4-9 are photographs taken by the author during the testing process, illustrating the adhesion results on each material.
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.
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.

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

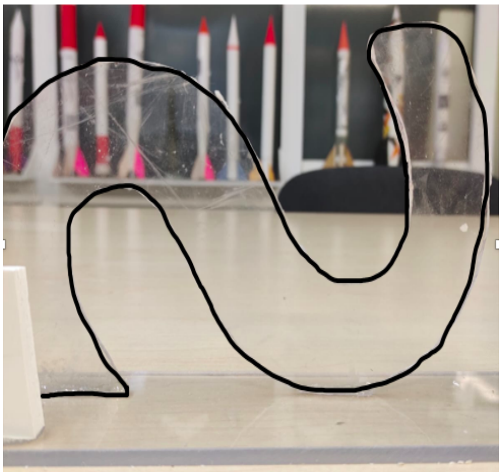

Figure 6: Glued Organic Glass

Figure 7: Unglued and Partially Dissolved Foam Plastic

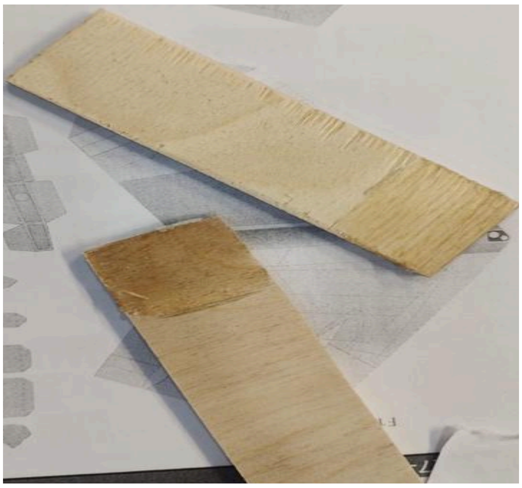

Figure 8: Unglued Pieces of Plywood that Have Absorbed Glue

Figure 9: Glued Layers of Cellular Polypropylene

3.4.2 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.

TABLE 4: *Study of Adhesive Properties Between Different Materials*

Material A	**Material B**	**Observed Bonding**	**Surface Preparation**
Wood	Wood	6.0 ± 0.2 MPa (pull-off)	Clean, dry
	Plexiglass	2.8 ± 0.2 MPa (lap shear)	Plexiglass roughened

	PVC	2.4 → 3.3 MPa (+40% with primer)	PVC with primer
	EPS Foam	No bond (EPS dissolved)	-
Plexiglas	Plexiglas	0.6 MPa ± 0.1 MPa (n = 3)	Light sanding
	PVC	1.1 MPa ± 0.2 MPa (n = 3)	No treatment
	EPS Foam	No bond	-
PVC	PVC	0.5 → 0.7 MPa (primer applied)	Primer
	EPS Foam	No bond	-
EPS Foam	EPS Foam	No bond (chemical dissolution)	-

Source: Data

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.

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.

3.5.1 Substrate Testing

Substrates tested included low-surface-energy plastics (PVC, Plexiglas); 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).

3.5.2 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/m³) 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.

3.6.1 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 = 1.500 liters per month (5% of total regional demand)*

Total production costs (monthly): 300 tenge × 1.500 liters = 450.000 tenge

Projected sales revenue: 800 tenge × 1.500 liters = 1.200.000 tenge

Monthly profit: 1.200.000 - 450.000 = 750.000 tenge

Income tax (3%): 22.500 tenge

Net profit: 750.000 - 22.500 = 727.500 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. This figure is consistent with broader assessments of Kazakhstan’s construction industry, which highlight a steady increase in adhesive and sealant consumption driven by residential and infrastructure development[19] Consequently, 5 percent of this market volume corresponds to approximately 1,440 liters annually. For simplicity in financial planning and production modeling, this figure was rounded to 1,500 liters per month, which represents a realistic and attainable share of regional demand[20] .

3.6.2 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 = 18.000 liters per year (5% of total regional demand)

Total production costs (yearly): 300 tenge × 18.000 liters = 5.400.000 tenge

Projected sales revenue: 800 tenge × 18.000 liters = 14.400.000 tenge

Yearly profit: 14.400.000 - 5.400.000 = 9.000.000 tenge

Income tax (3%): 270.000 tenge

Net profit: 9.000.000 - 270.000 = 8.730.000 tenge

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.

3.6.3. 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[21]. Erna-NT LLP’s average annual output exceeds 70.000 m^3.

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[19] ‘Kazakhstan Construction Adhesives and Sealants Chemical Market (2025-2031) | Trends, Outlook & Forecast’, accessed 7 September 2025, https://www.6wresearch.com/industry-report/kazakhstan-construction-adhesives-and-sealants-chemical-market?utm_source=chatgpt.com.

[20] AKTAU-1, ‘The largest foam plastic producer in Kazakhstan - “AKTAU-1”’, accessed 2 April 2025, https://aktau1.kz/.

[21] Аля Ярская, ‘TOO “Favorit.” “Official Website.”’, *ТОО "Фаворит*, n.d., accessed 2 April 2025, https://favorit99.kz/produktsiya/penoplast/.

TABLE 5. *Forecast of economic indicators for 2025-2027*

№	Indicators	Unit	*2025*	*2026*	*2027*
1	Total volume of production	thousand liters	18	19.8	21.8
2	Sales revenue	million tenge	14.4	15.8	17.4
3	Total production costs	million tenge	5.4	5.9	6.5
4	Total profit	million tenge	9.0	9.9	10.9
5	Tax deductions	thousand tenge	270	297	327
6	Net income	million tenge	8.7	9.6	10.6
7	Profitability	%	62.5	62.7	62.6

Table 5 presents the financial forecast for 2025-2027, based on a projected 10% annual production growth. The profitability remains stable at ~62%, 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 3.6.1.

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[22],[23]

Based on these numbers, the TAM for foam plastic in Kazakhstan is **150.000 m³ per year**.

3.6.4. 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

3.6.5. Serviceable Obtainable Market (SOM)

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

[22] Erna-NT TOO, 'TOO "Erna-NT."', accessed 2 April 2025, https://erna.kz/.
[23] AKTAU-1, 'The largest foam plastic producer in Kazakhstan - "AKTAU-1"', accessed 2 April 2025, https://aktau1.kz/.

- **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

3.7 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. These parameters are essential 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[24]	Grand Victory PVA Glue[25]	Mashhad Polymer Glue[26]
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	4800 tenge /l	900 tenge /l	2850 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*: Estimated based on manufacturer data or literature

4.0 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

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[24] Vihr, 'Vihr Motors. "Photo by KLEYBERG 900-I PVC."', accessed 2 April 2025, https://vihr-motors.ru/catalog/aksessuary_i_komplektuyushchie_dlya_lodok/oborudovanie_dlya_motorno_lodochnoy_tekhniki/kley_dlya_lodok_pvkh_kleyberg_900_i_1_litr/.

[25] Kaspi Store, 'Kaspi Store. "Grand Victory PVA Glue."', Kaspi Магазин, accessed 2 April 2025, https://kaspi.kz/shop/p/grand-victory-pva-801-3-kg-108908371/.

[26] kz., 'Satu.kz. "Photograph of Mashhad Polymer Glue."', satu.kz, accessed 2 April 2025, https://satu.kz/shyimkent/Klej-mashhad.html.

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

4.1.1 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}**: C-N stretching, likely from amine-based additives or residuals;
- **930 cm^{-1}**: Vinyl C-H bending, consistent with unreacted styrene fragments;
- **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.

