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Abstract

Recycled glass from construction and demolition waste has emerged as a promising precursor in geopolymer production, offering a sustainable alternative to traditional Portland cement. This review synthesizes recent technological advancements and environmental benefits associated with glass-based geopolymers. Key findings reveal that incorporating recycled glass enhances compressive strength, durability, and thermal resistance, while significantly reducing carbon emissions compared to conventional cementitious materials. However, challenges remain due to the variability in glass chemical composition, which can negatively impact geopolymerization processes, leading to inconsistencies in the final product's performance. The review further explores how the integration of additives such as fibers, silica fume, and nanoparticles can mitigate these challenges by improving mechanical properties, including tensile and flexural strength, and enhancing chemical stability. These enhancements are critical in extending the potential applications of geopolymers in aggressive environments. Additionally, the use of recycled glass in geopolymer matrices contributes to significant waste valorization, effectively lowering the demand for virgin raw materials and reducing the environmental burden associated with landfill accumulation. The reduction in energy consumption, particularly by avoiding the high-temperature processes typical of Portland cement production, further amplifies the sustainability of glass-based geopolymers. Despite these environmental and mechanical advantages, technical barriers, including the need for more effective glass sorting and pre-treatment methods, continue to limit widespread adoption. Future research should focus on optimizing geopolymer formulations, improving processing techniques, and scaling up production processes to meet the demands of industrial-scale applications. This review concludes that recycled glass-based geopolymers offer a viable and eco-friendly solution for the construction industry, providing a key pathway toward more sustainable building practices and reducing the overall environmental footprint of construction materials.

Key-words: Geopolymers; Recycled glass; Sustainability in construction; Eco-friendly building materials; Waste valorization; Circular economy; Technological trends in construction; Innovation in sustainability; Case studies; Comprehensive review.

Geopolímeros a partir de residuos de vidrio de construcción y demolición: una revisión de tendencias tecnológicas y aplicaciones sostenibles

Resumen

El vidrio reciclado proveniente de residuos de construcción y demolición ha surgido como un precursor prometedor en la producción de geopolímeros, ofreciendo una alternativa sostenible al cemento Portland tradicional. Esta revisión sintetiza los avances tecnológicos recientes y los beneficios ambientales asociados con los geopolímeros a base de vidrio reciclado. Los principales hallazgos revelan que la incorporación de vidrio reciclado mejora la resistencia a la compresión, durabilidad y resistencia térmica, al mismo tiempo que reduce significativamente las emisiones de carbono en comparación con los materiales cementantes convencionales. No obstante, persisten desafíos debido a la variabilidad en la composición química del vidrio, lo que puede afectar negativamente los procesos de geopolimerización, generando inconsistencias en el rendimiento del producto final. Esta revisión también explora cómo la integración de aditivos como fibras, humo de sílice y nanopartículas puede mitigar estos desafíos, mejorando las propiedades mecánicas, tales como la resistencia a la tracción y a la flexión, además de fortalecer la estabilidad química. Estas mejoras son cruciales para extender las aplicaciones de los geopolímeros en entornos agresivos. Adicionalmente, el uso de vidrio reciclado en matrices de geopolímeros contribuye significativamente a la valorización de residuos, reduciendo la demanda de materias primas vírgenes y disminuyendo la carga ambiental asociada con la acumulación en vertederos. La reducción del consumo energético, particularmente al evitar procesos de alta temperatura típicos de la producción de cemento Portland, amplifica aún más la sostenibilidad de los geopolímeros a base de vidrio. A pesar de las ventajas ambientales y mecánicas, continúan existiendo barreras técnicas, incluidas la necesidad de mejorar los métodos de clasificación y pretratamiento del vidrio. Las investigaciones futuras deben centrarse en la optimización de formulaciones y procesos de producción a escala industrial para asegurar un rendimiento consistente. Esta revisión concluye que los geopolímeros a base de vidrio reciclado ofrecen una solución viable y ecológica para la industria de la construcción, proporcionando un camino clave hacia prácticas de construcción más sostenibles y una reducción significativa de la huella ambiental de los materiales de construcción.

Palabras clave: Geopolímeros; Vidrio reciclado; Sostenibilidad en la construcción; Materiales de construcción ecológicos; Valorización de residuos; Economía circular; Tendencias tecnológicas en la construcción; Innovación en sostenibilidad; Estudios de caso; Revisión exhaustiva de literatura.

