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The environmental, economic, and social potential of industrial waste-based geopolymer materials toward the net zero emission 2050 target

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ABSTRACT

Background: The construction sector significantly contributes to global CO_2 emissions, primarily from Portland cement production, accounting for about 8% of total emissions. This study explores the environmental, economic, and social potential of industrial waste-based geopolymers as a sustainable alternative to conventional concrete, supporting the Net Zero Emission 2050 target. **Methods:** This research adopts a qualitative literature review approach, collecting and analyzing recent studies concerning the utilization of fly ash, slag, silica fume, and waste glass as binding precursors in geopolymer synthesis. Furthermore, a comparative analysis was conducted to assess the potential for CO_2 emission reduction and cost efficiency based on several implemented projects. **Findings:** The findings indicate that geopolymer concrete can reduce CO_2 emissions by approximately 18%–64% and production costs by up to 30%, while maintaining comparable mechanical performance and durability to Portland cement-based concrete. Large-scale applications in several countries have demonstrated the material's practical feasibility. From an environmental perspective, geopolymer technology substantially decreases embodied carbon; economically, it lowers maintenance expenses; and socially, it promotes green employment opportunities and enhances public awareness of sustainable construction practices. Nevertheless, the lack of standardized regulations and limited policy support remain key barriers to its broader implementation. **Conclusion:** Geopolymer technology demonstrates significant potential in achieving sustainable and low-carbon construction, thereby contributing to the realization of the Net Zero Emission 2050 goal. **Novelty/originality of this article:** The novelty of this study lies in its comprehensive integration of various industrial waste materials to holistically assess their environmental, economic, and social benefits as a unified approach toward sustainable construction.

KEYWORDS: geopolymer concrete; industrial waste utilization; sustainable construction.

1. Introduction

The escalating impacts of climate change have become one of the most pressing global challenges of the twenty-first century, exerting profound influences across various sectors, including energy, transportation, and construction. Among these sectors, the construction industry has emerged as a significant contributor to environmental degradation due to its high consumption of natural resources and intensive energy use (Al-Numan, 2024). In particular, conventional concrete production, which relies heavily on Portland cement as the primary binder, is associated with substantial carbon dioxide (CO_2) emissions, contributing markedly to anthropogenic climate change (Kaptan et al., 2024). Estimates indicate that the production of Portland cement alone accounts for approximately 8% of

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global CO_2 emissions, emphasizing the urgent need for the construction industry to adopt more sustainable practices (Sverdrup & Olafsdottir, 2023). Figure 1 illustrates the global CO_2 emissions from cement production in 2023, highlighting the significant environmental footprint of this sector (Purton, 2024).

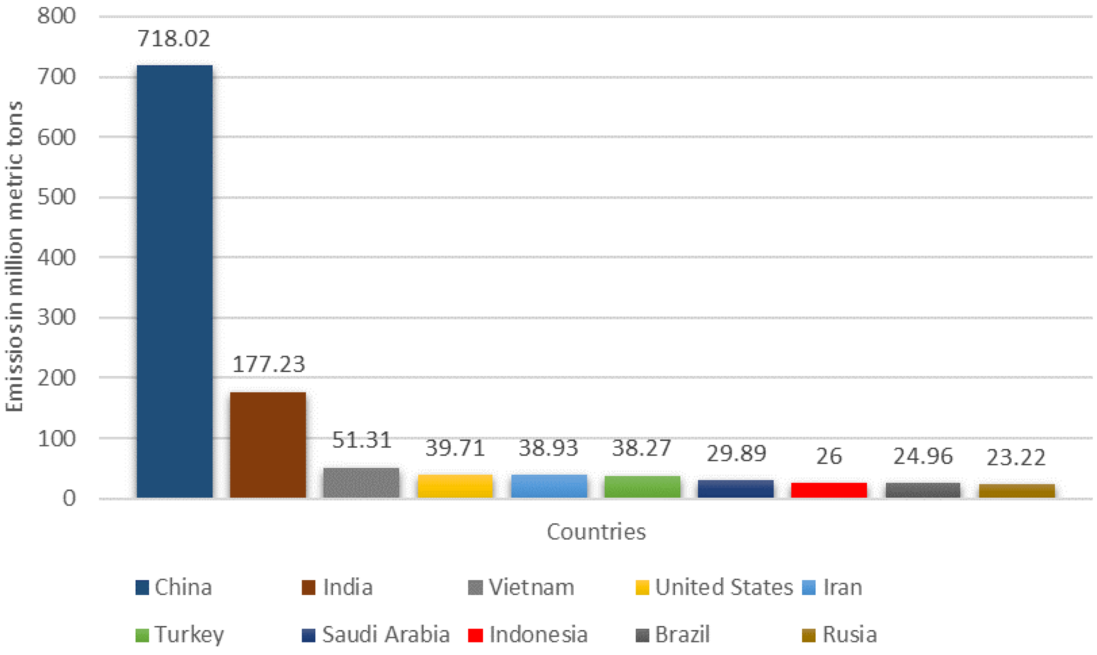

Fig. 1. Carbon dioxide (CO_2) emissions from the manufacture of cement worldwide in 2023 (in million metric tons)
(Purton, 2024)

The construction sector is not only a major source of greenhouse gas emissions but also a substantial consumer of energy. Globally, it is estimated that buildings and infrastructure contribute to approximately 36% of total energy consumption and 39% of overall CO_2 emissions (Singh et al., 2023). These figures underscore the pressing environmental challenges associated with conventional construction practices, particularly in the context of the accelerating climate crisis. The widespread recognition of these issues has driven governments, policymakers, and industry stakeholders to pursue ambitious strategies aimed at reducing greenhouse gas emissions, thereby aligning with the broader global commitment to achieve the Net Zero Emission (NZE) target by 2050. This international agenda emphasizes the critical need for decarbonizing key industrial sectors, including cement and construction, through technological innovation, material substitution, and enhanced resource efficiency.