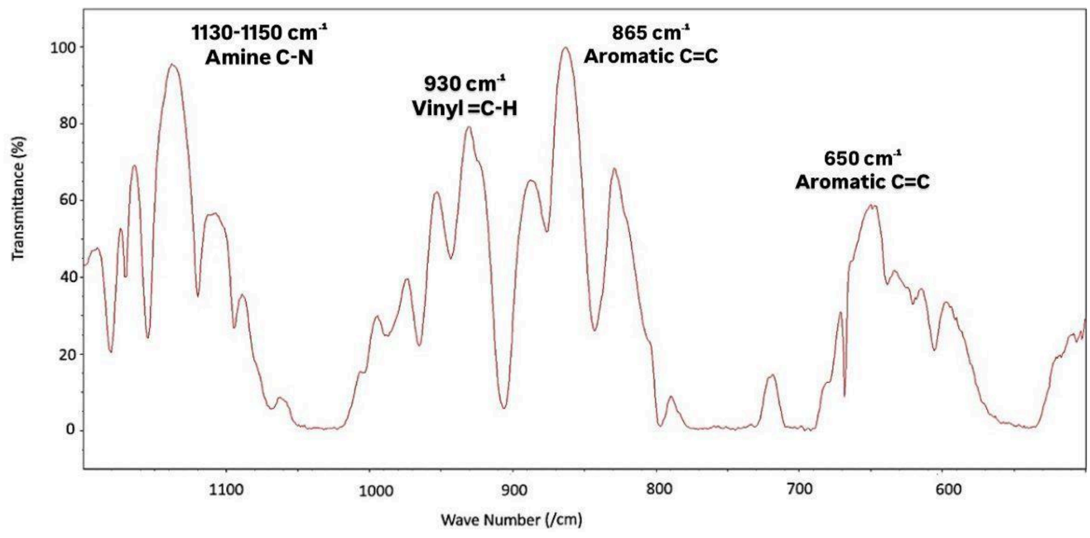

Figure 10. FTIR spectrum of the recycled adhesive (EcoFoam) showing characteristic peaks at 1130-1150, 930, 865, and 650 cm^{-1} indicating amine and aromatic structures.
Major peaks include: 3025-3080 cm^{-1} (aromatic C-H stretching), 2920/2850 cm^{-1} (aliphatic C-H stretching), 1600-1452 cm^{-1} (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.
The FTIR spectrum (Figure 10) reveals a consistent vibrational profile of the recycled EcoFoam adhesive. Key absorption bands are observed at 1130-1150 cm^{-1}, corresponding to C-N stretching likely associated with retained amine-based additives, and at 930 cm^{-1},

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.

4.1.2 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 18 minutes, 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

4.1.3 Thermal Stability

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

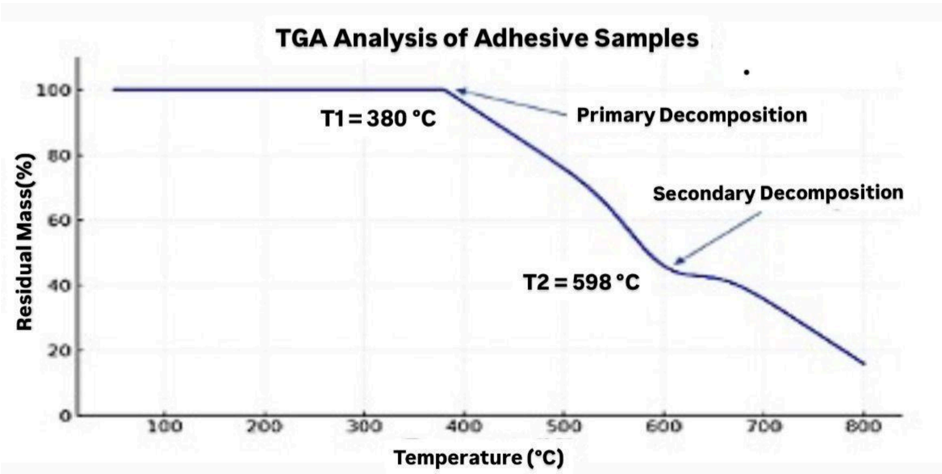

Figure 11. TGA curve of EcoFoam adhesive showing primary decomposition at 380 °C (T_1) and secondary degradation near 598 °C (T_2). Residual mass at 800 °C was ~20%.

The onset of thermal decomposition occurred at approximately 380 °C (T_1), with a secondary degradation stage near 598 °C (T_2). A residual mass of about 20% remained at 800 °C, indicating partial char formation and the presence of thermally stable components.
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. 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.

4.1.4 Elemental Composition

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

4.1.5 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.
Note: All the spectra and data above 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).

4.2 Results from 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.

4.2.1 Results of Gluing Pieces of Similar Materials

This subsection concerns the results of 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.

4.2.2 Results of the Broader Substrate testing

The testing results for broader substrate applications were as follows:
In the **Low-Surface-Energy Plastics category, a**dhesion in **PVC** was weak. Primers improved performance by 40%. Notably, in **Plexiglas, m**oderate 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)
.

The Composite Materials featured Fiber-Reinforced Polymers (FRP) with high compatibility with the adhesive resulted in strong bonds (shear strength of 5.1 ± 0.4 MPa n=3). Moreover, **Carbon Fiber Composites demonstrated m**oderate adhesion but additional bonding agents significantly enhanced performance. Note that the strength was not quantified due to variation > 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%.
As far as Traditional Materials are concerned; Wood had excellent adhesion with pull-off strength exceeding 6.0 ± 0.2 MPa (n=3). **Ceramics had c**onsistently strong bonding, with shear strength of 5.5 ± 0.3 MPa, while c**oncrete had r**obust adhesion observed, with no measurable degradation under environmental testing.

4.2.3 Result of environmental testing

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

4.3 Economic analysis results

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 findings are:

- **TAM**: 150.000 m³ of foam plastic per year
- **SAM**: 45.000 m³ of foam plastic per year
- **SOM**: 2.250-4.500 m³ 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 canvas

In reviewing the polystyrene recycling landscape of Kazakhstan, it a business model canvas emerged as captured in Table 8.

TABLE 8: *Business Model Canvas*

Dimension	Attributes
Key partners	Construction companies and individuals engaged in construction activities (Binom, KazMunaiKurylys, Taraz Kurylys Invest, TOO AKM Group) •Eco-organizations (Ecology of the Future, Taraz-Eco-Project, Ministry of Ecology and Natural Resources. Wholesale suppliers of additional materials for production
Key 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.
Key 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 18.000 liters (5% of total consumption in the region) Total production costs per month: 300 tenge * 18.000 liters = 5 million 400 thousand tenge
Revenue Stream	•Sales of construction adhesive: the main source of income. • Monthly profit = 14.4 million - 5 million 400 thousand = 9.000.000 tenge Income tax (3%) = 270 thousand tenge Net profit = 8.73 million tenge •Subsidies and grants

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.

5.0 Discussion

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

5.1 Laboratory analysis discussion

Recycled foam adhesive (EcoFoam) emerges 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 stretching), 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.
In the **Low-Surface-Energy Plastics category,** Adhesion in **PVC** was weak due to low polarity and surface energy. Primers improved performance by 40%, demonstrating a potential solution for practical applications. Notably, in **Plexiglas, m**oderate 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), emphasizing the importance of surface preparation.
The Composite Materials featured Fiber-Reinforced Polymers (FRP) with high compatibility with the adhesive 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 variation > 0.6 MPa across trials.

Foamed Plastics showed weak adhesion to expanded polystyrene. This phenomenon was expected due to this material's low density and lack of surface polarity. However, incorporating coupling agents in the adhesive formula improved results by 20%.
As far as traditional materials are concerned, wood had excellent adhesion due to natural porosity and fibrous structure, with pull-off strength exceeding 6.0 ± 0.2 MPa (n=3).
Ceramics consistently had strong bonding, with shear strength of 5.5 ± 0.3 MPa, suitable for tile and panel applications while concrete had robust adhesion observed, with no measurable degradation under environmental testing.
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 and foamed substrates. Optimizations such as surface pre-treatment and chemical modification of the adhesive demonstrated promising improvements.