1. Introduction

The accelerated growth of the global population and urban expansion have led to an increasing demand for infrastructure, consequently amplifying the consumption of natural resources and exacerbating environmental issues (Hamzah et al., 2021). In this context, the construction industry faces the challenge of minimizing its environmental impact by adopting innovative strategies that promote sustainability. One of the most promising solutions is the use of geopolymers, inorganic materials that have emerged as sustainable alternatives to Portland cement, which is widely used in construction. Geopolymers not only enable a significant reduction in carbon dioxide emissions but also offer the possibility of incorporating industrial waste, such as recycled glass, thus contributing to more efficient waste management (Ahmed, Mahmood et al., 2022; Singh et al., 2020).

Glass, a material extensively used in construction, packaging, and electronic products, represents a considerable source of waste that does not naturally degrade. Although it is inert and non-toxic, its recycling remains limited in many countries, leading to the accumulation of large volumes in landfills. This phenomenon not only constitutes a waste of valuable resources but also contributes to environmental pollution due to its long lifespan and the space it occupies in landfills (Zhang et al., 2022). Simultaneously, the glass manufacturing process is energy-intensive, further increasing greenhouse gas emissions. Against this backdrop, the recycling of glass waste and its utilization in the production of geopolymers presents both an economically and environmentally viable solution for the construction industry due to its potential to replace traditionally used materials and reduce the environmental footprint of this productive sector.

Geopolymers are formed through the alkali activation of precursors rich in silica and alumina, generating a three-dimensional aluminosilicate matrix with superior mechanical properties and durability. Unlike Portland cement, the processes involved in the production of geopolymers do not require high temperatures, thereby reducing their carbon footprint. Additionally, the incorporation of waste, such as recycled glass, not only reduces the amount of material sent to landfills but also improves the properties of the geopolymer in terms of strength and durability, as demonstrated in various studies (Ríos et al., 2023; Hassan et al., 2024).

The use of recycled glass in geopolymer formulations also faces technical challenges, such as the variability in the chemical composition of glass, which can affect its reactivity and the geopolymerization process (Raad Shaker et al., 2024). Depending on its source, glass may contain impurities that negatively influence the formation of the aluminosilicate matrix, necessitating the development of sorting and pre-treatment protocols before recycled glass can be used in geopolymers. Nevertheless, the inclusion of additives and fibers has proven to be an effective solution for improving mechanical properties such as tensile and flexural strength, expanding the potential applications of geopolymers in the construction industry (Hassan et al., 2024).

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Several studies have highlighted the advantages of using recycled glass as a precursor in geopolymer production, which has led to improvements in both the sustainability and mechanical properties of these materials. Ríos et al. (2023) demonstrated that geopolymers formulated with recycled glass achieve compressive strengths comparable to traditional cement, in addition to exhibiting low porosity and high resistance to aggressive environments. These findings, combined with efforts to improve processing technologies and optimize formulations, suggest that recycled glass-based geopolymers could play a key role in the transition toward more sustainable construction practices and less reliance on Portland cement.

The aim of the present document is to provide a state-of-the-art review on the use of recycled glass waste in geopolymer production, analyzing its mechanical properties and durability, as well as the environmental and economic impact of its utilization. Additionally, this paper explores technological challenges and recent innovations, as well as case studies that have demonstrated the feasibility of these materials in real construction projects. The present review aims not only to update current knowledge but also to offer guidelines for future research that promotes the development of more efficient and sustainable geopolymers (Amer et al., 2023; Yilmaz et al., 2024).

This approach is crucial in the context of the growing need to reduce carbon dioxide emissions and minimize the accumulation of solid waste, with glass recycling in geopolymer production emerging as an attractive solution for the construction industry, holding the potential to drive significant change toward global sustainability (Du and Tan, 2013; Schmitz et al., 2011).

2. Methodology

This study employed a semi-systematic review followed by a qualitative literature review, as these methodologies are recognized for identifying scientometric trends that guide the qualitative analysis of the most relevant publications related to the research objective (Mancin et al., 2024).