In response to these challenges, the construction industry has increasingly focused on the development and implementation of alternative construction materials that exhibit lower environmental impacts compared to conventional Portland cement-based concrete. Among these emerging solutions, geopolymer concrete has attracted considerable attention due to its potential to drastically reduce CO_2 emissions without compromising mechanical performance or durability (Anisa et al., 2021). Unlike conventional concrete, which relies on the hydration of Portland cement, geopolymer concrete utilizes aluminosilicate-rich materials as primary binders, initiating a chemical process known as geopolymerization (Firdous et al., 2018). This process results in the formation of three-dimensional polymeric networks, which provide comparable or superior structural performance relative to traditional concrete while offering significant environmental benefits (Ikotun et al., 2024). Previous studies have reported that substituting conventional cement with geopolymer binders can lead to a reduction in CO_2 emissions by as much as 80% (Tong et al., 2018), demonstrating the transformative potential of this material for sustainable construction practices.

The raw materials required for geopolymer production are often sourced from industrial byproducts and waste streams, which not only mitigates environmental pollution but also promotes the principles of the circular economy. Fly ash, a byproduct generated by coal-fired power plants, represents one of the most widely used precursors for geopolymer synthesis (Azad & Samarakoon, 2021). If not properly managed, fly ash can pose significant environmental hazards, including air and water pollution, heavy metal contamination, and soil degradation. The utilization of fly ash in construction materials not only addresses these environmental concerns but also converts a potential waste liability into a valuable resource. Other industrial byproducts with substantial potential for geopolymer applications include non-biodegradable glass waste, slags, and silica fume derived from silicon and ferroalloy production (Hamed et al., 2024; Orhan et al., 2023). The production of these wastes is projected to increase in the coming decades due to industrial expansion and urbanization, emphasizing the growing importance of sustainable waste valorization strategies. Metakaolin, obtained through the thermal activation of kaolin clay, also serves as a high-purity aluminosilicate precursor, providing an additional option for geopolymer synthesis and further expanding the portfolio of sustainable construction materials (Kriven et al., 2024).

Despite the promising potential of geopolymer technology, its widespread adoption faces several technical, logistical, and regulatory challenges. A key limitation lies in the variability and limited availability of industrial wastes that meet the specific chemical and physical requirements necessary for consistent geopolymerization. Variations in the chemical composition, fineness, and reactivity of precursors can significantly affect the mechanical properties and durability of geopolymer concrete, necessitating stringent quality control measures (Barbhuiya et al., 2025). Moreover, supply chain constraints, including transportation, storage, and processing of waste materials, further complicate large-scale implementation. The absence of universally accepted technical standards and building codes for geopolymer materials also represents a critical barrier to commercialization, as regulatory uncertainty can discourage investment and limit market penetration. These challenges underscore the need for a comprehensive assessment framework that evaluates not only the environmental benefits but also the economic viability and practical feasibility of industrial waste-based geopolymer concrete.

Previous research efforts have predominantly focused on single-source materials, such as fly ash, ground granulated blast-furnace slag (GGBS), silica fume, glass powder, or metakaolin, assessing their respective CO_2 reduction potential and cost efficiency. While these studies have demonstrated promising environmental outcomes, there remains a significant gap in understanding the synergistic effects of combining multiple industrial waste streams to produce geopolymer materials with enhanced performance and broader applicability. Integrating diverse waste sources could potentially overcome limitations associated with precursor variability, ensure a more consistent supply of raw materials, and optimize the chemical composition for superior mechanical properties. Furthermore, such an approach aligns with the principles of sustainable resource management, waste minimization, and the circular economy, providing a holistic strategy for decarbonizing the construction industry.

The economic dimension of geopolymer adoption is another critical aspect that warrants thorough investigation. While environmental benefits such as CO_2 emission reduction and waste valorization are well-documented, the cost implications associated with raw material procurement, processing, and production must be carefully analyzed to ensure commercial feasibility. For example, the availability and pricing of industrial byproducts vary regionally, and transportation costs can significantly influence the overall economic viability of geopolymer concrete (Assi et al., 2020). Additionally, energy requirements for thermal activation or chemical processing of precursors, as well as labor and infrastructure costs, contribute to the total production cost. Therefore, a comprehensive evaluation encompassing both environmental and economic factors is essential to provide a realistic understanding of the potential benefits and limitations of geopolymer technology in the context of large-scale construction applications.

In light of these considerations, this study aims to provide a comprehensive assessment of the environmental, economic, and practical potential of integrating multiple industrial waste materials, including fly ash, slag, glass powder, and silica fume, as low-carbon alternatives in the construction industry. The research methodology involves evaluating the availability of these industrial wastes, estimating their potential for cement substitution, quantifying the resulting CO_2 emission reductions, and assessing economic efficiency based on material costs, processing requirements, and logistical considerations. By adopting an integrative approach, this study seeks to bridge existing knowledge gaps and provide evidence-based recommendations for the practical implementation of multi-source geopolymer materials in construction.

Moreover, the outcomes of this research are expected to contribute significantly to achieving global climate objectives, particularly the Net Zero Emission 2050 target. By demonstrating the feasibility of industrial waste-based geopolymer concrete, this study not only promotes sustainable construction practices but also supports broader societal goals, including resource efficiency, waste reduction, and environmental protection. The findings have implications for policymakers, engineers, material scientists, and industry practitioners, providing insights into strategic material selection, waste management, and sustainable infrastructure development. Additionally, the research highlights the importance of innovation and interdisciplinary collaboration in addressing complex environmental challenges, reinforcing the critical role of science and technology in facilitating the transition toward a low-carbon, circular economy.