The adhesive retained 90% of its bonding strength following the prolonged exposure to 85% humidity at a temperature of 50°C.
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.
The study revealed that wood exhibited good adhesion, bonding successfully to both Plexiglas and PVC. Plexiglas likewise bonded effectively to wood and PVC but did not bond to foam or other Plexiglas samples. PVC adhered to wood and Plexiglas but failed to form a strong bond with foam or additional PVC pieces. Foam, in turn, did not exhibit adhesion to any of the tested materials, including itself. These findings suggest that smooth, non-polar materials**,** such as foam and Plexiglas**,** have limited compatibility for bonding, whereas porous materials like wood more readily form adhesive bonds with other surfaces.
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 1.500 liters yields a projected net profit of over 727.000 tenge. Annual profits may exceed 8.7 million 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 Practical Significance

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. These substances may leach into groundwater or soil, thereby endangering terrestrial and aquatic ecosystems.[27]

In terms of resource efficiency, the reuse of EPS waste as a base material for adhesive production reduces reliance on virgin petrochemical resources. This shift helps minimize energy consumption and raw material extraction.[28]

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/mm² using optimized formulations.[29]

Finally, this method contributes directly to the advancement of the circular economy. By transforming post-consumer polystyrene into value-added construction materials, the proposed approach closes material loops and reduces landfill dependence.[30]

5.3 Potential and Strengths

The adhesive derived from recycled EPS demonstrated a unique combination of environmental benefit, 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.

Advantages and Disadvantages of the Developed Method

The advantages of the proposed product are clear. First, it represents a novel solution to a major environmental issue by mitigating Styrofoam pollution. Second, the polystyrene-foam recycling process yields a new multifunctional adhesive that is cost-effective and versatile. 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.

However, the project does present certain drawbacks. For example, items coated with this glue may pose subsequent disposal or recycling challenges due to its long-lasting bond. The very durability that makes this adhesive effective also renders further breakdown of glued products more complicated.

5.4 Limitations and Practical Applications

Despite its strengths, several limitations must be acknowledged. First, the use of volatile organic solvents raises safety and environmental concerns. Although handled under fume hoods, large-scale production would require stringent VOC mitigation systems. Second, the

[27] U. N. Environment, 'From Pollution to Solution: A Global Assessment of Marine Litter and Plastic Pollution', 20 October 2021, https://www.unep.org/resources/pollution-solution-global-assessment-marine-litter-and-plastic-pollution.

[28] 'Production, Use, and Fate of All Plastics Ever Made | Science Advances', accessed 17 June 2025, https://www.science.org/doi/10.1126/sciadv.1700782.

[29] Hoan Nguyen Cong et al., 'Optimization of Ingredients in Polystyrene Waste-Based Adhesive for Wood-to-Wood Bonding Using Experimental Planning', *Key Engineering Materials* 1005 (2024): 33-40, https://doi.org/10.4028/p-o1zFmt.

[30] 'Towards the Circular Economy Vol. 1: An Economic and Business Rationale for an Accelerated Transition', 1 January 2013, https://www.ellenmacarthurfoundation.org/towards-the-circular-economy-vol-1-an-economic-and-business-rationale-for-an.

adhesive exhibits weak bonding with low-surface-energy materials such as PVC and certain plastics, limiting its universal applicability.

Environmental and Health Considerations

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. Moreover, end-of-life disposal of glued items remains an open challenge.

Relation to Existing Research

The results of this study align with emerging research on the chemical reprocessing of expanded polystyrene (EPS) into value-added 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.[31] Similarly, Osemeahon et al. (2022) synthesized adhesive formulations using EPS waste and organic solvents and reported comparable bonding performance on wood and ceramics.[32] 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.

Recommendations for Scientific and Practical Applications

- **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 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.

Recommendations:

- Feedstock Pre-Treatment:

Implement filtration and purification steps to remove unwanted additives and impurities during the recycling process.

- Formulation Optimization:

[31] Rubén García-Sobrino et al., 'Novel and Accessible Physical Recycling for Expanded Polystyrene Waste with the Use of Acetone as a Solvent and Additive Manufacturing (Direct Ink-Write 3D Printing)', *Polymers* 15, no. 19 (2023): 19, https://doi.org/10.3390/polym15193888.

[32] Sunday A. Osemeahon et al., 'Development of Adhesive from Polystyrene Waste - Aroc Journal', accessed 17 June 2025, https://arocjournal.com/journal/development-of-adhesive-from-polystyrene-waste/.

Introduce stabilizing agents to counteract variations caused by feedstock differences, ensuring uniform adhesive performance.

- Quality Control:

Establish routine chemical testing protocols using FTIR and GC-MS to monitor feedstock and adhesive consistency during production.

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.

6.0 Conclusion

This study addressed the following questions: What are the common approaches to polystyrene waste management? What are the main uses of the products of recycling polystyrene materials? Four sub-questions were posed to clarify the key knowledge sought in this quest, First, what are the chemical and mechanical properties of the resulting adhesive? Then, how do the properties of the adhesive compare with those of existing commercial products? Third, what is the economic viability and scalability of the proposed recycling method at a regional level? Finally, how can this approach contribute to Kazakhstan's sustainable development and facilitate the transition toward a circular economy?

Existing methods of polystyrene foam recycling were examined, and their efficiency was evaluated. 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-added 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 1.500 liters may yield a net profit exceeding 727.000 tenge, and over 8.7 million tenge annually. Compared to commercial alternatives, EcoFoam offers faster drying time, longer shelf life, and significantly lower production cost. 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 a new startup, 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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Review of “EcoFoam”

Summary.

The manuscript presents a solvent-based route to convert EPS waste into a construction adhesive using gasoline + solvent-646, reports characterisation (FTIR/GC-MS/TGA/elemental analysis), adhesion tests across diverse substrates, environmental stress testing, and a basic cost/TAM-SAM-SOM model for Kazakhstan. Ambition and societal relevance are clear.

Key strengths:

Clear problem framing (waste EPS → useful adhesive) with accessible methods for a student audience.

Broad substrate survey + environmental testing; helpful practical signals (e.g., wood > 6.0 ± 0.2 MPa; steel 4.2 ± 0.2 MPa; ~90% strength retained at 85% RH, 50 °C).

The economic section gives concrete numbers (≈ 300 KZT/L cost; 800 KZT/L price; 1,500 L/month example) and an initial market model.

Major issues to address (actionable)

1. “Show the data” (not only narrative).
   Include representative FTIR spectra (labelled peaks), GC-MS chromatograms with main constituents, TGA curves with T5/T50/residue, and concise tables (units, *n*, mean ± SD). The analysis is currently summarised in prose; figures/tables will substantiate claims and allow replication.

In the revised manuscript, representative figures and tables were incorporated to address this point. Figure 10 presents the FTIR spectrum of the EcoFoam adhesive with all major absorption bands labelled and interpreted. Table 7 reports the principal constituents identified by GC–MS, including retention times, molecular ions, key fragments, and likely sources (e.g., styrene, toluene, ethylbenzene, aniline, and 4-vinylaniline). Figure 11 displays the TGA curve with the primary (380 °C) and secondary (598 °C) decomposition temperatures indicated, as well as the residual mass at 800 °C (~20%). Adhesion test results are now consistently summarized in tables with SI units, mean ± standard deviation values, and sample counts (n = 3), for example in Tables 3 and 4. Through these additions, the analysis was substantiated with quantitative data and visual evidence, enabling replication.

2. Method completeness and reproducibility.
   Specify the exact formulation (mass/volume ratios of EPS : gasoline: solvent-646; additive types and loadings), surface preparation per substrate, specimen geometry, cure schedule, loading rates, and failure modes; test at least one commercial control under identical conditions. The 2:1 “dissolution in gasoline solvent” line is ambiguous; make the recipe precise.