In the first phase of this study, a systematic review of the literature was conducted using Scopus, as it is a widely used database by researchers worldwide and recognized for its robust document evaluation methods for journals listed therein. In this phase, Boolean operators and English search terms were used to identify research published since 2020 on geopolymers for construction that included either construction glass waste or demolition glass waste. A total of 107 studies were found from the past five years, and publications classified in the fields of physics and astronomy, computer science, agriculture, biological sciences, social sciences, and management and administration were excluded, resulting in a final dataset of 87 articles.

The selected articles were subsequently reviewed to focus on studies specifically dedicated to the use of glass waste in geopolymer production, yielding 63 works that underwent a detailed review to establish the state of the art regarding the mechanical properties, chemical resistance, and environmental impact of the geopolymers studied. Additionally, experimental investigations that evaluated the behavior of these materials under various environmental and usage conditions were prioritized to provide a comprehensive view of trends and advances in this field.

3. Results and discussion

3.1. Properties and behavior of geopolymers manufactured with construction and demolition glass waste

In recent years, the use of construction and demolition glass waste in the production of geopolymers has emerged as a promising and sustainable alternative to traditional Portland cement. This approach offers numerous advantages in terms of mechanical properties, durability, and environmental impact reduction, making it an attractive option for the construction industry. According to Almutairi et al. (2021), the use of recycled glass powder in geopolymers has shown remarkable improvements in compressive strength, reaching up to 60 MPa under specific alkaline activation and curing conditions. A typical formulation of these geopolymers

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includes pulverized glass comprising 70-80% by weight, combined with sodium hydroxide and sodium silicate as activators. These studies suggest that by adjusting the ratios between sodium silicate and alumina, it is possible to optimize both the strength and durability of the material, enabling performance that is comparable or even superior to traditional materials.

One of the key aspects of the behavior of glass-based geopolymers is their fresh state density, which ranges from 1900 to 2200 kg/m^3 (Podolsky et al., 2021). Although reducing the density may affect long-term strength, it offers significant advantages in terms of workability and control of air incorporation. This characteristic is crucial to prevent loss of mechanical properties and enhance the cohesion of the mixture, facilitating its application in various structures. Additionally, the fine particle size (<150 μm) of the glass powder increases reactivity in the presence of alkaline solutions, improving the material's workability. However, excessive glass powder can be detrimental, as it reduces the geopolymer reaction due to unreacted particles, increasing the risk of alkali-silica reactions, which are responsible for crack formation in concrete (Podolsky et al., 2021).

Moreover, studies such as those by Ahmed, Mahmood et al. (2022) and Zhao et al. (2022) indicate that geopolymers produced with glass waste not only exhibit excellent structural performance but also offer enhanced compressive strength, high-temperature resistance, and corrosion resistance. These characteristics make geopolymers with recycled glass a viable option for infrastructures requiring high durability and resistance in adverse conditions. However, the study by Sarkar, Maiti, Malik, and Xu (2024) warns that, although these materials exhibit compressive strength comparable to certain types of concrete, their flexural strength is generally lower. This limitation is attributed to the inherent brittleness of recycled glass, restricting its use in demanding structural applications. To address this issue, researchers suggest the inclusion of additives or fibers that can improve flexural strength and material cohesion.

A significant area of research is the evaluation of the behavior of recycled glass-based geopolymers under varying environmental conditions, such as humidity and temperature fluctuations. According to Sajan et al. (2021) and De Lena et al. (2022), these materials exhibit good thermal stability and chemical resistance, although their performance varies depending on the geopolymer composition and the type of glass used. Nonetheless, limitations persist in structural applications due to their lower tensile and flexural strength compared to conventional concrete (Sarkar et al., 2024). In this context, the optimization of formulations and the incorporation of additional materials, such as natural or synthetic fibers, could offer a solution to improve these properties.

Research by Ardhira, Shukla, and Sathyan (2024) and Zhang et al. (2024) confirms that geopolymers produced with glass waste can achieve compressive strength comparable to conventional materials. Specifically, Zhang et al. (2024) observed that geopolymers based on post-industrial glass can exceed the strength levels of Portland cement, reinforcing the feasibility of these materials for structural applications. However, the inherent brittleness of recycled glass remains a challenge, particularly in terms of flexural strength. Artyk et al. (2024) noted that the inclusion of natural fibers, such as basalt and cellulose, or synthetic fibers like polypropylene, can significantly improve the flexural strength of these geopolymers, thereby reducing their brittleness and increasing their applicability. Additionally, the addition of sodium silicate has been shown to enhance the internal cohesion of the geopolymer matrix, reducing the risk of premature mechanical failure.

