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Assessing the Environmental Impact of Glass Waste and Substantiating its Secondary Use in the Production of Silicate Construction Materials

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ABSTRACT

Glass waste poses significant environmental challenges, including soil and water contamination, particularly from leaching substances like lead. In Kazakhstan, glass waste recycling remains inefficient, with only 10-11% of total glass waste being processed. This study aims to evaluate the environmental impact of glass waste and explore its secondary use in producing silicate construction materials. The research employs waste life cycle analysis, environmental impact assessment, and experimental glass processing into construction components such as foam glass and concrete additives. Findings show that utilizing glass waste in construction materials can reduce CO_2 emissions by up to 30%, enhance the strength and durability of concrete, and substitute up to 30% of cement in mixes. Additionally, foam glass from crushed glass bottles exhibits excellent insulation and mechanical properties. The study concludes that the secondary use of glass waste in construction offers significant ecological and economic benefits. Implementing advanced recycling technologies and integrating these materials into Kazakhstan's construction industry can mitigate environmental impacts and promote sustainability.

1. INTRODUCTION

Today, one of the most promising directions in reducing the anthropogenic impact on the environment and people doing construction or household chores is the development of environmentally friendly energy-saving technologies. Using secondary raw materials as the main raw material reduces the amount of waste released into the environment, as this waste is recycled instead, and presents the opportunity to utilize these materials in construction.

Glass waste that cannot be recycled ends up in the natural environment, polluting the soil and surface and ground water. Leaching products resulting from interaction with water take the land out of economic use due to contamination by glass shards. In Kazakhstan, glass waste recycling is limited. The most environmentally hazardous glass containing lead is not recycled at all and is not traditionally separated from the general flow of glass waste, which makes it difficult to integrate this waste into the life cycle. Recycling is one of the most complex and significant challenges in waste management. There are many reasons why recycling rates in Kazakhstan remain low and the waste management system is not functioning effectively. All these reasons are interconnected. Some of the leading problems include low tariffs for the collection, transportation, utilization, recycling, and disposal of municipal solid waste (MSW); insufficient waste sorting; lack of funding in this sector; lack of a competitive environment; the underdeveloped market for secondary raw materials; and systemic problems.

In recent years, the economic and environmental expediency of utilizing glass waste has been confirmed by research findings and the experience of its use in developed countries. Expert studies conducted in the European Economic Community show that each ton of utilized glass waste can save more than a ton of primary raw materials and that for every 10-15% increase in the use of glass waste, it is possible to save at least 2% of energy. Developed countries thus pay a lot of attention to recycling and utilizing glass waste.

The adopted legislative measures should contribute to the national glass industry becoming an organizer and direct participant in the collection and recycling of glass waste, as it happens abroad, for example, in Switzerland and Germany. Another factor that encourages the glass industry to participate in the recycling and utilization of glass waste is the saving of energy and basic raw materials. The greatest incentive is the opportunity to save on raw materials. For example, Switzerland and Germany have the highest recycling rates of glass waste – 11.5 and 9.0 kg per capita, respectively. To boost the utilization of glass waste, it is necessary to establish an effective system of collecting this waste from the population. Particular attention should be paid to the separation of glass waste from household waste, as the share of glass waste in household waste is significant.

The effective use of glass waste can be promoted by establishing specialized processing enterprises, where the glass is crushed, cleaned, and sorted [1]. Furthermore, it is important to develop a rational method of using glass waste that will make it possible to save on primary raw materials [2].

Given the environmental hazards posed by non-recyclable glass waste, developed countries use low-waste technologies to produce environmentally friendly construction materials and reuse them [3]. Our study focuses on Kazakhstan because the issue of utilizing glass waste is not sufficiently studied, including the lack of research on its environmental impact and its use in construction materials. Therefore, the recycling of glass waste, specifically, its utilization in construction materials, is a topical research direction.

Each year, Kazakhstan generates millions of tons of waste, 7-9% of it being glass waste. Of these, about 330 thousand t, which make up 10-11% of the total amount of waste, are recycled and utilized. The volumes of different types of MSW in Kazakhstan are provided in Figure 1.

