The University of Tehran Press

Pollution

Print ISSN: 2383-451X
Online ISSN: 2383-4501

https://jpoll.ut.ac.ir/

Life cycle assessment of concrete manufacturing incorporating recycled waste glass powder as a pozzolanic cement substitute

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Article Info

Article type:
Research Article

Article history:
Received: 23 February 2025
Revised: 23 September 2025
Accepted: 16 February 2026

Keywords:
Waste Recycling
Cement Replacement
Glass Powder
Global Warming
Enhanced Concrete

ABSTRACT

Cement production is a leading source of global CO_2 emissions, while vast quantities of glass waste remain underutilized and are often sent to landfills. This study investigates the environmental potential of using finely ground waste glass powder (GP) as a partial pozzolanic substitute for cement in concrete. A cradle-to-gate Life Cycle Assessment (LCA) was conducted to compare conventional concrete with GP-enhanced concrete, using SimaPro 9.2 and Ecoinvent 3.2, and applying the IMPACT 2002+ method. Four scenarios were modeled to assess the effects of key variables, including extended service life, transportation distances, and emissions from the glass grinding process. To evaluate result robustness, Monte Carlo simulations (10,000 runs) and sensitivity analyses were performed. The results show that GP concrete consistently outperforms conventional concrete across all impact categories. The most notable reduction was a 25.7% decrease in CO_2-equivalent emissions, alongside significant reductions in human health (21.3%), resource use (16.6%), and ecosystem quality (15.4%) impacts. Scenario 1, incorporating a 20% longer concrete lifespan, achieved the lowest overall environmental burden without introducing trade-offs. Contribution analysis identified clinker production as the primary environmental hotspot, particularly for global warming, respiratory inorganics, and non-renewable energy use. These findings highlight the dual benefit of GP concrete in reducing emissions and diverting waste, offering a viable strategy for sustainable construction, especially in regions with local glass waste availability and supportive processing infrastructure.

Cite this article: Pazoki, A., Amiri, M,J, Nohegar, A., & Nabi Bidhendi, Gh. (2026). Life cycle assessment of concrete manufacturing incorporating recycled waste glass powder as a pozzolanic cement substitute. *Pollution*, 12(1), 1-15. https://doi.org/10.22059/poll.2025.391003.2813

DOI: https://doi.org/10.22059/poll.2025.391003.2813

INTRODUCTION

Concrete, the most widely used construction material worldwide (Guignone et al., 2022; Heard et al., 2012), underpins nearly every aspect of modern infrastructure due to its strength, versatility, and cost-effectiveness. It consists primarily of cement, aggregates (both coarse and fine), and water, with chemical admixtures often added to tailor its performance for specific applications (Guo et al., 2023; Marinković et al., 2021). Globally, the scale of its use is staggering—on average, about one metric ton of concrete is consumed annually for every person on the planet (Flower & Sanjayan, 2007). At the heart of this demand lies cement, the binder responsible for concrete's performance—and for its outsized environmental footprint. Cement production consumes vast quantities of raw materials and energy and accounts for roughly 7% of total global CO_2 emissions (Supriya et al., 2023). For every ton of cement produced, approximately 0.9 tons of CO_2 are released into the atmosphere (Hasanbeigi et al., 2012; Krstic & Davalos, 2019; Tajfar et al., 2023a). While the process is energy-intensive, its emissions are

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driven more by the chemistry of calcination than by combustion: the thermal decomposition of limestone ($CaCO_3 \rightarrow CaO + CO_2$) accounts for 50–60% of total emissions, or around 540 kg CO_2 per ton of clinker (Guo et al., 2024; Hasanbeigi et al., 2012; Saberian et al., 2022). The remaining emissions result from fossil fuel combustion and electricity use during kiln heating and milling processes (Dobiszewska et al., 2023; Supriya et al., 2023).

In parallel with growing concerns about climate change, the pressure to reduce cement's environmental burden is further compounded by its unsustainable use of natural resources. The concrete industry consumes more than 9 billion tons of aggregates and over 2 billion tons of freshwater annually (Abbas et al., 2021; Dobiszewska et al., 2023). These impacts, combined with rising global construction demand, create an urgent need to rethink the production of building materials. The continued expansion of both population and urban infrastructure has intensified the pressure on natural reserves and waste systems alike. Each year, nearly 2.01 billion tons of municipal solid waste are generated, with projections rising to 3.4 billion tons by 2050—yet less than 20% is recycled (Abdelzaher, 2023; Kaza et al., 2018). Among the various mitigation strategies explored—ranging from kiln efficiency and renewable fuels to carbon capture—the partial replacement of cement with supplementary cementitious materials (SCMs) remains one of the most practical and immediately impactful options (Heard et al., 2012; Heidary, 2017; Malhotra). Conventional SCMs like fly ash and ground granulated blast furnace slag (GGBFS) have demonstrated strong potential, but their availability is increasingly constrained. In the United States alone, a significant number of coal-fired power plants have shut down or switched to natural gas due to economic and environmental factors, leading to reduced fly ash production (Hodge, 2015; Pazoki et al., 2020; Roston & Migliozzi, 2015; Sheikh, 2018). Meanwhile, GGBFS is produced in limited quantities and is geographically concentrated—primarily in Japan, Canada, and Spain—making global access uneven and cost-prohibitive in many regions (Survey, 2017).