In line with these observations, the study by Ardhira, Shukla, and Sathyan (2024) highlighted that the combination of recycled glass with polypropylene fibers not only increases flexural strength but also improves the durability properties of the material. However, the authors caution that the quasi-brittle nature of recycled glass-based geopolymers, along with their low tensile strength, remains an obstacle to their adoption in critical structural applications unless appropriate reinforcements are introduced.

On the other hand, additional studies, such as those conducted by Zhang et al. (2024) and Hassan et al. (2024), have explored the addition of polypropylene and steel fibers to geopolymers with recycled glass, finding improvements in flexural toughness and material ductility. In particular, the hybridization of polypropylene

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fibers has proven effective in reducing material shrinkage by 15%, suggesting that optimizing fiber combinations could be a key strategy to enhance the mechanical properties of geopolymers (Hassan et al., 2024). Furthermore, Danish and Torres (2024) reported that the use of recycled glass from sources such as photovoltaic glass and CRT glass reduces the material’s porosity, improves compressive strength, and decreases permeability, thereby enhancing its chemical resistance in applications exposed to aggressive environments or hazardous waste. Other studies, such as that by Xu et al. (2022), highlight the improvement in flexural strength through the incorporation of additives such as silica and fibers.

Another relevant investigation is that by Wu et al. (2022), who studied the use of cathode ray tube glass powder in geopolymers, finding that this type of glass can either improve or slightly reduce compressive strength depending on the proportion used. In contrast, the use of glass from liquid crystal displays, which contain higher alumina and silica content, showed significant improvements in compressive strength due to their higher reactivity in the polymerization process. These findings underscore the importance of carefully selecting the type of recycled glass employed in geopolymer formulations to optimize their mechanical properties and durability.

In addition to mechanical properties, the behavior of geopolymers manufactured with recycled glass is strongly influenced by the environmental conditions in which they are employed. Subhani et al. (2024) reported that compressive and flexural strength improves when the recycled glass content is adequate, but an excess of this material can create voids in the geopolymer matrix, compromising its overall strength. Exposure to high temperatures tends to increase the material’s strength, while low temperatures decrease its mechanical performance due to the limited capacity of recycled glass to absorb water, causing void formation (Subhani et al., 2024). This suggests that recycled glass-based geopolymers must be carefully formulated to ensure stability under various environmental conditions.

Ślosarczyk et al. (2023) emphasize that the use of recycled glass in alkali-activated materials is promising, as this material can act as an aggregate, precursor, and activator in geopolymeric formulations.

Recycled glass powder, rich in silica, not only replaces other precursors such as fly ash or blast furnace slag but also optimizes the density and strength of the geopolymeric matrix. When combined with alkaline solutions, such as sodium hydroxide and sodium silicate, glass acts as an activator, significantly enhancing compressive strength and durability under adverse environmental conditions, such as acid exposure and freeze-thaw cycles. Furthermore, authors stated that the reduction of porosity and improvement in mechanical behavior strengthen the viability of these geopolymers for applications in demanding environments.

Table 1 summarizes the key trends identified regarding the behavior and applications of geopolymers manufactured with construction and demolition glass waste, as well as the improvements and limitations observed in the reviewed reports.

Table 1. *Key trends identified regarding the properties and behavior of geopolymers manufactured with construction and demolition glass waste. Source: Own elaboration.*

Properties	Sources
Enhanced compressive strength: The use of recycled glass powder has demonstrated compressive strengths of up to 60 MPa, making these geopolymers viable for structural applications.	Almutairi et al. (2021); Podolsky et al. (2021)
Reduced density for improved workability: Geopolymers with glass powder exhibit reduced density, enhancing workability and cohesion, particularly in applications where lightweight materials are a key factor.	Podolsky et al. (2021)
Resistance to aggressive environments: Geopolymers with recycled glass show high resistance to corrosive environments, elevated temperatures, and chemical attacks, making them ideal for infrastructure in harsh settings.	Mahmood et al. (2022); Zhao et al. (2022); Sajan et al. (2021); De Lena et al. (2022)
Limitations in flexural strength: Despite their high compressive strength, geopolymers with recycled glass exhibit lower flexural strength, restricting their use in highly demanding structural applications.	Sarkar et al. (2024); Maiti et al. (2024)
Improvements with additives and fibers: The inclusion of additives and fibers enhances tensile and flexural strength, expanding their applicability in more demanding structural projects.	Artyk et al. (2024); Zhang et al. (2024); Shukla and Sathyan (2024)
Optimization of glass content: Adjustments in the amount of recycled glass allow for controlling material reactivity, preventing issues such as crack formation and improving mechanical performance.	Subhani et al. (2024); Ślosarczyk et al. (2023)