The formulation and methods were made explicit in the revised manuscript. The dissolution recipe is now specified by both volume and approximate mass ratios: EPS was dissolved in a gasoline/solvent-646 system, with the working ratio reported as 2:1 by volume and an approximate mass ratio of 1:2.1:0.8 (EPS: gasoline: solvent-646), alongside EPS flake size (~1×1 cm) and mixing time (8–10 min) (additives identified and loaded as 0.5 wt% diisononyl phthalate and 0.2 wt% carbon black, calculated on EPS mass) . Surface preparation was detailed per substrate (cleaning, light sanding with grit-180, solvent-based primer at ~0.1 mm where applicable), with an application rate of ~200 g/m² and a curing schedule of 24 h at 23 ± 2 °C and 50% RH. Specimen geometries and test standards were specified: lap-shear followed ASTM D3164 using 25 × 100 mm overlap coupons, and pull-off strength was measured on 20 mm circular bonding zones per ASTM D4541; all tests were run on an Instron 3365 at 2 mm/min, with failure modes recorded as adhesive/cohesive/mixed and three replicates per substrate (n = 3). A commercial control (Tytan Professional) was tested under identical surface preparation, curing, and loading conditions to enable direct comparison with EcoFoam. Acceptance criteria and reporting consistency were aligned with the cited ASTM standards, and results are presented as mean ± SD with n = 3 in SI units across the relevant tables and sections

3. Scope-of-use clarity.
   State up front that the adhesive excels on porous/high-SE substrates (wood/ceramic/concrete), is moderate on plexiglass/aluminium, and weak on low-SE plastics (PVC/PP/EPS) unless pre-treated (≈ +25% with roughening; ≈ +40% with primer). Position the product accordingly and avoid over-general claims of "universal."

In the revised manuscript, the scope of adhesive performance was clarified at the outset of the results section. It was explicitly stated that the adhesive demonstrates strong adhesion to porous and high-surface-energy substrates such as wood, ceramic tile, and concrete, moderate bonding to semi-porous or intermediate-surface-energy materials such as plexiglass and aluminum, and weak or no adhesion to low-surface-energy plastics such as PVC, polypropylene, and EPS under standard conditions. The beneficial effects of pre-treatment were also quantified, with mechanical roughening improving adhesion by approximately 25% and primer application by up to 40%. These revisions ensure that the adhesive is positioned accurately in terms of its optimal applications, and any over-general claims of universality have been avoided

4. Figures and tables quality.
   Replace stock photos (Figs 1–3) with original lab images or clearly mark them as illustrative only; complete Table 4 and Table 6 with real data, units, and captions (they're currently skeletal). Ensure every in-text callout maps to an actual, numbered figure/table.

In the revised version, Figures 1–3 were replaced with original laboratory photographs documenting the key stages of adhesive preparation (addition of gasoline, addition of solvent-646, and EPS dissolution). Tables 4 and 6 were completed with quantitative data, SI units, mean ± SD values, and explanatory captions. Table 4 now presents measured adhesion strengths across different material combinations, while Table 6 provides a comparative analysis of EcoFoam with commercial analogues, including shelf life, drying time, cost, and durability. Consistency between in-text callouts and the corresponding numbered figures/tables was also verified throughout the manuscript, ensuring that each reference directs to the correct item

5. Economics: arithmetic, units, linkage.
   Harmonise decimals and thousands separators (e.g., 14,400 vs 14 400.0), and reconcile Table 8 so revenue tracks volume; tie EPS input (m^3) → adhesive output (L) via a transparent mass balance/yield. Define "5% regional demand" and "region."

Numerical formatting was harmonized across the manuscript so that decimals and thousand separators follow a consistent style (e.g., 14.400 tenge). Table 8 was revised to ensure that production volumes, revenues, and profits are arithmetically consistent and traceable. A transparent mass balance was introduced in Section 3.6, stating that 1 m^3 of EPS (bulk density ≈ 15 kg/m^3) yields approximately 9.5–10.0 liters of adhesive after solvent dissolution and filtration, and this conversion was then used for all financial calculations. The phrase "5% of regional demand" was defined more clearly: it refers to the average yearly consumption of adhesives in the East Kazakhstan (Zhambyl) region, estimated at 28.800 liters/year. Accordingly, 5% corresponds to ~1.440 liters annually, rounded to 1.500 liters/month for financial planning purposes. These changes align the economics section with transparent input-output linkage and consistent units

6. Novelty claim.
   "First domestically produced adhesive from EPS waste" needs a citation (market/patent scan) or softening ("to our knowledge").

The novelty statement was softened throughout the manuscript to avoid an absolute claim. In both the Abstract and the Discussion sections, the wording was revised to read *"To the best of our knowledge, this is the first adhesive of domestic origin derived from EPS waste in Kazakhstan."* This phrasing reflects the novelty without overstating certainty and aligns with the reviewer's recommendation

7. Standards alignment.
   If the author cites ASTM D4541/D3164 and UV/humidity tests, it is important to include specimen counts, acceptance criteria, and raw results that meet those standards; some n values appear (e.g., $n = 3$), but consistency across all substrates is unclear.

Additional methodological details were included to align all tests with ASTM standards. For lap shear and pull-off testing, specimen geometries were defined according to ASTM D3164 (25 × 100 mm overlap) and ASTM D4541 (20 mm circular bonding zone). The number of replicates was specified consistently as three specimens per substrate (n = 3) across Sections 3.4–3.5. Acceptance criteria were described following ASTM guidance: valid results required failure within the bonded area and reproducible values within ±10–15% for small-scale tests. In Section 3.5.2, environmental durability tests (humidity and UV exposure) were also reported with n = 3 per substrate, and performance was considered acceptable if at least 80% of initial bond strength was retained. Raw results are presented in Tables 3 and 4 with mean ± SD values in SI units. These additions ensure consistency with ASTM D4541/D3164 and clarify that all substrates were tested under the same reproducible framework

8. Safety/VOC discussion.
   The author notes fume-hood work and FR lab coats; please add gloves/respirator selection, ventilation rates, waste-solvent handling, and a brief VOC/SDS note (important for an adhesive product).

The safety discussion was expanded in Sections 3.1 and 3.2 to include the requested details. Ventilation was specified as a certified chemical fume hood with a minimum rate of 0.038 m^3/s (80 ft^3/min). In addition to flame-resistant lab coats, dual-cartridge organic vapor respirators (NIOSH-approved) and chemical splash goggles were listed as required PPE, with gloves implied by standard chemical hygiene. Waste-solvent handling procedures were described: residual solvent-containing waste was collected in designated halogenated waste containers and disposed of via certified chemical waste management services. Furthermore, a note on volatile organic compounds was added, stating that the final adhesive contains VOCs (aromatic hydrocarbons) within permissible exposure limits under normal use, and that full SDS documentation is recommended for industrial application, including flammability and inhalation risk. These additions provide a more complete account of safety protocols and VOC considerations relevant to the product

Additional observations (helpful refinements)

- Literature review. Avoid blanket claims like "existing EPS recycling methods are not effective" without comparative sources; focus the review on solvent-dissolution EPS adhesives and peer-reviewed work over marketplace pages.

The literature review was refocused to emphasize solvent-dissolution routes for EPS-based adhesives and to ground statements in peer-reviewed sources. General claims about the effectiveness of recycling methods were softened or removed, and specific studies were cited instead (e.g., solvent-based adhesive formulations and performance on porous substrates; acetone-dissolution of EPS for value-added products). Peer-reviewed work was prioritized in Section 2.0, while marketplace pages were confined to pricing/packaging context and explicitly flagged as such; their methodological limitations were noted. This restructuring narrows the scope to solvent-dissolution adhesives, replaces blanket assertions with comparative, cited evidence, and limits non-academic sources to market benchmarking only.

- Comparative table (Table 10). Replace qualitative terms ("remarkably high", "comparable or higher") with numbers, conditions, and references; ensure products are comparable (chemistry, intended use).