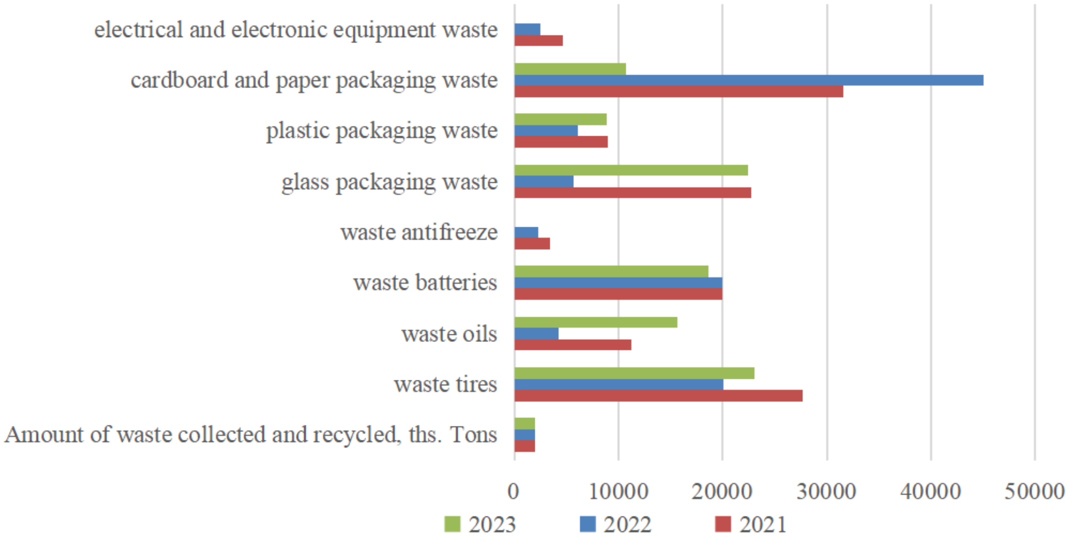

Figure 1. Amount of MSW in Kazakhstan, thousand t

Kazakhstan is developing measures across all areas to minimize the amount of industrial and municipal waste. The country's waste management program includes measures improving the effectiveness of procedures for assessing changes in the volume and composition of waste to develop a waste minimization strategy that could be implemented through economic or other means focused on improving production and consumption patterns.

However, Kazakhstan, including the West Kazakhstan Region, has no organizations involved in recycling glass waste. The amounts of collected and recycled glass waste in European countries [4] and Kazakhstan are shown in Figure 2.

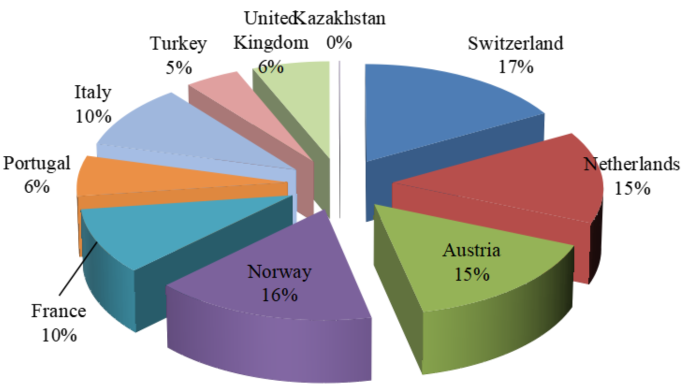

Figure 2. The volume of collected and recycled glass waste in European countries and Kazakhstan

Effective waste management is vital to deal with the growing amount of waste. One technical solution for this is to use an improved machine-to-machine product-service system to collect glass waste. Our study aims to evaluate the environmental impact of glass waste and substantiate its secondary use to produce silicate construction materials.

The research objectives set to achieve this purpose are to analyze the current situation with glass waste in Kazakhstan, identify the leading factors in the environmental impact of glass waste, and study the properties of glass waste with regard to its potential secondary use in the production of new materials.

2. METHODS

2.1 Research design

The study utilizes a comprehensive set of research methods to evaluate the environmental impact of glass waste and study its potential in the framework of secondary use in the production of silicate construction materials.