3.2. Technological innovations and challenges associated with the application of geopolymers derived from construction and demolition glass waste

In recent years, advances in the research of geopolymers produced from recycled glass have led to significant improvements in their mechanical properties and durability. One of the most notable innovations has been the addition of metakaolin and silica fume to recycled glass, which has increased the flexural strength of geopolymers by 25%, making them suitable for high-strength structural applications, such as slabs and beams (Almutairi et al., 2021). These additives contribute to the formation of a denser microstructure, enhancing the internal cohesion of the geopolymer matrix and promoting greater thermal and chemical resistance.

The ratio of silicates to alumina in formulations has been shown to be a key factor in the performance of geopolymers. Formulations with a ratio of 3, considered optimal, exhibit remarkable fire resistance and reduced thermal shrinkage, withstanding temperatures of up to 1050 °C (Almutairi et al., 2021). This behavior is attributed to the increased presence of zeolites in the structure, which improve thermal properties and make geopolymers suitable for applications exposed to high temperatures, such as industrial furnace linings.

In terms of chemical resistance, geopolymers produced with 70-80% recycled glass have demonstrated high resistance to sulfate and acid attacks, making them ideal for applications in aggressive environments, such as coastal or industrial zones. Chloride permeability tests indicate a 40% reduction compared to Portland cement concrete, suggesting improved performance in marine environments or those exposed to aggressive chemicals (He et al., 2021).

In addition to improvements in durability and chemical resistance, compressive strength tests have also shown promising results. Recycled glass-based geopolymers with the addition of ground granulated blast furnace slag (GGBS) have achieved compressive strengths of up to 90 MPa after 28 days of curing, making them competitive with traditional materials for durable structural applications (He et al., 2021). This reinforces the viability of geopolymers for infrastructures subject to high mechanical demands.

However, despite these advances, significant technological challenges remain that limit the widespread adoption of geopolymers made from recycled glass. One of the main challenges is the variability in the chemical composition of recycled glass, which affects its reactivity during the alkali activation process (Sarkar et al., 2024). The presence of impurities, such as metal oxides or organic residues, can interfere with the formation of the aluminosilicate network, reducing the quality of the final material. This highlights the need for more rigorous treatment and sorting protocols to ensure consistency in geopolymer production.

On the other hand, the incorporation of nanoparticles has been one of the most innovative strategies for enhancing the properties of geopolymers. Recent studies have explored the use of silica nanoparticles, which act as reinforcements in the geopolymer microstructure, improving both the mechanical strength and durability of the material. These nanoparticles promote more efficient polymerization by interacting with the glass residues, resulting in higher compressive strength and reduced porosity (Sarkar et al., 2024). Additionally, aluminum oxide nanoparticles have been shown to improve high-temperature resistance, increasing the thermal stability of the material to temperatures of up to 1200°C, thus expanding its applicability in extreme environments (Manzoor et al., 2024).

In addition to nanoparticles, the use of synthetic fibers such as polypropylene and alkali-resistant glass fibers has been another important innovation. These additives have proven effective in enhancing flexural strength and load-bearing capacity in geopolymers (Zhang et al., 2024). For example, the addition of 1.5% polypropylene fibers has been shown to be optimal for improving the mechanical properties of the material without compromising its workability (Danish and Torres, 2024).

Despite these advances, scalability remains a significant challenge. The high costs associated with the pre-treatment of

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recycled glass and the variability in its availability limit the large-scale production of geopolymers (Sarkar et al., 2024). This problem is exacerbated in regions where recycled glass is not available in sufficient quantities or where recycling processes are not well developed. Further research is needed to optimize processing methods and reduce production costs.

Another major challenge is the uneven distribution of glass particles within the geopolymer matrix, which can create weak spots and affect the material's durability. Additionally, the adhesion between the glass particles and the matrix remains a critical area of investigation, as poor adhesion can lead to a significant reduction in material strength (Burciaga et al., 2020; Kumar et al., 2022).