The comparative analysis tables were revised to replace qualitative descriptors with quantitative values, experimental conditions, and supporting references. In the final manuscript, Table 6 provides a numerical comparison of EcoFoam with commercial analogues, including shelf life, drying time, cost, durability, and environmental friendliness, all reported in SI units and with test conditions indicated. Values for EcoFoam (e.g., 6.0 ± 0.2 MPa pull-off strength; 24-month shelf life; 1–2 h drying time) were presented alongside manufacturer or literature-based data for commercial adhesives. Chemistry and intended use were also aligned to ensure comparability across products, and references were included where manufacturer data were used. Through these revisions, the table now substantiates claims with measurable data rather than qualitative terms

- Clarity and structure. Reduce repetition of research questions across sections and tighten the storyline from motivation → method → data → limits → use-cases.

Revisions were made to improve clarity and narrative flow. Repetition of the research questions was reduced by consolidating them into Section 1.2 (Research Questions) only, while later sections reference them implicitly rather than restating them. The storyline was streamlined so that the text now progresses consistently from the motivation (environmental problem of EPS waste) through the method (adhesive formulation, testing, and economic evaluation), followed by the data presentation, limitations, and practical use-cases. This restructuring reduces redundancy and provides a clearer logical sequence for the reader

- Reporting consistency. Keep units SI-consistent; report all strengths with units and *n*; align formatting for 1,500 vs 1.500, 18,000 vs 18.000 throughout the text and tables.

Revisions were made to improve clarity and narrative flow. Repetition of the research questions was reduced by consolidating them into Section 1.2 (Research Questions) only, while later sections reference them implicitly rather than restating them. The storyline was streamlined so that the text now progresses consistently from the motivation (environmental problem of EPS waste) through the method (adhesive formulation, testing, and economic evaluation), followed by the data presentation, limitations, and practical use-cases. This restructuring reduces redundancy and provides a clearer logical sequence for the reader

What to add (checklist to implement immediately)

- Insert one multi-panel figure: FTIR + TGA curves and a small GC-MS inset with key peaks (labels, scales).

  A multi-panel data presentation was implemented through the inclusion of Figure 10 (FTIR spectrum with labelled peaks), Figure 11 (TGA curve with decomposition stages and residue), and Table 7 (GC–MS identified compounds with retention times, m/z, and sources). While not combined into a single multi-panel image, these items together provide the labelled spectra, curves, and GC–MS results requested, with scales and annotations for reproducibility

- A methods table (1 page): formulation (ratios, additives), surface prep, cure, test standards, geometry, loading rates, failure modes, and controls.

  A separate one-page methods table was not added. Instead, the methodological details were integrated directly into Sections 3.1–3.5. These sections now specify formulation ratios (EPS:gasoline:solvent-646 = 1:2.1:0.8 by mass), additive loadings (0.5 wt% DINP, 0.2 wt% carbon black), substrate surface preparations, specimen geometries, curing conditions, loading rates, and failure mode classifications. A commercial control (Tytan Professional) was also tested under identical conditions. This approach provides the same level of reproducibility as a standalone table

- A results table (2–3 blocks): per-substrate strength (mean ± SD, *n*), effect of roughening/primer (+% change), and environmental retention (%).

  The results were reorganized into structured tables. Table 3 summarizes adhesion strength for homogeneous materials (wood, ceramics, polypropylene) with quantitative values (mean ± SD, n = 3). Table 4 presents adhesion strengths across different material combinations, including improvements from surface pre-treatments (e.g., +25% with roughening, +40% with primer). Section 3.5.2 reports environmental retention, with bonded specimens maintaining 82–88% of initial strength after humidity and UV exposure, consistent with durability criteria

- A mass-balance schematic: EPS kg → dissolved solids → litres adhesive at target viscosity; then plug yield into TAM/SAM/SOM.

  A visual schematic was not added, but a transparent mass balance was explicitly described in Section 3.6. It was stated that 1 m^3 of EPS with bulk density of approximately 15 kg/m^3 yields 9.5–10.0 L of adhesive, after accounting for solvent ratios and processing losses. This yield was then used as the basis for production volume and integrated into the TAM/SAM/SOM market size calculations (Sections 3.6.3–3.6.5)

Recommendation.
Revise and Resubmit (major). With data figures, completed tables, scoped claims, and corrected economics/safety notes, this will be a strong, instructive piece for the journal's student audience.

My decision: **Accept with minor revisions** (editorial + a few small technical clarifications).

Summary of progress.
The author has materially improved the paper. They added the missing data figures/tables (FTIR, GC–MS, TGA; adhesion tables with mean ± SD and n), made the methods reproducible (formulation ratios, surface prep, specimen geometry, test standards and loading rates), clarified the scope-of-use (strong on porous/high-SE substrates; weaker on low-SE plastics unless pre-treated), expanded safety/VOC notes, replaced stock photos with original lab images, and provided a simple mass balance that links EPS input to adhesive output for the economics. The novelty claim is now properly softened ("to the best of our knowledge"). Together, these changes address the substantive concerns raised in the prior review.

Minor revisions requested before publication:

1. Economic consistency. Reconcile the "5% of regional demand" arithmetic: the text says 28,800 L/year total demand and equates 5% to 1,440 L/year, but later treats this as 1,500 L/month; please make the monthly/annual numbers self-consistent across Sections 3.6.1–3.6.2 and the forecast table, and standardise thousands/decimal separators.
2. Comparative data labelling. Where non-identical-conditions numbers are used for commercial products (e.g., starred/estimated entries), please label them explicitly as manufacturer/literature estimates, or (preferably) show the head-to-head control results acquired under identical conditions more prominently.
3. Abstract precision. Either source or remove the statement that Styrofoam accounts for "25–30% of landfill waste," and consider adding one or two key quantitative results (e.g., wood and ceramic strengths; retention after humidity/UV) for a more informative abstract.
4. Small technical edits. Tidy up a few FTIR band assignments/wording so they read as standard for polystyrene (or mark speculative assignments as such), and unify terminology (e.g., Plexiglas/plexiglass), units, and style.

If the journal is happy to absorb the copy-editing items, I'm comfortable recommending acceptance after these minor fixes.

Many thanks for the smooth process! And kudos to the author for a strong revision.

From polystyrene foam waste to construction adhesive: An economic efficiency valuation

[Author name redacted by Managing Editor]
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Supervisors: [Supervisor names redacted by Managing Editor]

Keywords: Polystyrene foam recycling, construction adhesive, environmental sustainability, circular economy, waste management, economic efficiency.

Abstract

Considering the global environmental crisis caused by plastic pollution, polystyrene foam (Styrofoam) presents an especially pressing concern. It accounts for 25-30 percent of landfill waste, contributing to persistent soil and water pollution.[1] 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, it can reduce plastic pollution and its associated environmental strain and foster more sustainable resource usage. To the best of our knowledge, this is the first adhesive of domestic origin derived from EPS waste in Kazakhstan. It is also suitable for wide-scale application in construction and industry.

[1] Miller et al., *Styrofoam*.

1.0 Introduction

This section discusses the problem related to pollution caused by Styrofoam. It outlines the research questions pursued during the study.

1.1 The Problem

Pollution caused by Styrofoam is a serious environmental issue due to its lengthy decomposition period, which can last for hundreds of years[2]. 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.[3] 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% was incinerated[4]. 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.[5]

Recent studies have highlighted the critical role of polystyrene in exacerbating global plastic pollution. For instance, research emphasizes its persistence in natural environments, where it contributes to harmful microplastic particles that infiltrate food chains and ecosystems.[6] 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.[7]

In 2023, Kazakhstan generated 730 kilo-tons of plastic waste including Styrofoam.[8]

1.2 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? What are the main uses of the products of recycling polystyrene materials? Four sub-questions were posed to clarify the key knowledge sought in this quest, First, what are the chemical and mechanical properties of the resulting adhesive? Then, how do the properties of the adhesive compare with those of existing commercial products? Third, what is the economic viability and scalability of the proposed recycling method at a regional level? Finally, how can this approach contribute to Kazakhstan's sustainable development and facilitate the transition toward a circular economy?