The pressing environmental and energy challenges associated with conventional Portland cement-based concrete necessitate urgent innovation in construction materials. Geopolymer concrete, derived from industrial byproducts such as fly ash, slag, glass powder, silica fume, and metakaolin, represents a promising low-carbon alternative with substantial potential to reduce CO_2 emissions and promote sustainable development (Azad & Samarakoon, 2021). Despite existing challenges related to material variability, supply chain logistics, and regulatory frameworks, a comprehensive assessment of environmental, economic, and practical feasibility can provide actionable insights to advance large-scale adoption. By integrating multiple industrial waste streams, this study seeks to enhance the performance, availability, and sustainability of geopolymer materials, thereby contributing to the global effort to achieve Net Zero Emissions by 2050 and fostering the development of a resilient, environmentally responsible construction industry.

2. Methods

2.1 Research design and data sources

This study employed a qualitative research approach, focusing on the systematic examination and synthesis of secondary data obtained from a wide range of credible academic sources. The choice of a qualitative methodology was guided by the nature of the research objectives, which sought to explore and evaluate the environmental, economic, and practical potential of industrial waste-based geopolymer materials as sustainable alternatives in the construction sector. Qualitative approaches are particularly well-suited for studies aiming to develop conceptual frameworks, generate comprehensive understanding, and identify patterns across multiple studies, especially when experimental or primary data collection may be limited due to logistical, temporal, or financial constraints (Luft et al., 2022). By relying on secondary data, this research leveraged the breadth and depth of existing knowledge while ensuring that the insights generated are grounded in robust, peer-reviewed evidence.

The primary sources of data comprised academic journals, indexed scientific publications, conference proceedings, books, and policy documents related to sustainable construction, geopolymer technology, and industrial waste utilization. These sources were carefully selected to provide comprehensive coverage of the most recent developments in geopolymer research and to ensure that the findings were aligned with current scientific discourse and industrial practices. To maintain rigor and credibility, the literature search was restricted to publications released from 2020 to 2025, thereby prioritizing the most up-to-date information on material innovations, environmental assessments, and policy developments. Additionally, sources were selected based on their indexing in reputable databases such as Scopus, Web of Science, and Google Scholar, ensuring that only peer-reviewed and high-impact literature contributed to the analysis. The research process commenced with the clear identification of research objectives and the formulation of guiding research questions. The central aim of this study was to examine the environmental and economic feasibility of integrating multiple industrial waste streams, including fly ash, slag, silica fume, metakaolin, and glass powder into geopolymer concrete production.

2.2 Systematic literature review and data analysis techniques

Following the identification of research objectives, a systematic literature review was conducted to ensure the collection of the most relevant and high-quality data. The literature review process involved several sequential steps. Initially, keyword-based searches were performed using combinations of terms such as "geopolymer concrete," "industrial waste utilization," "fly ash," "slag," "silica fume," "metakaolin," "glass powder," "low carbon construction materials," "CO_2 emission reduction," and "economic feasibility." Boolean operators, truncation, and filters were applied to refine search results and exclude irrelevant or outdated studies (Alharbi & Stevenson, 2020). Each identified article was subjected to a preliminary screening process, which included assessment of titles, abstracts, and keywords to evaluate relevance to the research focus. This initial screening ensured that the pool of selected literature maintained both topical relevance and methodological rigor.

The second stage of the literature selection process involved the application of specific inclusion and exclusion criteria to ensure that the resulting dataset was both comprehensive and relevant (Cooper et al., 2018). The inclusion criteria comprised direct relevance to the use of industrial waste in geopolymer material production, empirical or theoretical analysis of environmental, economic, or social implications, availability of quantitative or qualitative data on CO_2 emission reduction or cost analysis, and publication in peer-reviewed journals or reputable scientific outlets within the past five years. Studies were excluded if they lacked sufficient methodological detail, focused solely on conventional cement-based concrete without comparison to geopolymer alternatives, or were published in non-peer-reviewed sources. This rigorous selection protocol ensured that the literature included in the analysis represented the most reliable, up-to-date, and scientifically valid information available.

Once the literature was selected, a detailed content analysis was conducted to extract, categorize, and synthesize key findings. Content analysis is a systematic technique that enables researchers to identify patterns, themes, and relationships within qualitative data. In the context of this study, the extracted information was organized into thematic categories, including: material availability and chemical composition of industrial wastes, potential for CO_2 emission reduction relative to conventional concrete, economic considerations such as production cost, transportation, and processing requirements, logistical and supply chain challenges, and regulatory and policy-related constraints. Each theme was analyzed to identify common findings, discrepancies, and emerging trends across multiple studies, providing a comprehensive overview of both opportunities and limitations associated with geopolymer material adoption.

The content analysis process was further enhanced by employing comparative synthesis techniques, whereby results from individual studies were systematically compared and contrasted to identify patterns and best practices. For example, variations in CO_2 reduction estimates between fly ash-based geopolymers and metakaolin-based geopolymers were analyzed in the context of precursor chemical composition, curing methods, and mix design parameters. Similarly, cost analyses across different regions and production scales were compared to determine factors influencing economic feasibility, such as availability of industrial byproducts, transportation distances, and local energy costs. By integrating findings across multiple studies, the research was able to generate holistic insights into the environmental and economic performance of multi-source geopolymer materials, as well as identify knowledge gaps and research priorities for future investigations.