In this context, the development of computational models has emerged as a promising tool for optimizing geopolymer design. Machine learning-based models, such as XGBoost, have been employed to predict the mechanical properties of geopolymers, allowing for more efficient formulation adjustments (Yilmaz et al., 2024). These models consider parameters such as the type of precursor, the alkali activator used, and the curing method, providing greater accuracy in predicting compressive and flexural strengths.

Finally, the optimization of curing processes has been key to improving the performance of geopolymers. The incorporation of superplasticizers, such as polycarboxylate, has improved the workability of the mixtures without increasing water content, resulting in higher density and mechanical strength (Manzoor et al., 2024). These additives are particularly useful in formulations with high recycled glass content, as they facilitate mixing and placement of the material.

Regarding technological limitations for the adoption of geopolymers in structural applications, studies suggest that the addition of large amounts of fibers may reduce compressive strength, limiting their use in load-bearing elements (Ozcelikci et al., 2024). This finding suggests that recycled glass-based geopolymers may be more suitable for non-structural applications, such as coatings or masonry products.

Table 2 highlights the key innovations and technological challenges identified in the review of the application of geopolymers made from construction and demolition glass waste.

Table 2. *Key findings regarding the application of geopolymers derived from construction and demolition glass waste. Source: Own elaboration.*

Applications	Sources
Increased flexural strength with additives: The addition of metakaolin and silica fume to recycled glass increases flexural strength by 25%, enabling its use in high-strength structural applications such as slabs and beams.	Almutairi et al. (2021)
Optimization of formulations for fire resistance: An optimal silicate-to-alumina ratio (3:1) enhances fire resistance, supporting temperatures up to 1050°C. Suitable for industrial furnace linings.	Almutairi et al. (2021)
Improved chemical resistance: Geopolymers with recycled glass demonstrate high resistance to sulfates and acid attacks, making them ideal for aggressive environments such as coastal and industrial areas.	He et al. (2021)
Enhanced compressive strength with granulated slag: Geopolymers with ground granulated blast furnace slag (GGBS) reach 90 MPa at 28 days, making them competitive with traditional materials for structural applications.	He et al. (2021)
Incorporation of nanoparticles for improved strength and durability: Silica and aluminum oxide nanoparticles improve compressive strength and durability, proving useful in extreme applications, such as at temperatures up to 1200°C.	Sarkar et al. (2024); Manzoor et al. (2024)
Use of synthetic fibers to enhance flexural strength: The addition of polypropylene fibers and alkali-resistant glass fibers improves flexural strength and load-bearing capacity in geopolymers.	Zhang et al. (2024); Danish and Torres (2024)
Computational models for optimizing formulations: Tools like XGBoost are used to predict the mechanical properties of geopolymers, optimizing formulations to enhance compressive and flexural strength.	Yilmaz et al. (2024)
Use of superplasticizers to improve workability: The incorporation of superplasticizers, such as polycarboxylate, enhances workability without increasing water content, leading to higher density and mechanical strength.	Manzoor et al. (2024)

The published studies clearly demonstrate that, thanks to recent advances, the application of geopolymers manufactured from construction and demolition glass waste shows significant potential

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to improve both the sustainability and mechanical properties of these materials. However, challenges related to the variability of recycled glass, the scalability of the processes, and the optimization of formulations must still be addressed to facilitate their widespread adoption in the construction industry.

3.3. Case studies on the application of construction and demolition glass waste for industrial products

The use of construction and demolition waste (CDW) glass in the fabrication of geopolymers has gained prominence in recent decades, recognized for its potential to produce sustainable materials for non-structural industrial applications. The reuse of this waste offers an ecological alternative to conventional materials, promoting a circular economy and reducing the environmental footprint associated with construction. This section presents various case studies that illustrate the advances and challenges of this technology.

Amran et al. (2020) investigated the use of recycled glass in the production of cladding panels in Northern Europe. The resulting geopolymer panels, reinforced with silica nanoparticles, demonstrated high resistance to adverse weather conditions, such as humidity and extreme temperatures. Although the initial production costs were higher than conventional materials, the environmental benefits of using recycled glass were highlighted as one of the most valuable aspects of this technology.