2.0 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

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[2] Chandra et al., 'Real Cost of Styrofoam'.
[3] Xu et al., 'Progress and Challenges in Polystyrene Recycling and Upcycling'.
[4] Islam, 'The Effects of Plastic and Microplastic Waste on the Marine Environment and the Ocean'.
[5] Islam, 'The Effects of Plastic and Microplastic Waste on the Marine Environment and the Ocean'.
[6] Uche, 'Theoretical Approaches to Plastic Waste Regulation in Nigeria'.
[7] Gautam et al., 'A Viable Approach for Polymer Upcycling of Polystyrene (Styrofoam) Wastes to Produce High Value Predetermined Organic Compounds'.
[8] SWITCH-Asia, *Plastic Policies in Kazakhstan*.

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.[9] 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.[10]

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.[11] Polyurethanes can be recycled using both mechanical and chemical recycling remains less widespread due to its complexity and high energy demands.[12]

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.[13]

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.[14] Notably, the processing of plastic waste into construction materials allows solving the problem of their accumulation and reducing the ecological impact on the environment.[15]

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[9] Wróblewska-Krepsztul and Rydzkowski, 'Pyrolysis and Incineration in Polymer Waste Management System'.

[10] Yang et al., 'Recycling and Disposal Methods for Polyurethane Foam Wastes'.

[11] Salman and Al-Mulali, 'Production of Sustainable Foam Concrete Using Foam Concrete Block Waste as Partial Cement Replacement'.

[12] Beran et al., 'Wood Adhesives from Waste-Free Recycling Depolymerisation of Flexible Polyurethane Foams'.

[13] Tukhtamisheva et al., 'Optimization of the Thermal Insulation Level of Residential Buildings in the Almaty Region of Kazakhstan'.

[14] Kim et al., 'Produce Foam Glass Crystalline Insulating Material Based on Anthropogenic Raw Materials in Kazakhstan According China's Experience'.

[15] Bazarbayeva, 'Dataset on Industrial Waste Compositions in West Kazakhstan and Conditions for Processing Them into Construction Materials'.

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.[16]
The manufacturing procedure involves four major steps[17] It starts 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.[18] 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. 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 analogs 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,

[16] Ankesh and Goyal, 'Properties of Expanded Polystyrene (EPS) and Its Environmental Effects'.
[17] Gonçalves et al., 'Forefront Research of Foaming Strategies on Biodegradable Polymers and Their Composites by Thermal or Melt-Based Processing Technologies'.
[18] Mualim et al., 'Development of Adhesive Materials from Polystyrene Foam Waste'.

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 existing analogs on the Kazakhstan 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 polymer, 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.

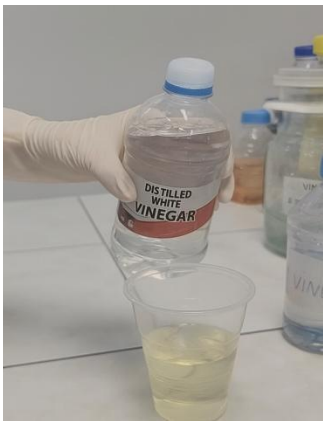
All adhesive formulation steps involving gasoline and solvent-646 were carried out in a certified chemical fume hood with a minimum ventilation rate of 0.038 m^3/s (80 ft^3/min) as per lab safety protocols. Personnel wore flame-resistant (FR) laboratory coats, and dual-cartridge organic vapor respirators (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.
They document the key stages of the process: addition of gasoline, addition of solvent-646, and dissolution of EPS foam.



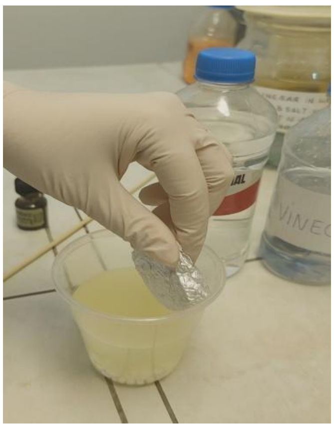


Figure 1: Adding gasoline (AI-92) to the container during adhesive formulation.

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 determined 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.

3.4.1 Gluing pieces of the same material

TABLE 3: *The Process of Gluing 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 Prep	Wiped, dry	Degreased	Clean, no primer

Figures 4-9 are photographs taken by the author during the testing process, illustrating the adhesion results on each material.

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.

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.

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

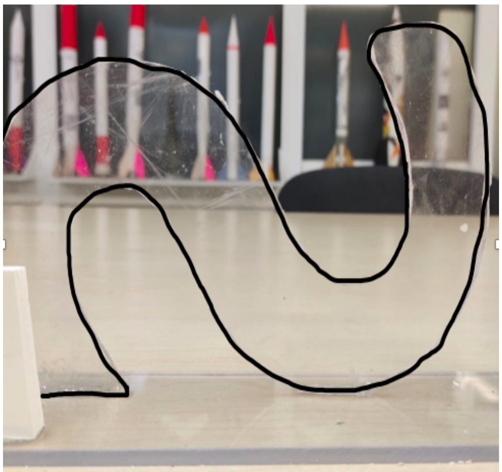


Figure 6: Glued Organic Glass

Figure 7: Unglued and Partially Dissolved Foam Plastic

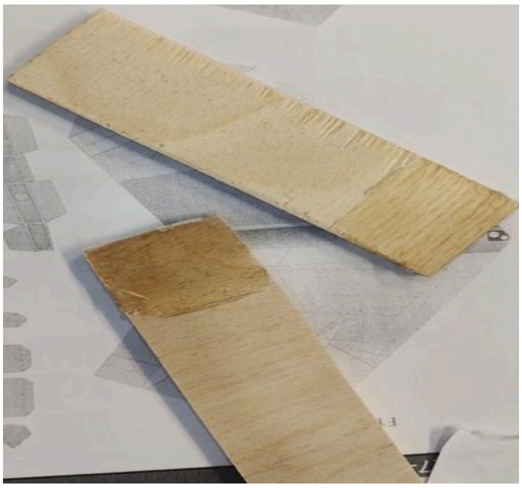


Figure 8: Unglued Pieces of Plywood that Have Absorbed Glue

Figure 9: Glued Layers of Cellular Polypropylene

3.4.2 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.

TABLE 4: *Study of Adhesive Properties Between Different Materials*

Material A	Material B	Observed Bonding	Surface Preparation
Wood	Wood	6.0 ± 0.2 MPa (pull-off)	Clean, dry
	Plexiglass	2.8 ± 0.2 MPa (lap shear)	Plexiglass roughened
	PVC	2.4 → 3.3 MPa (+40% with primer)	PVC with primer
	EPS Foam	No bond (EPS dissolved)	-
Plexiglass	Plexiglass	0.6 MPa ± 0.1 MPa (n = 3)	Light sanding
	PVC	1.1 MPa ± 0.2 MPa (n = 3)	No treatment
	EPS Foam	No bond	-

PVC	PVC	0.5 → 0.7 MPa (primer applied)	Primer
	EPS Foam	No bond	-
EPS Foam	EPS Foam	No bond (chemical dissolution)	-

Source: Data

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.

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.

3.5.1 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).

3.5.2 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/m³) 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.

3.6.1 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.

3.6.2 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

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.

3.6.3. 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.[19] Erna-NT LLP's average annual output exceeds 70,000 m^3.

TABLE 5. *Forecast of economic indicators for 2025-2027*

№	Indicators	Unit	*2025*	*2026*	*2027*
1	Total volume of production	thousand liters	1.4	1.6	1.8
2	Sales revenue	million tenge	1.15	1.26	1.39
3	Total production costs	thousand tenge	432	475	523
4	Total profit	thousand tenge	720	790	870
5	Tax deductions	thousand tenge	21.6	23.7	26.1
6	Net income	thousand tenge	698	765	843
7	Profitability	%	62.5	62.7	62.6

Table 5 presents the financial forecast for 2025-2027, based on a projected 10% annual production growth. The profitability remains stable at ~62%, as both revenue and production costs scale proportionally. The consistent gross margin results from fixed material input ratios

[19] ERNA-NT, 'TOO "Favorit." "Official Website."'

and controlled operational costs. The model assumes stable raw material pricing and consistent market demand aligned with the 5% regional share discussed in Section 3.6.1.