The theoretical foundation of the study is provided by the works of Tagibergenova and Bazhenova [5] and Lelah et al. [6] on managing glass waste. The problem is proposed to be solved using nanotechnology and other types of solutions to control and manage waste. The research was conducted in the West Kazakhstan Region, with experimental work carried out at Zhangir Khan West Kazakhstan Agrarian-Technical University (Uralsk).

An environmental impact assessment (EIA) was conducted to evaluate the negative environmental impact of glass waste, including the leaching of harmful chemicals into soil and water. It was conducted in accordance with the Environmental Code of Kazakhstan and guided by international frameworks such as ISO 14001 and UNEP's environmental assessment standards for waste management. The purpose of the EIA was to evaluate the negative effects of improperly managed glass waste on soil, surface water, groundwater, and land resources in the West Kazakhstan Region.

The assessment focused on several key parameters:

- Soil and groundwater contamination;
- Surface water quality degradation;
- Impact on land use;
- Carbon footprint analysis.

Life cycle analysis was conducted to assess the ecological footprint of glass waste from its collection and disposal to recycling and secondary use in construction.

2.2 Materials

The materials chosen for the study were window glass and white and colored container glass. Glass waste is generated by the glass industry, waste from cafes and restaurants, medical glass waste, glass sludge, etc. All these wastes are thrown to dumps and MSW landfills and hardly ever recycled.

Laboratory analyses were performed to determine the pH of leachates using potentiometric methods and to identify concentrations of leached ions such as Pb^{2+}, Na^{+}, and Ca^{2+} using atomic absorption spectroscopy (AAS).

To standardize the results, each environmental impact parameter was scored using a five-point environmental risk scale based on the European Commission's EIA guidelines, ranging from negligible to severe.

All experiments were conducted in triplicate, and results were reported as mean ± standard deviation. A confidence level of 95% ($p < 0.05$) was used to determine statistical significance.

2.3 Experimental processing of glass waste

The first step of the recycling process was to collect different types of glass waste (including clear, brown, and green glass). The glass was sorted and then crushed using hammer crushers to different granule sizes (≤ 2 mm, 2-5 mm, 5-10 mm, and > 10 mm) according to the standards set out in GOST 22552.7-2019.

The granulated glass was then washed and cleaned with distilled water at room temperature to remove impurities and ensure the required quality of the final material. The pH of the aqueous extract was determined through potentiometry.

The dispersed composition of the glass waste obtained under laboratory conditions is shown in Figure 3. Following this, we weighed the ground glass powder, chalk, and wollastonite-containing slag in different ratios and milled them together to obtain a homogeneous mass.

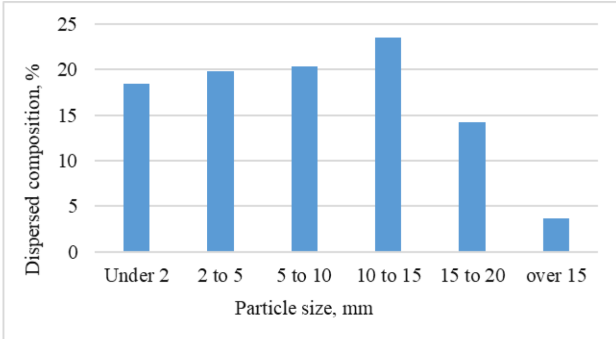

Figure 3. Dispersed composition of glass waste

Almost one-third of the glass waste comes in pieces under 5 mm. Therefore, sorting is an essential technical task before recycling municipal glass waste. This labor-intensive process can be performed manually or with optical and mechanical equipment [7].

The firing was carried out in a laboratory furnace at the optimal temperature. Firing makes the foam glass, which has uniform porosity due to finely ground glass powder and chalk containing calcium carbonate, swell up.

As a result of our study, we propose a methodology based on life cycle analysis. These solutions will make it possible to reduce negative environmental impact [6].