In addition to the environmental and economic dimensions, the analysis also considered policy and regulatory frameworks influencing the implementation of geopolymer technology. To ensure methodological rigor and transparency, the study followed established protocols for systematic literature review and qualitative synthesis. All data sources, inclusion and exclusion criteria, and analytical procedures were meticulously documented, enabling reproducibility and verification of findings. Furthermore, triangulation was employed by cross-referencing information across multiple sources, thereby enhancing the credibility and validity of the results. Where quantitative data were reported, such as CO_2 emission reductions or cost metrics, values were standardized to common units to enable meaningful comparison across studies. In cases of conflicting results, the underlying assumptions, experimental conditions, or geographical contexts were examined to provide an informed interpretation.

Finally, the findings of this methodological process were synthesized to develop an integrative conceptual framework illustrating the potential of multi-source industrial waste-based geopolymer materials in reducing carbon emissions, promoting economic efficiency, and supporting sustainable construction practices. This framework not only summarized the empirical evidence but also provided theoretical insights into the mechanisms by which industrial waste valorization contributes to environmental and economic sustainability. By bridging empirical findings with conceptual understanding, the study offers practical guidance for policymakers, engineers, and industry practitioners seeking to implement geopolymer technology on a large scale, while simultaneously contributing to global climate mitigation targets, including the Net Zero Emission 2050 goal.

In summary, this study employed a qualitative research design centered on systematic literature review and content analysis of secondary data. The research process encompassed clearly defined objectives, comprehensive literature search and selection based on inclusion criteria, thematic content analysis, comparative synthesis, and consideration of policy and regulatory contexts. By integrating findings across environmental, economic, and practical dimensions, this study provides a comprehensive and scientifically grounded assessment of the feasibility, potential benefits, and implementation challenges associated with multi-source industrial waste-based geopolymer materials in construction. The methodological approach ensures rigor, credibility, and relevance, positioning the study to offer meaningful contributions to the advancement of sustainable construction technologies and climate mitigation strategies.

3. Results and Discussion

3.1 The potential of industrial waste for geopolymer materials

The cement production process is one of the largest contributors to global carbon dioxide (CO_2) emissions, accounting for a significant portion of anthropogenic greenhouse gases (Barbhuiya et al., 2025). Portland cement, the primary binder in conventional concrete, requires high-temperature calcination of limestone, which releases CO_2 both from the chemical decomposition of calcium carbonate and from the combustion of fossil fuels (Mohammed et al., 2023). This dual source of emissions highlights the urgent need for alternative materials in the construction sector. Simultaneously, the global generation of industrial waste has increased exponentially due to rapid industrialization and urbanization, creating both environmental and health challenges. Among these wastes, fly ash, ground granulated blast-furnace slag (GGBS), silica fume, glass powder, and metakaolin remain largely underutilized in many regions. These byproducts, when properly managed, can be harnessed as precursors for the production of geopolymer materials, offering a sustainable alternative to Portland cement.

The chemical composition of industrial waste is crucial in determining its suitability for geopolymerization (Hassani & Kazemian, 2024). For instance, fly ash, a byproduct of coal combustion, is rich in silica (SiO_2) and alumina (Al_2O_3), which are essential for forming the aluminosilicate networks that constitute geopolymer binders (Bhardwaj et al., 2024). The high reactivity of fly ash, particularly class F and class C variants, allows it to participate actively in the geopolymerization process when activated with alkaline solutions such as sodium hydroxide or potassium hydroxide (Jiao et al., 2023). Ground granulated blast-furnace slag, generated during iron production, also contains substantial calcium oxide (CaO), which can improve the early strength development of geopolymer concrete (Ahmed et al., 2025). Additionally, silica fume, obtained from silicon or ferrosilicon alloy production, possesses an extremely fine particle size and a high silica content, contributing to both the mechanical and durability properties of geopolymer composites. Glass powder, derived from post-consumer or industrial glass, offers another high-silica source, while metakaolin, produced by calcining kaolin clay, provides highly reactive aluminosilicate material suitable for enhancing geopolymer performance.

Table 1 presents a detailed comparison of the chemical compounds found in various industrial wastes. The data indicate significant variations in SiO_2 and Al_2O_3 content among materials, which influences their geopolymerization potential. For example, silica fume exhibits the highest SiO_2 content (72.26%), whereas fly ash and GGBS show moderate silica levels (32% and 38.2%, respectively), making them complementary materials in blended geopolymer systems. The alumina content is notably high in metakaolin (46%), supporting the formation of strong aluminosilicate bonds essential for compressive strength. Moreover, other oxides, such as CaO, Fe_2O_3, and MgO, play secondary roles in influencing setting time, durability, and chemical stability. Understanding the precise chemical composition of these industrial wastes is therefore critical in designing geopolymer mixtures optimized for both environmental and structural performance.

Table 1. Chemical compounds in industrial waste materials

Chemical copound (%)	Fly ash (Afriansya et al., 2023)	Glass powder (Afriansya, 2021)	Slag (GGBS) (Kozlova et al., 2023)	Metakaolin (Kamath et al., 2021)	Silica fume (Frýbort et al., 2023)
SiO_2	32	42.6	38.20	52	72.26
Al_2O_3	13	-	8.10	46	0.33
Fe_2O_3	27	1.2	0.80	0.6	0.10
CaO	19.5	8.34	45.40	0.09	0.30
MnO	0.28	0.08	-	-	0.03
K_2O	2.02	5.16		0.03	1.07
TiO_2	1.52	-	-	0.65	0.01
SrO	0.97	-	-	-	-
MgO	-	-	3.20	0.03	0.85
Na_2O	-	-	-	0.1	0.28

Previous studies have explored the feasibility of using these industrial wastes in geopolymer concrete, as summarized in Table 2. The CO_2 reduction potential varies considerably depending on the material type, proportion of cement replacement, and curing conditions. Fly ash-based geopolymer concrete, for instance, can achieve CO_2 reductions ranging from 44% to 64% (Bajpai et al., 2020; Tang et al., 2021), demonstrating the material's significant environmental advantages. Similarly, metakaolin and GGBS-based geopolymer systems exhibit reductions of up to 45% and 39%, respectively, while glass powder incorporation contributes to moderate CO_2 mitigation (18-14%). These studies collectively indicate that industrial waste-derived materials offer considerable potential in reducing the carbon footprint of concrete without compromising structural performance.