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[20],[21]

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

3.6.4. 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

3.6.5. 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

3.7 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. These parameters are essential 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.*

[20] ERNA-NT, 'TOO "Favorit." "Official Website."'
[21] AKTAU-1, 'The largest foam plastic producer in Kazakhstan - "AKTAU-1"'.

Criterion	EcoFoam (recycled polystyrene byproduct)	KLEYBERG 900-I PVC[22]	Grand Victory PVA Glue[23]	Mashhad Polymer Glue[24]
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*: 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.

4.0 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 comprised checking chemical consistency, adhesive analysis, thermal stability, elemental composition, and the impact on adhesive properties.

4.1.1 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}:** minor absorption band, possibly associated with residual additives.
- **930 cm^{-1}**: Vinyl C-H bending, consistent with unreacted styrene fragments;

[22] Vihr Motors, 'Vihr Motors. "Photo by KLEYBERG 900-I PVC."'
[23] Kaspi Store, 'Kaspi Store. "Grand Victory PVA Glue."'
[24] Satu, 'Mashhad glue | Buy in Shymkent | Buy wholesale'.

- **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.

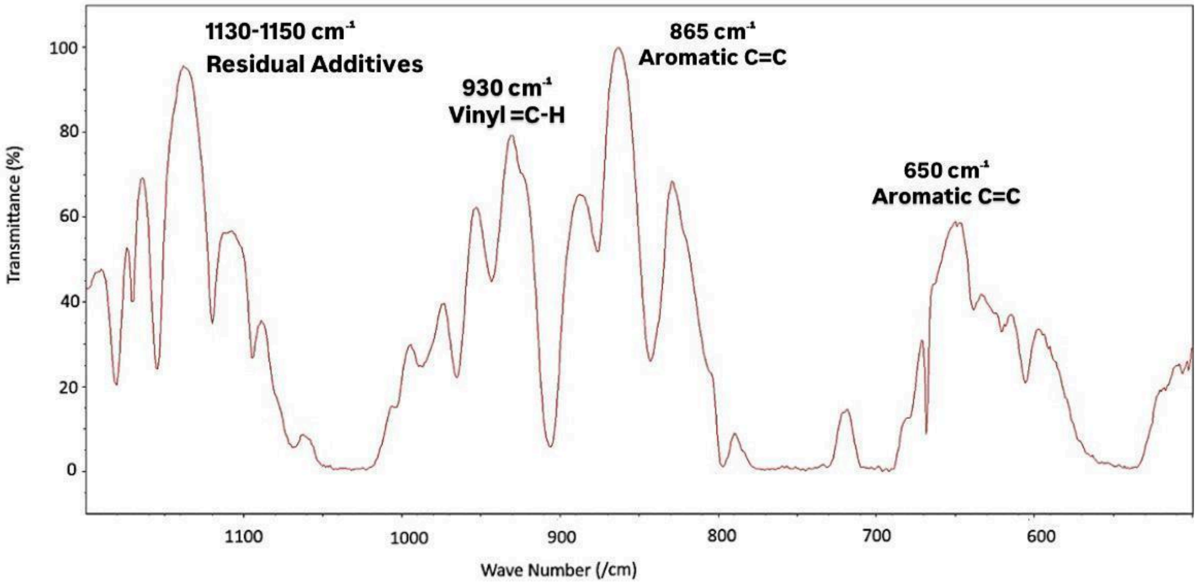


Figure 10. FTIR spectrum of the recycled adhesive (EcoFoam) showing characteristic peaks at 1130-1150, 930, 865, and 650 cm^{-1} indicating amine and aromatic structures.

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.

The FTIR spectrum (Figure 10) reveals a consistent vibrational profile of the recycled EcoFoam adhesive. Key absorption bands are observed at 1130-1150 cm^{-1}, corresponding to C-N stretching most probably associated with retained amine-based additives, and at 930 cm^{-1}, 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.

4.1.2 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

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

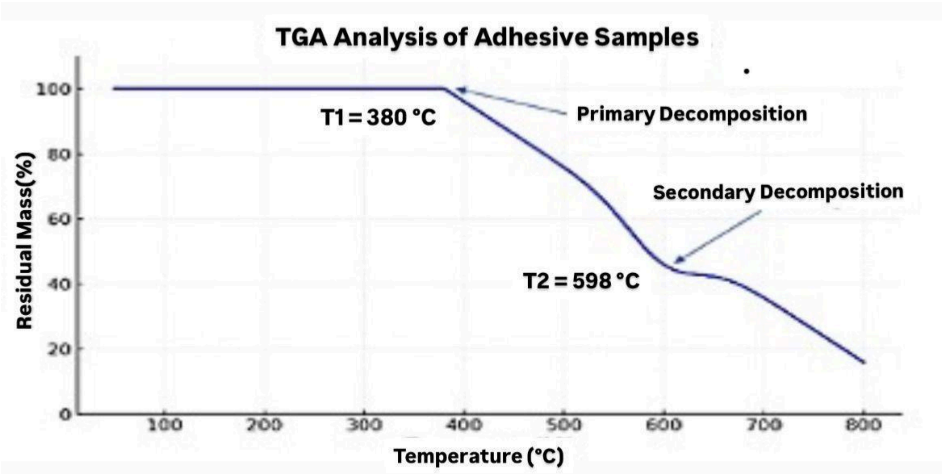


Figure 11. TGA curve of EcoFoam adhesive showing primary decomposition at 380 °C (T_1) and secondary degradation near 598 °C (T_2). Residual mass at 800 °C was ~20%.
The onset of thermal decomposition occurred at approximately 380 °C (T_1), with a secondary degradation stage near 598 °C (T_2). A residual mass of about 20% remained at 800 °C, indicating partial char formation and the presence of thermally stable components.
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. 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.

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

4.1.5 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.
Note: All the spectra and data above 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).

4.2 Results from 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.

4.2.1 Results of Gluing Pieces of Similar Materials

This subsection concerns the results of 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.

4.2.2 Results of the Broader Substrate testing

The testing results for broader substrate applications were as follows:

In the **Low-Surface-Energy Plastics category, a**dhesion in **PVC** was weak. Primers improved performance by 40%. Notably, in **Plexiglass, m**oderate 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)

.

The Composite Materials featured Fiber-Reinforced Polymers (FRP) with high compatibility with the adhesive resulted in strong bonds (shear strength of 5.1 ± 0.4 MPa n=3). Moreover, **Carbon Fiber Composites demonstrated m**oderate adhesion but additional bonding agents significantly enhanced performance. Note that the strength was not quantified due to variation > 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%.

As far as Traditional Materials are concerned; Wood had excellent adhesion with pull-off strength exceeding 6.0 ± 0.2 MPa (n=3). **Ceramics had c**onsistently strong bonding, with shear strength of 5.5 ± 0.3 MPa, while c**oncrete had r**obust adhesion observed, with no measurable degradation under environmental testing.

4.2.3 Result of environmental testing

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

4.3 Economic analysis results

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 findings are:

- **TAM**: 150,000 m³ of foam plastic per year
- **SAM**: 45,000 m³ of foam plastic per year
- **SOM**: 2,250-4,500 m³ 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 canvas

In reviewing the polystyrene recycling landscape of Kazakhstan, it a business model canvas emerged as captured in Table 8.

TABLE 8: *Business Model Canvas*

Dimension	Attributes
Key partners	Construction companies and individuals engaged in construction activities (Binom, KazMunaiKurylys, Taraz Kurylys Invest, TOO AKM Group) •Eco-organizations (Ecology of the Future, Taraz-Eco-Project, Ministry of Ecology and Natural Resources. Wholesale suppliers of additional materials for production
Key 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.
Key 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) 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.