3. RESULTS AND DISCUSSION

The literature review suggests that a major problem with glass is its single-time use, for example, in the form of beverage bottles, which is one of the main uses of glass. Glass waste is estimated to account for 5-8% of the total MSW generated globally in 2023, with recycling rates varying across the globe and within regions. The number of MSW storage facilities in Kazakhstan as of 2020 is presented in Figure 4.

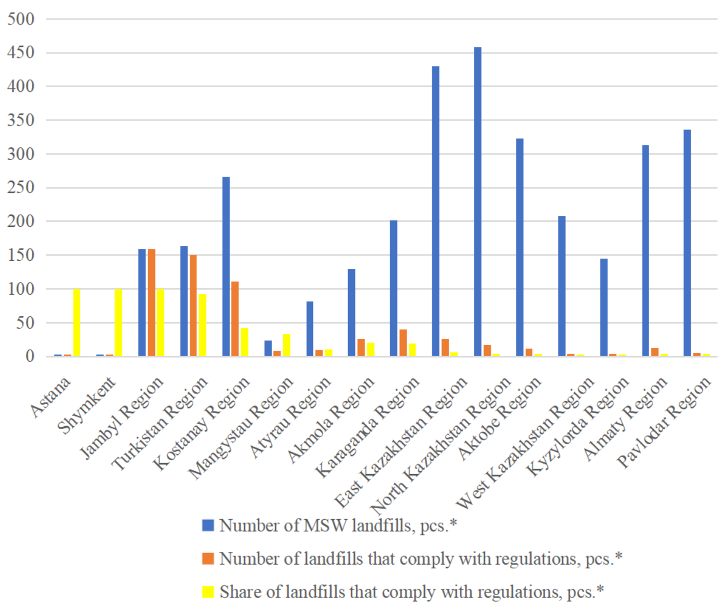

Figure 4. The number of MSW storage facilities

The total number of MSW storage facilities amounts to 3,292; only 601 of them comply with ecological and sanitary regulations. The smallest share of landfills is located in the West Kazakhstan Region (0.96% of the total – 208). Data on the amount of waste in the West Kazakhstan Region is presented in Figure 5.

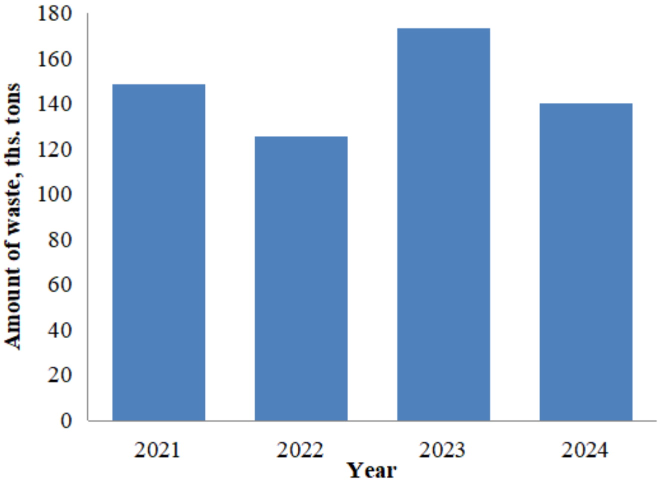

Figure 5. Data on the amount of waste in the West Kazakhstan Region in 2021-2024

The West Kazakhstan Region generates more than 160 million t of waste, 8% of which, i.e., 12.8 million t, is made up by glass waste.

Statistics on the West Kazakhstan Region demonstrate that the amount of industrial and municipal waste is growing, although environmental emissions have been greatly reduced (Figure 6).