From an economic perspective, industrial waste-based geopolymer materials can significantly lower construction costs. Since materials such as fly ash and GGBS are byproducts, their procurement cost is generally lower than that of Portland cement. Reports indicate cost savings of up to 30% when fly ash is utilized as a primary binder, with similar reductions observed for glass powder-based geopolymer systems (Barbhuiya et al., 2025; Siddika et al., 2021). The cost-effectiveness, combined with environmental benefits, positions geopolymer materials as a highly attractive alternative in both public and private construction projects. Furthermore, the use of these wastes alleviates environmental pollution associated with landfilling or improper disposal, providing additional societal benefits.

The mechanical properties of geopolymer materials are intrinsically linked to their chemical composition and microstructure. Higher silica and alumina contents facilitate the formation of three-dimensional aluminosilicate networks, which improve compressive strength, tensile strength, and durability. For instance, Afriansya et al. (2023) reported that geopolymer concretes with elevated SiO_2 content exhibit superior compressive strength compared to conventional concrete, while blending materials including fly ash can optimize the silica-to-alumina ratio to achieve balanced performance. Additionally, geopolymer concrete demonstrates enhanced resistance to chemical attack, high-temperature stability, and reduced shrinkage and cracking, which are critical for long-term structural integrity. The combination of multiple industrial wastes in geopolymer systems has emerged as a promising approach to further enhance material performance. By blending high-silica materials such as silica fume or glass powder with moderate-silica industrial wastes like fly ash and GGBS, it is possible to tailor the SiO_2/Al_2O_3 ratio, improving both mechanical properties and CO_2 reduction potential. Such hybrid geopolymer systems also allow for greater flexibility in raw material sourcing, mitigating regional supply limitations and variability in waste composition. This approach supports the scalability of geopolymer technology, making it more viable for widespread adoption in diverse geographic contexts.

Table 2. Utilization of industrial waste for geopolymer materials

Previous studies	Type of industrial waste	Material innovation	CO_2 reduction potential	Cost reduction	Remarks
(Ahmed et al., 2025)	Glass Powder and Ground Granulated Blast Furbacae Slag (GGBS)	Low-carbon concrete	Up to 39%	Up to 16%	Low-carbon concrete can enhance mechanical properties, mitigate environmental impact, and reduce production costs.
(Cong et al., 2024)	Fly ash	Geopolymer concrete	50%	30%	In particular, CO_2 emissions from fly ash-silica fume geopolymer concrete are significantly lower than those of OPC concrete.
(Shi et al., 2021)	Metakaolin	Geopolymer concrete	27-45%	-	Metakaolin in geopolymer concrete has the potential to substantially reduce CO_2 emissions.

(Bajpai et al., 2020)	Fly Ash	Geopolymer concrete	44-64%	10.87-17.7%	The incorporation of fly ash-based geopolymer in the construction industry can enhance sustainability.
(Tang et al., 2021)	Fly Ash	Geopolymer Mortar	49.7%	-	Geopolymer mortar possesses the potential to substitute conventional ordinary Portland cement (OPC).
(Siddika et al., 2021)	Glass Powder	Geopolymer concrete	18%	14%	The incorporation of glass powder in geopolymer concrete can provide environmental benefits by reducing greenhouse gas emissions.
(Cong et al., 2024)	Slag	Geopolymer concrete	45%	-	The average net cost of slag-based geopolymer concrete is considerably lower than that of OPC concrete.
(Barbhuiya et al., 2025)	Fly ash	Low carbon concrete	30-50%	Up to 15%	This technology offers stakeholders and producers the opportunity to reduce their CO_2 footprint while maintaining both cost efficiency and material performance.
(Khankhaje et al., 2023)	Fly ash	Pozzolanic materials	22%	-	The utilization of waste materials, such as fly ash, provides an opportunity to reduce global CO_2 emissions and lower the lifecycle costs of construction.

3.2. Environmental, economic, and social benefits of geopolymer innovation

3.2.1 Environmental benefits

The environmental advantages of utilizing industrial waste-based geopolymer materials in construction are among the most compelling drivers for their adoption. Traditional Portland cement production contributes significantly to global CO_2 emissions due to the calcination process and the combustion of fossil fuels required for high-temperature kilns. By substituting cement with geopolymer binders derived from industrial byproducts, the carbon footprint of concrete can be markedly reduced. As documented in prior studies, CO_2 emission reductions for fly ash-based geopolymer concrete range from 44% to 64%, while metakaolin and GGBS contribute reductions of 27–45% and 30–39%, respectively (Ahmed et al., 2025; Bajpai et al., 2020; Shi et al., 2021). These figures underscore the significant environmental mitigation potential associated with industrial waste utilization.

A notable real-world example of the environmental benefits of geopolymer implementation is the construction of the Brisbane West Wellcamp Airport in Australia, where runways, taxiways, and aprons utilized approximately 40,000 m^3 (100,000 tons) of geopolymer concrete (Madhavi & Rameshwaran, 2020). This large-scale application resulted in an estimated reduction of 6,600 tons of CO_2 emissions compared to conventional Portland cement-based concrete. The project illustrates the feasibility of applying geopolymer technology in critical infrastructure, demonstrating not only environmental benefits but also the practical scalability of this sustainable material solution.