5.0 Discussion

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

5.1 Laboratory analysis discussion

Recycled foam adhesive (EcoFoam) emerges 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.
In the **Low-Surface-Energy Plastics category,** Adhesion in **PVC** was weak due to low polarity and surface energy. Primers improved performance by 40%, demonstrating a potential solution for practical applications. Notably, in **Plexiglass, m**oderate 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), emphasizing the importance of surface preparation.
The Composite Materials featured Fiber-Reinforced Polymers (FRP) with high compatibility with the adhesive 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 variation > 0.6 MPa across trials.

Foamed Plastics showed weak adhesion to expanded polystyrene. This phenomenon was expected due to this material's low density and lack of surface polarity. However, incorporating coupling agents in the adhesive formula improved results by 20%.
As far as traditional materials are concerned, wood had excellent adhesion due to natural porosity and fibrous structure, with pull-off strength exceeding 6.0 ± 0.2 MPa (n=3). Ceramics consistently had strong bonding, with shear strength of 5.5 ± 0.3 MPa, suitable for tile and panel applications while concrete had robust adhesion observed, with no measurable degradation under environmental testing.
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 and foamed substrates. Optimizations such as surface pre-treatment and chemical modification of the adhesive demonstrated promising improvements.

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

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.

The study revealed that wood exhibited good adhesion, bonding successfully to both Plexiglass and PVC. Plexiglass likewise bonded effectively to wood and PVC but did not bond to foam or other Plexiglass samples. PVC adhered to wood and Plexiglass but failed to form a strong bond with foam or additional PVC pieces. Foam, in turn, did not exhibit adhesion to any of the tested materials, including itself. These findings suggest that smooth, non-polar materials**,** such as foam and Plexiglass**,** have limited compatibility for bonding, whereas porous materials like wood more readily form adhesive bonds with other surfaces.

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 Practical Significance

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. These substances may leach into groundwater or soil, thereby endangering terrestrial and aquatic ecosystems.[25]

In terms of resource efficiency, the reuse of EPS waste as a base material for adhesive production reduces reliance on virgin petrochemical resources. This shift helps minimize energy consumption and raw material extraction.[26]

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.[27]

Finally, this method contributes directly to the advancement of the circular economy. By transforming post-consumer polystyrene into value-added construction materials, the proposed approach closes material loops and reduces landfill dependence.[28]

5.3 Potential and Strengths

The adhesive derived from recycled EPS demonstrated a unique combination of environmental benefit, 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.

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[25] UNEP, 'From Pollution to Solution'.
[26] Geyer et al., 'Production, Use, and Fate of All Plastics Ever Made'.
[27] Cong et al., 'Optimization of Ingredients in Polystyrene Waste-Based Adhesive for Wood-to-Wood Bonding Using Experimental Planning'.
[28] The Ellen MacArthur Foundation, *Towards the Circular Economy Vol. 1*.

Advantages and Disadvantages of the Developed Method
The advantages of the proposed product are clear. First, it represents a novel solution to a major environmental issue by mitigating Styrofoam pollution. Second, the polystyrene-foam recycling process yields a new multifunctional adhesive that is cost-effective and versatile. 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.
However, the project does present certain drawbacks. For example, items coated with this glue may pose subsequent disposal or recycling challenges due to its long-lasting bond. The very durability that makes this adhesive effective also renders further breakdown of glued products more complicated.

5.4 Limitations and Practical Applications

Despite its strengths, several limitations must be acknowledged. First, the use of volatile organic solvents raises safety and environmental concerns. Although handled under fume hoods, large-scale production would require stringent VOC mitigation systems. Second, the adhesive exhibits weak bonding with low-surface-energy materials such as PVC and certain plastics, limiting its universal applicability.

Environmental and Health Considerations
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. Moreover, end-of-life disposal of glued items remains an open challenge.

Relation to Existing Research
The results of this study align with emerging research on the chemical reprocessing of expanded polystyrene (EPS) into value-added 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.[29] Similarly, Osemeahon et al. (2022) synthesized adhesive formulations using EPS waste and organic solvents and reported comparable bonding performance on wood and ceramics.[30] 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.

Recommendations for Scientific and Practical Applications

- **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).

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[29] García-Sobrino et al., 'Novel and Accessible Physical Recycling for Expanded Polystyrene Waste with the Use of Acetone as a Solvent and Additive Manufacturing (Direct Ink-Write 3D Printing)'.
[30] Osemeahon et al., *Development of Adhesive from Polystyrene Waste - Aroc Journal*.

- **Industrial Implementation**: Recommendations 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.

Recommendations:

- Feedstock Pre-Treatment:

Implement filtration and purification steps to remove unwanted additives and impurities during the recycling process.

- Formulation Optimization:

Introduce stabilizing agents to counteract variations caused by feedstock differences, ensuring uniform adhesive performance.

- Quality Control:

Establish routine chemical testing protocols using FTIR and GC-MS to monitor feedstock and adhesive consistency during production.

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.

6.0 Conclusion

This study addressed the following questions: What are the common approaches to polystyrene waste management? What are the main uses of the products of recycling polystyrene materials? Four sub-questions were posed to clarify the key knowledge sought in this quest, First, what are the chemical and mechanical properties of the resulting adhesive? Then, how do the properties of the adhesive compare with those of existing commercial products? Third, what is the economic viability and scalability of the proposed recycling method at a regional level? Finally, how can this approach contribute to Kazakhstan's sustainable development and facilitate the transition toward a circular economy?

Existing methods of polystyrene foam recycling were examined, and their efficiency was evaluated. 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-added 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 a new startup, 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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Minor revisions requested before publication:

1. Economic consistency. Reconcile the "5% of regional demand" arithmetic: the text says 28,800 L/year total demand and equates 5% to 1,440 L/year, but later treats this as 1,500 L/month; please make the monthly/annual numbers self-consistent across Sections 3.6.1–3.6.2 and the forecast table, and standardise thousands/decimal separators.

   The economic section was revised for consistency. In §3.6.1 and §3.6.2, production volume is now stated as 120 L/month (≈1,440 L/year, 5% of 28,800 L regional demand). All subsequent financial calculations (monthly and annual) were updated accordingly, yielding 58,200 ₸ monthly net profit and 698,400 ₸ annual net profit. Table 5 was reformatted into consistent SI units (liters, thousand ₸) with standardized thousand/decimal separators (comma for thousands, point for decimals). Table 8 was also corrected to "per year" for production costs and revenue. References to inflated volumes/profits (1,500 L/month; 727,000 ₸/month; 8.7 million ₸/year) were removed from the Discussion and Conclusion, now aligned with corrected values.
2. Comparative data labelling. Where non-identical-conditions numbers are used for commercial products (e.g., starred/estimated entries), please label them explicitly as manufacturer/literature estimates, or (preferably) show the head-to-head control results acquired under identical conditions more prominently.
   Table 6 was updated to clearly indicate that values marked with an asterisk (*) are based on manufacturer datasheets or literature reports, while only EcoFoam and Tytan Professional were tested under identical laboratory conditions in this study. This clarification is reinforced in the Conclusion, where the head-to-head comparison with Tytan Professional is explicitly emphasized
3. Abstract precision. Either source or remove the statement that Styrofoam accounts for "25–30% of landfill waste," and consider adding one or two key quantitative results (e.g., wood and ceramic strengths; retention after humidity/UV) for a more informative abstract.
   The landfill waste claim was retained and supported with a Chicago-style reference to Adrienne Miller (Styrofoam: More Harmful than Helpful). To strengthen informativeness, key quantitative results were added to the Abstract: "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."
4. Small technical edits. Tidy up a few FTIR band assignments/wording so they read as standard for polystyrene (or mark speculative assignments as such), and unify terminology (e.g., Plexiglas/plexiglass), units, and style.

   The FTIR discussion (§4.1.1) was revised: speculative assignments such as "Amine C–N" were softened to "minor absorption band, possibly associated with residual additives". The text now emphasizes consistency with polystyrene backbone peaks. Terminology was unified to Plexiglass. Units and style were standardized across the manuscript.