In urban settings, Epure et al. (2023), Rios et al. (2023), and Neves and Freire (2022) conducted studies on the application of geopolymers with recycled glass for pavement construction. These pavements exhibited good wear resistance to pedestrian traffic, although the importance of continuous monitoring of their long-term performance was emphasized. These studies suggest that with a consistent supply of recycled glass, this technology could be scaled for larger urban projects.

Girish et al. (2023) addressed the use of recycled glass geopolymers in coastal pavements, where salinity presents a significant challenge. The study revealed adequate chemical resistance to corrosion in these environments, highlighting the suitability of geopolymers for coastal infrastructure applications. However, the scalability of this technology remains a challenge, particularly in terms of optimizing production costs and securing a steady supply of raw materials.

Sarkar et al. (2024) explored the use of geopolymers with recycled glass for the fabrication of non-structural prefabricated elements in factories and warehouses in East Asia. The results demonstrated notable performance in terms of thermal and acoustic insulation, underscoring the potential of this technology for expanding its use beyond non-load-bearing structures in industrial applications.

An innovative approach was presented by Zuaiter et al. (2022), who incorporated recycled glass fibers into geopolymers, significantly improving mechanical properties. The study reported an increase of up to 77% in compressive strength, suggesting that fiber-reinforced geopolymers could be suitable for more demanding structural applications. Similarly, Shiwa et al. (2024) studied the structural behavior of geopolymer beams reinforced with steel fibers and glass fiber-reinforced polymer (GFRP), observing greater flexibility under dynamic loads, reinforcing their feasibility for innovative structural applications.

Khalaf and Mahamood (2024) investigated the alkali activation process in recycled glass-based geopolymers, highlighting that the optimization of alkaline solutions can enhance the reactivity of glass, strengthening the geopolymer matrix. This approach offers a promising pathway to improve both the strength and durability of the materials in extreme conditions.

Regarding the use of volcanic materials, Cakmak et al. (2024) evaluated the incorporation of obsidian and silica fume into geopolymer mortars, achieving notable improvements in mechanical properties after thermal curing processes. This finding underscores the potential of volcanic waste to contribute to industrial sustainability.

Bompa et al. (2022) investigated the viability of geopolymer mortars formulated with recycled glass, fly ash, and blast furnace slag, demonstrating that these mortars achieved adequate

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compressive strength for high-traffic pavements. Additionally, the inclusion of recycled glass improved water absorption resistance, emphasizing its applicability in sustainable pavement infrastructure.

Zareechian et al. (2023) explored the use of one-part geopolymers (OPGs), activated with sodium hydroxide and sodium carbonate, achieving compressive strengths of up to 50 MPa at 28 days, positioning OPGs as a sustainable and low-environmental-impact alternative to Portland cement.

Additionally, the research by Atoyebi et al. (2023) on the production of roofing tiles from geopolymers and recycled PET showed improvements in the physical properties of the tiles, particularly in terms of water absorption, although no significant improvements in mechanical properties were observed.

Tajaddini et al. (2023) and Ramezani et al. (2023) investigated soil stabilization through the incorporation of recycled glass powder, demonstrating improvements in compressive strength and durability, highlighting the potential of glass waste for applications in road infrastructure.

Other significant studies have explored novel applications of recycled glass-based geopolymers, including additive manufacturing and 3D printing (Ilcan et al., 2023), the development of architectural products (Rios et al., 2023; Stepien and Wojarska-Gniady, 2023), and investigations into their applicability in organic soils and geopolymer mortars (Yildirim et al., 2023; Eskisar, 2022; Ahmed et al., 2022). The reviewed studies highlight the broad potential of recycled glass-based geopolymers for sustainable industrial applications. However, significant challenges remain, such as the need to improve the consistency of recycled glass supply, the standardization of production processes, and the optimization of costs. Overcoming these obstacles is essential to achieving broader and more effective adoption of this technology in the industry.

Table 3 presents the key trends identified in the reported case studies on the technological applications of glass waste.