Beyond CO_2 mitigation, geopolymer concrete contributes to reduced air pollution and enhanced local environmental quality. The use of industrial byproducts diverts fly ash, slag, and other waste from landfills or uncontrolled disposal sites, which are potential sources of soil and water contamination. For example, fly ash, if improperly managed, can lead to the leaching of heavy metals and particulate emissions into the surrounding environment. By integrating these materials into concrete production, the negative environmental impacts associated with industrial waste are mitigated. Additionally, the improved durability and chemical resistance of geopolymer concrete reduce the frequency of repair and reconstruction, indirectly decreasing energy consumption and further lowering environmental impact over the life cycle of infrastructure.

From a lifecycle assessment (LCA) perspective, the adoption of geopolymer technology significantly reduces embodied carbon emissions, which include emissions from raw material extraction, transportation, processing, and construction. Studies have shown that geopolymer materials not only reduce initial CO_2 emissions but also enhance long-term sustainability through lower maintenance and replacement rates. Moreover, the production of geopolymer concrete generally requires lower kiln temperatures compared to OPC production, leading to further energy savings and a reduced overall environmental footprint. In addition, integrating multiple industrial wastes, such as fly ash blended with silica fume or glass powder, can maximize environmental benefits by optimizing material reuse while achieving high-performance concrete properties.

3.2.2 Economic benefits

The economic implications of implementing industrial waste-based geopolymer materials are equally significant. Conventional construction relies heavily on Portland cement, which constitutes a major portion of material costs. The substitution of cement with industrial byproducts such as fly ash, GGBS, and metakaolin not only reduces raw material expenses but also leverages otherwise low-value or waste materials, enhancing cost efficiency. For instance, fly ash-based geopolymer concrete has been reported to achieve cost reductions up to 30%, while glass powder incorporation can lower costs by approximately 14% (Cong et al., 2024; Siddika et al., 2021). These savings are particularly relevant in large-scale projects where material costs constitute a substantial fraction of the overall budget.

Furthermore, geopolymer concrete offers long-term economic benefits through increased durability and reduced maintenance requirements. Traditional concrete is susceptible to chemical attack, corrosion of reinforcement, and shrinkage-related cracking, necessitating frequent repair and replacement. In contrast, geopolymer concrete exhibits enhanced resistance to chemical and thermal degradation, thereby extending the service life of infrastructure. Studies indicate that integrating energy-efficient construction methods and recycled industrial byproducts can reduce operational costs by 20–30% compared to conventional construction methods (Mahardika et al., 2025). Such cost savings, combined with the environmental benefits, create a compelling value proposition for construction firms and developers seeking sustainable and economically viable solutions.

In addition, the adoption of geopolymer materials enhances the competitiveness of construction companies in markets increasingly emphasizing green building certifications, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method). Companies demonstrating environmental stewardship through low-carbon construction materials can gain market recognition, attract environmentally conscious clients, and benefit from potential incentives associated with sustainable building certifications. These economic incentives, coupled with material cost reductions and extended infrastructure lifespan, position geopolymer technology as a financially prudent alternative in both public and private construction projects.

3.2.3 Social benefits

The social dimension of adopting geopolymer technology is equally important, reflecting the broader impacts on communities and society at large. The production and utilization of industrial waste-based geopolymer materials create employment opportunities within the green economy, from raw material collection and processing to concrete production and construction implementation. This fosters a collaborative ecosystem involving academia, government, and industry, encouraging innovation and skill development while stimulating local economies. Moreover, incorporating industrial byproducts in construction reduces environmental pollution, particularly in regions surrounding coal-fired power plants or other industrial facilities. Fly ash, if improperly disposed, poses health risks due to airborne particulates and leaching of toxic elements. Utilizing these wastes in geopolymer concrete mitigates such hazards, improving public health outcomes and contributing to higher quality of life in affected communities (Mahardika et al., 2025). Beyond health, the use of environmentally sustainable materials in public infrastructure projects, such as bridges, schools, and government buildings, serves an educational purpose, raising awareness about sustainable development and demonstrating institutional commitment to environmental responsibility.

Geopolymer projects also promote social engagement by involving local communities in waste collection, material preparation, and construction activities. This participatory approach not only provides practical training but also fosters environmental stewardship and ownership, encouraging continued support for sustainable construction initiatives. Additionally, large-scale demonstrations of geopolymer technology, such as the Brisbane West Wellcamp Airport and the Global Change Institute Building, act as high-visibility exemplars of sustainable engineering, inspiring future projects and reinforcing the social value of adopting low-carbon construction materials.

3.3 Policies and regulations in the implementation of geopolymer concrete

The adoption of geopolymer concrete on a large scale is not solely dependent on technical feasibility but is significantly influenced by the policy and regulatory frameworks established by governments and industry standards. Despite the clear environmental and economic benefits of geopolymer materials, many countries, particularly developing nations, face a lack of comprehensive guidelines or legal standards for their use in structural applications. In Indonesia, for instance, there are no national standards or official technical guidelines specifically addressing the use of geopolymer concrete in critical infrastructure, such as bridges, high-rise buildings, or transportation networks (Barbhuiya et al., 2025). This regulatory gap leads to hesitation among contractors, engineers, and investors, who may perceive the technology as unproven or risky in comparison to conventional Portland cement-based concrete.

In addition to national regulations, the standardization of technical specifications is essential for ensuring consistent quality and performance of geopolymer materials. Geopolymer concrete properties are influenced by the chemical composition of raw materials, mix design, curing conditions, and processing techniques. Without standardized protocols for testing, certification, and approval, stakeholders may encounter variability in mechanical strength, durability, and environmental performance, which can undermine confidence in the material. Establishing comprehensive technical standards covering aspects such as allowable chemical composition ranges, compressive strength benchmarks, curing methods, and quality control measures is, therefore, critical for facilitating widespread adoption.