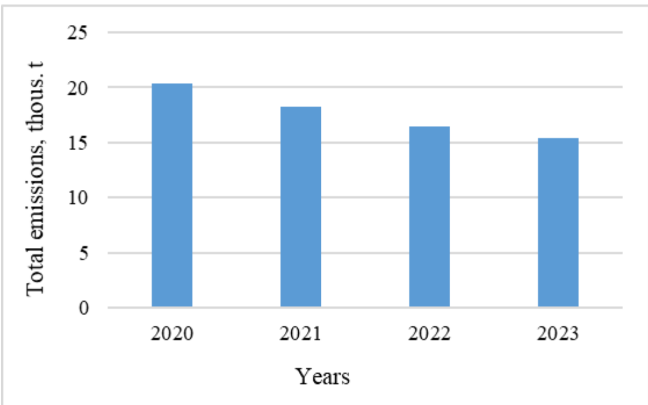

Figure 6. Total amount of emissions in the West Kazakhstan Region in 2020-2023

Total emissions generated by the region dropped from 63.1to 55.32 thousand t in 2017-2019, lowering further to 20.4 thousand t by 2020, and hit 15.4 thousand t in 2023.

The primary focus of sustainable development in individual countries is to significantly increase the efficiency of resource use, provided that such use does not lead to environmental degradation.

Commitments to increasing recycling rates have become an important strategy for waste management. Certain problems are faced both in sorting glass waste and recycling it. The solution has been to use waste as a secondary raw material to produce construction materials, such as aggregate and cement.

Theoretically speaking, glass waste can be recycled in its entirety [8, 9]. However, if the glass is contaminated, contains impurities, is broken, or has different colors, remelting becomes impractical [10-12]. Therefore, the optimal solution for the secondary use of the material for recycling is to use glass waste in construction, for example, in concrete mixtures as a fine aggregate [13, 14].

In terms of its characteristics, glass waste behaves much like cement [15, 16]. This application is ecologically advantageous, as waste is utilized in the composition of concrete. In-depth studies have been conducted on the use of different fractions of glass powder as a substitute for cement in mixtures to improve strength and durability and replace expensive components with cheap ones.

Our results demonstrate that glass powder with a particle size of 0.038 can replace up to 30% of cement due to its modifying effect combined with pozzolanic activity. Adding glass powder also lowers CO_2 emissions almost to 30% [17]. Sudharsan et al. [18] researched glass powder to use it in mortar and concrete. Ground glass powder possesses excellent pozzolanic properties. Its use in concrete has both economic and environmental advantages since it replaces components such as coarse aggregate, and sand. Our results align with the studies of Kalakada et al. [19] who established the potential of CO_2 reduction when replacing a percentage of cement with glass powder. In their study they concluded that 30% was the ideal replacement level as it exhibits quite comparable strengths, better workability and higher resistance to chloride ion penetration. It also aligns with these studies of Pashtoon [20] and Raydan et al. [21] who concluded that at 10-15% replacement, glass powder below 75µm exhibited pozzolanic activity, improved durability and strength and inhibited alkali-silica reaction [20, 21]. Although complete replacement is not possible yet, models are being created to determine the ideal replacement proportion based on the particle size.

The results of studies demonstrating the successful use of glass waste in concrete [22, 23], pavements [24, 25], and foam glass emphasize its high effectiveness and potential sustainable application in construction [26-29]. Several studies investigate the impact of disposing of glass waste in landfills [30-33]. The findings suggest that when accounting for greenhouse gas emissions, it is important to carefully analyze energy sources [34-36], especially electricity, and savings at the stage where materials are substituted [37-39].

In previous studies, we developed a resource- and energy-saving technology to produce foam glass based on glass waste (crushed glass bottles) [40].

The obtained material is uniformly porous and has low thermal conductivity [41, 42]. The produced foam glass is marked by high performance indicators and low thermal insulation properties, which widens the scope of its application. The resulting products can be used as thermal insulation material and in load-bearing and enclosing structures. The reduced density of the final product can also lead to lower transportation energy requirements and, consequently, a smaller overall carbon footprint. In foam glass fabrication, the nature of the raw materials, foaming agents and sintering system play crucial roles in determining its properties. Researches are ongoing in advancing thermal management, process control and alternative foaming agents like NaOH to enable efficient energy use, lower sintering temperature and reduce CO_2 emission during foaming. Through meticulous optimization of the heating profile, the process guarantees that the glass particles achieve a homogeneous viscosity at reduced temperatures, therefore leading to energy conservation [43, 44]. The application of fluxing agents like borax, which reduce the melting point, also boosts energy efficiency, thereby presenting a green approach to recycling glass waste without incurring the elevated energy expenses typically linked to conventional glass melting procedures [45, 46]. Use of waste glass in the production of foam glass supports the primary concept of a circular economy. It prevents indiscriminate waste disposal and the demand for primary raw materials, thus preventing environmental effects of raw material extraction and processing. The use of waste glass assists in making significant savings in CO_2 emissions along with supporting sustainable construction practices.