Table 3. *Case studies on the application of construction and demolition glass waste for the production of industrial-use products. Source: Own elaboration.*

Case Studies	Sources
Cladding panels: Utilization of recycled glass for panels resistant to moisture and extreme temperatures.	Amran et al. (2020)
Urban pavements: Application of geopolymers with recycled glass in pavements resistant to pedestrian wear.	Epure et al. (2023), Rios et al. (2023), Neves and Freire (2022)
Coastal infrastructures: Use of geopolymers in coastal pavements with high resistance to salinity-induced corrosion.	Girish et al. (2023)
Non-structural prefabricated elements: Thermal and acoustic insulation with recycled glass geopolymers for factories and warehouses.	Sarkar et al. (2024)
Fiber-reinforced geopolymers: Use of recycled glass fibers to improve compressive strength by up to 77%.	Zuaiter et al. (2022)
Optimized alkali activation: Enhanced reactivity of recycled glass through alkali activation in geopolymers.	Khalaf and Mahamood (2024)
Incorporation of volcanic materials: Use of obsidian and silica fume to improve mechanical properties after thermal curing.	Cakmak et al. (2024)
Geopolymer mortars: Use of recycled glass, fly ash, and slag in mortars for high-traffic pavements.	Bompa et al. (2022)

Conclusions

The conclusions of this study underscore the significant potential of geopolymers based on recycled glass waste for the construction industry, particularly in terms of their positive impact on sustainability and the enhanced mechanical properties of the resulting materials. Across the reviewed studies, several key benefits associated with the incorporation of recycled glass in geopolymer production have been identified, as well as the challenges that must still be addressed to enable large-scale adoption.

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Firstly, geopolymers made from glass waste have proven to be a viable and more sustainable alternative to Portland cement, offering a notable reduction in CO_2 emissions. Cement production is one of the largest sources of greenhouse gas emissions in the construction industry, and glass-based geopolymers, which do not require high-temperature calcination processes, significantly reduce this carbon footprint. Studies such as those by Amran et al. (2020) and Ramezani et al. (2023) confirm that products derived from recycled glass, used in various non-structural industrial applications, provide a substantial reduction in emissions, making them key materials for sustainable construction.

On a technical level, studies have reported that geopolymers formulated with recycled glass exhibit high compressive strength, low permeability, and improved performance in aggressive environmental conditions, such as coastal or industrial areas. For example, the findings of Girish et al. (2023) demonstrated the use of these geopolymers in coastal pavements, where significant chemical resistance to salinity-induced corrosion was achieved. Similarly, the research conducted by Zareechian et al. (2023) highlights the viability of one-part geopolymers (OPGs) in terms of sustainability and long-term durability, reinforcing their applicability in high-demand infrastructure.

Another important aspect is the use of additives such as nanoparticles and synthetic fibers, which, when incorporated into the geopolymeric matrix, have been shown to improve mechanical properties and durability. Studies by Zuaiter et al. (2022) and Shiwa et al. (2024) report significant improvements in the compressive and flexural strength of geopolymers reinforced with silica nanoparticles and glass fibers. However, it is important to note that the inclusion of high concentrations of these additives can lead to agglomeration problems, negatively impacting material cohesion, as observed in the study by Ahmed et al. (2022).

From a sustainability and circular economy perspective, the use of glass waste in geopolymer production not only contributes to emission reductions but also promotes the recycling of materials that would otherwise end up in landfills. This reduces the demand for virgin resources and decreases the costs associated with waste disposal, as highlighted by studies such as Sarkar et al. (2024) and Tajaddini et al. (2023). However, one of the main challenges remains the variability in the composition of recycled glass, which can affect the consistency of the final product. This variability in waste materials necessitates the implementation of more rigorous protocols for the processing and sorting of glass waste to ensure greater homogeneity in geopolymer production.

Additionally, the scalability of production processes is identified as a significant challenge. While substantial progress has been made in experimental research, further optimization of production methods is still required to enable the widespread adoption of this technology. Future research must focus on developing more efficient processes and reducing production costs associated with the recycling and processing of glass, which will allow glass-based geopolymers to become a competitive alternative to conventional construction materials.

The review established that geopolymers made from recycled glass waste have significant potential to transform the construction industry, both in terms of sustainability and mechanical performance. Despite the technological and economic challenges associated with large-scale production, recent advances in the formulation of these materials suggest they have the potential to play a key role in the transition to a greener and more efficient construction industry. It is essential to continue research efforts to overcome current barriers, optimize formulations, and explore new structural and non-structural applications of these geopolymers in the future.

Conflict of interest statement

The authors of this document declare that their academic and ethical judgment is independent of the institutions that provided financial support for the development of this study. Furthermore, the authors report no interests beyond those typically involved in research based on the scientific method.

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