Public education and awareness campaigns complement policy initiatives by enhancing stakeholder knowledge regarding the benefits and applications of geopolymer materials. Educational programs targeting engineers, architects, and construction managers, combined with pilot projects and demonstration sites, can showcase the performance and sustainability advantages of industrial waste-based concrete. Such initiatives also inform policymakers, enabling evidence-based decision-making and the development of supportive regulatory frameworks. International cooperation and knowledge exchange, particularly with countries that have successfully implemented geopolymer technology, such as Australia and parts of Europe, provide valuable insights into best practices and can accelerate the local adoption of these materials.

Green certification programs, such as LEED (Leadership in Energy and Environmental Design), BREEAM (Building Research Establishment Environmental Assessment Method), and EDGE (Excellence in Design for Greater Efficiencies), further reinforce policy measures by incentivizing low-carbon construction practices. Projects that integrate geopolymer concrete and other sustainable materials may earn points toward certification, enhancing their market competitiveness and public recognition. Additionally, funding for research and development in geopolymer materials supports continuous innovation, allowing for the optimization of material performance, the discovery of new industrial waste sources, and the reduction of associated costs. Collectively, strengthened policies, technical standards, economic incentives, and public education create an enabling environment for the successful integration of geopolymer technology within mainstream construction practices.

3.4 Contribution to net zero emission 2050

The utilization of industrial byproducts as precursors for geopolymer concrete represents a strategic pathway toward achieving the Net Zero Emission (NZE) target by 2050, in alignment with international climate agreements such as the Paris Agreement. Conventional cement production contributes significantly to global greenhouse gas emissions, with estimates suggesting that it accounts for approximately 8% of total anthropogenic CO_2 emissions (Sverdrup & Olafsdottir, 2023). Replacing a substantial portion of Portland cement with geopolymer binders derived from fly ash, GGBS, silica fume, and waste glass powder can drastically reduce the embodied carbon content of concrete, thereby contributing to global decarbonization efforts.

The Net Zero Emission target aims to balance anthropogenic greenhouse gas emissions with carbon sequestration and mitigation measures, ensuring that overall net emissions reach zero by mid-century. In the construction sector, which accounts for roughly 36% of global energy consumption and 39% of total CO_2 emissions (Singh et al., 2023), the adoption of low-carbon materials is critical for meeting this objective. Industrial waste-based geopolymer concrete directly addresses this challenge by providing an alternative material pathway that reduces dependency on high-emission Portland cement while utilizing waste materials that would otherwise contribute to environmental degradation.

From a technical standpoint, geopolymer materials provide not only environmental benefits but also structural advantages. High-silica and alumina content in fly ash, metakaolin, and silica fume facilitates the formation of stable three-dimensional aluminosilicate networks during geopolymerization, resulting in superior compressive strength, durability, and resistance to chemical attack. These properties ensure that geopolymer concrete can substitute conventional concrete in both non-structural and structural applications, including pavements, precast panels, bridges, and public buildings. Real-world examples, such as the Brisbane West Wellcamp Airport and the Global Change Institute Building, demonstrate that large-scale applications are feasible, with documented reductions in CO_2 emissions and satisfactory technical performance (Madhavi & Rameshwaran, 2020).

The integration of multiple industrial waste sources further enhances the contribution of geopolymer technology to the NZE target. Blending high-silica materials such as silica fume with moderate-silica industrial wastes like fly ash or GGBS allows for optimized chemical composition, improving polymerization efficiency, mechanical performance, and durability. This approach not only maximizes CO_2 reduction potential but also ensures material availability and scalability, mitigating supply constraints associated with single-source industrial waste. By strategically combining multiple waste streams, the construction sector can achieve both environmental and operational efficiencies, reinforcing its role in global decarbonization initiatives.

Geopolymer technology also aligns with several Sustainable Development Goals (SDGs). SDG 9 emphasizes industry, innovation, and infrastructure; SDG 11 focuses on sustainable cities and communities; and SDG 13 underscores climate action. By adopting industrial waste-based geopolymer materials, the construction sector can contribute to sustainable industrialization, reduce urban environmental impacts, and mitigate climate change, supporting broader societal objectives. Moreover, the use of geopolymer concrete in public infrastructure projects provides tangible demonstrations of governmental commitment to sustainable development, enhancing public awareness and trust in environmental policies. The long-term benefits of geopolymer adoption extend beyond CO_2 reduction. Improved durability and reduced maintenance requirements contribute to lower life-cycle costs and reduced environmental impact over the lifespan of infrastructure. This lifecycle approach to sustainability ensures that geopolymer concrete not only addresses immediate carbon emission concerns but also promotes resource efficiency, waste minimization, and economic savings over decades. Additionally, the valorization of industrial waste streams encourages circular economy principles, transforming byproducts into valuable construction materials and reducing landfill dependency.

Beyond environmental benefits, the economic implications of adopting geopolymer technology are equally significant. The production of geopolymer binders generally requires lower energy inputs than the calcination process essential for Portland cement, which directly translates to energy savings. Moreover, the use of industrial waste as the primary raw material provides an additional economic advantage, as these materials are typically readily available at minimal cost. Studies indicate that the lifecycle cost of geopolymer concrete may be reduced by approximately 30% when waste disposal savings, lower maintenance expenses, and extended material durability are considered. This economic efficiency positions geopolymer materials as an attractive solution for both developed and developing countries seeking cost-effective strategies for decarbonizing construction.