When entering the environment, glass waste is subjected to leaching by precipitation water. The leached ions can enter groundwater and have a detrimental impact on the environment. For example, sodium-calcium glass can become a source of sodium and calcium ions and lead-containing glass can release lead (II) compounds. In the latter case, the problem is aggravated by the fact that there is no reliable technology for secondary use of lead-containing glass. Once this waste gets to landfills, lead compounds containing significant amounts of lead (II) start leaching from the glass and entering groundwater. Secondary use of glass waste can also reduce carbon monoxide (IV) emissions if specially welded glass is substituted or if material processing temperatures are reduced and waste glass is used as flux. Studies on Na+ leaching from various grades of glass in different fractions show that the finer fractions of brown bottle glass and window glass are most affected by leaching [47].

Silicate glass used in the production of glass containers is produced by fusing a mixture of SiO_2, Na_2CO_3, and CaO in special glass furnaces, where, as a result of several processes, complex compounds form that can undergo hydrolysis when interacting with water. The silicate gel formed on the surface has a loose structure that facilitates the diffusion of water and NaOH. This process promotes the breakdown of the glass and the formation of the gel on its surface. The rate of these processes depends proportionally on the composition of the glass and the surface area of the glassware that comes into contact with water. If the size of the glass particles is less than 2 mm, the ratio of leached to unleached alkali may change, increasing the pH of the external water environment. The more alkali oxides, the more the glass is subject to chemical corrosion. The accumulation of glass waste at landfills is also accompanied by chemical pollution of soils, surface, and groundwater by MSW landfill leachate due to alkalinization resulting from the chemical interaction of glass and precipitation [48].

The technogenic load associated with glass waste is mainly caused by two factors: the withdrawal of land to dispose of glass waste and the leaching of chemical components from the composition of glass. The latter factor is especially dangerous when disposing of glass containing lead. The technical solution to minimize the adverse environmental impact of glass waste is the secondary use of glass to produce necessary construction products.

Our literature review shows a growing trend of glass waste used as a secondary raw material to produce construction materials. However, there are limitations stemming from the fact that waste glass is cheaper than virgin glass and the physical and chemical properties of glass are not fully understood. This also acts as a constraint, because no single processing technology can be used as the basis for robust recycling technology. For glass waste to be reused, it is necessary to develop technologies for recycling glass waste as a low-cost environmentally friendly material relying on the resource potential of glass waste and the specific properties of glass, such as ion exchange properties, while also considering the environmental and economic effects.

4. CONCLUSIONS

Our study demonstrates the significant potential of recycled glass waste in sustainable construction materials. Leaching tests confirmed that glass waste, particularly lead-containing glass, poses environmental risks by releasing harmful ions into soil and water. Using finely ground glass powder as a partial replacement for cement showed notable improvements in concrete performance. At substitution levels of up to 30%, concrete mixtures exhibited enhanced compressive strength and durability due to the pozzolanic activity of the glass. Additionally, foam glass produced from crushed glass waste displayed excellent thermal insulation properties, uniform porosity, and mechanical stability, broadening its potential uses in construction. Life cycle analysis highlighted the environmental benefits of using recycled glass, including up to a 30% reduction in CO_2 emissions, significant energy savings, and decreased reliance on primary raw materials.

Despite the promising findings, this study has several limitations. First, the environmental assessment focused primarily on glass waste and did not include a full comparative analysis with other recyclable materials. Second, the experiments were conducted under laboratory conditions, which may not fully represent industrial-scale processes and real-world variability in glass waste composition. Future research should expand the material range, incorporate pilot-scale trials, and assess the long-term mechanical and environmental performance of materials produced using glass waste under diverse climatic and operational conditions.

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