From an environmental standpoint, the benefits of industrial waste-based geopolymers extend beyond carbon reduction. By diverting industrial waste from landfills and repurposing it into construction materials, geopolymer technology actively supports the principles of the circular economy. The revalorization of waste materials reduces the need for natural resource extraction, helps mitigate the environmental impacts associated with mining, and prevents land contamination caused by improper waste disposal. Furthermore, the absence of high-temperature kiln processes significantly lowers the fuel consumption and air pollution typically generated by the cement industry. The improved durability, reduced shrinkage, and enhanced resistance to chemical and sulfate attacks reinforce the environmental superiority of geopolymer concrete by extending the lifespan of structures and reducing repair frequencies.

Economically, the shift toward geopolymer construction offers benefits not only at the material production level but also throughout the entire lifecycle of infrastructure. Geopolymer concrete demonstrates superior performance in high-risk environments, particularly those with elevated chemical exposure or extreme weather conditions. Due to its high durability and low permeability, this material reduces maintenance costs and extends service life, making it particularly advantageous for large-scale infrastructure such as bridges, marine structures, and industrial facilities. Case studies, such as the Brisbane West Wellcamp Airport and Australia's Global Change Institute Building, provide concrete evidence that geopolymer technology can be applied successfully on a commercial scale without compromising technical performance. These projects confirm that geopolymer concrete can meet industry requirements for strength, durability, and structural reliability while delivering measurable reductions in carbon emissions and operational costs.

Despite these promising outcomes, this study also highlights several barriers that may hinder the widespread adoption of geopolymer concrete. One of the most significant challenges is the lack of standardized regulatory frameworks and design guidelines. In many countries, including Indonesia, geopolymer materials are not yet fully incorporated into building codes, making contractors hesitant to use them for structural applications. The absence of clear technical specifications, performance criteria, and safety guidelines contributes to this uncertainty. Additionally, limited financial incentives, such as tax reductions, subsidies for waste processing, or government-supported pilot projects restrict market expansion. Without strong policy intervention, the transition from Portland cement to geopolymer binders is likely to progress slowly.

To overcome these challenges, strengthening policy frameworks is essential. Governments must develop technical standards, quality control procedures, and certification mechanisms to ensure the safe and reliable use of geopolymer materials. Providing fiscal incentives, such as reduced taxes for low-carbon materials or subsidies for industrial waste processing, can accelerate industry adoption. Promoting green building certifications and incorporating geopolymer materials into public infrastructure projects would further encourage their use. Additionally, enhanced funding for research and development can improve material performance, optimize mix designs, and support pilot demonstrations in diverse environmental conditions. The findings of this research affirm that geopolymer technology represents not merely a material innovation but a comprehensive sustainability strategy. Its adoption supports environmental conservation, enhances economic efficiency, and contributes positively to social development. As climate change continues to exert unprecedented impacts globally, transforming the construction sector through sustainable material alternatives becomes an urgent priority. Industrial waste–based geopolymers offer a practical and effective solution for reducing the carbon intensity of buildings and infrastructure while addressing the growing environmental burden associated with industrial waste.

4. Conclusions

This study concludes that industrial waste–based geopolymer materials present a highly promising pathway for advancing sustainability within the construction sector, particularly in relation to the global agenda of achieving Net Zero Emission (NZE) 2050. Through a comprehensive analysis of previous studies, this research demonstrates that geopolymer binders derived from industrial byproducts, such as fly ash, ground granulated blast-furnace slag (GGBS), silica fume, metakaolin, and waste glass powder can serve as viable alternatives to conventional Portland cement. These materials not only reduce the environmental burden associated with cement manufacturing but also promote the utilization of waste streams that would otherwise contribute to land pollution and greenhouse gas emissions. The literature consistently shows that the substitution of Portland cement with geopolymer binders can lead to substantial reductions in carbon dioxide (CO_2) emissions, in some cases reaching up to 64%, thereby offering a practical and scalable contribution to carbon mitigation efforts.

The social implications of geopolymer technology are equally noteworthy. The transition toward environmentally responsible construction materials contributes to community well-being by improving air quality, reducing environmental degradation, and minimizing pollution around power plants and industrial sites. Moreover, the growth of the geopolymer sector stimulates new employment opportunities in research, manufacturing, and construction, particularly within the emerging green economy. Increased public awareness of sustainable construction practices also fosters broader societal participation in climate action initiatives. Importantly, collaboration among universities, government institutions, and private industry in advancing geopolymer technology strengthens national innovation ecosystems, encouraging future growth in low-carbon technological solutions.

In summary, this study emphasizes that the integration of geopolymer materials into construction practices is essential for achieving Net Zero Emission 2050. With adequate policy support, technological refinement, and multi-stakeholder collaboration, geopolymers can emerge as a foundational component of sustainable construction systems. Continued investment in research, market development, and regulatory alignment will be crucial to realizing the full potential of these materials. As nations commit to ambitious climate targets, the strategic use of industrial waste in producing high-performance, low-carbon construction materials represents a pivotal step toward a more sustainable, resilient, and environmentally responsible future.

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Author Contribution

Conceptualization, E.A.A.; Methodology, E.A.A.; Validation, E.A.A.; Formal Analysis, E.A.A.; Investigation, E.A.A.; Resources, E.A.A.; Data Curation, E.A.A.; Writing Original Draft Preparation, E.A.A.; Writing Review & Editing, E.A.A.

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This study did not involve human participants or animal experiments.

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No new data were created or analyzed in this study. Data sharing is therefore not applicable.

Conflicts of Interest

The author declares no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the author did not use any generative artificial intelligence (AI) tools. The author takes full responsibility for the content of the publicationDuring the preparation of this work, the author did not use any generative artificial intelligence tools. The author takes full responsibility for the content of the publication.

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