These constraints have catalyzed interest in alternative SCMs that are both effective and locally accessible. One such candidate is finely ground waste glass powder (GP), which has drawn attention due to its pozzolanic properties (Mohammadianroshanfekr et al., 2024; Shao et al., 2000; Shayan & Xu, 2004; Shi et al., 2005). When finely milled, GP can react with calcium hydroxide in the presence of moisture to form calcium silicate hydrate (C-S-H), the same compound responsible for concrete's strength development (Deschamps et al., 2018). Experimental studies have demonstrated that replacing up to 20% of cement with GP can improve compressive strength, particularly at later curing stages (28–90 days) (Ibrahim, 2021; Matos & Sousa-Coutinho, 2012; Mohammadyan-Yasouj & Ghaderi, 2020; Shao et al., 2000; Tajfar et al., 2023a; Zanwar & Patil, 2021). These findings highlight GP's potential not just as a filler, but as a reactive material that enhances concrete performance.

It is worth noting that most studies on GP's pozzolanic behavior have focused on soda-lime glass—the dominant type of glass used in containers and lighting products, accounting for over 80% of global production (Du & Tan, 2014; Mohajerani et al., 2017; Shi & Zheng, 2007). Initial concerns over alkali-silica reaction (ASR) due to GP's high silica content have largely been addressed, with research showing that very fine glass particles (<100 μm) can actually inhibit ASR, rather than exacerbate it Furthermore, GP has been shown to outperform even fly ash in certain durability metrics, reducing chloride ion penetration by 40%–90%, thereby improving concrete resistance to corrosive environments (Tajfar et al., 2023b). Beyond its mechanical and chemical merits, GP also offers advantages in fire resistance and workability. Studies have found that concrete containing GP exhibits improved performance under elevated temperatures and shows better rheological properties, including increased slump and ease of placement (Balasubramanian et al., 2021; Gao et al., 2020).

In 2018, the United States alone generated over 12,000,000 tons of glass waste, with only 3 million tons being recycled while a substantial 7.5 million tons were disposed of in landfills (Maleki Delarestaghi et al., 2018; Pazoki et al., 2014; United States Environmental Protection, 2019). In New York City, 140,000 tons of this waste is collected annually, with approximately 50% destined for recycling (United

States Environmental Protection, 2019). Conversely, in Tehran, a city of similar population size, 66,000 tons of glass waste is collected each year (Hatami et al., 2017), with nearly 2% being recycled and the remainder ending up in landfills (Omrani et al., 2009). These low recycling rates underscore the inefficiency of current glass recycling practices in Tehran and highlight the urgent need for systems to utilize glass waste before landfills reach capacity.

While recycling glass can reduce the strain on raw materials used in glass production (Du & Tan, 2014), not all glass is recyclable due to factors like cost and mixed colors (Krstic & Davalos, 2019). Glass that cannot be recycled is often used as aggregate in asphalt concrete, for creating bedding for pipelines, developing gas venting systems in landfills, and as pseudo-gravel backfill in drainage systems (Nejatian et al., 2023). However, in practice, much of this unrecyclable waste glass waste ends up in landfills. Consequently, there remains a steady and ongoing supply of glass waste available for alternative uses.

Despite its promising environmental and technical performance, the practical implementation of waste glass powder (GP) as a cement substitute faces several real-world constraints (Gimenez-Carbo et al., 2021). One of the primary limitations is the absence of dedicated infrastructure for the large-scale collection, sorting, and processing of glass waste in many regions, particularly in developing countries (Bristogianni & Oikonomopoulou, 2023). Glass intended for concrete applications must be clean, homogenous, and finely ground—requirements that are difficult to meet when the waste stream is heavily contaminated with ceramics, metals, labels, or mixed-color glass fractions (Zhan et al., 2022). The energy intensity of grinding glass to pozzolanic fineness is another concern, as it introduces additional environmental burdens and operational costs that must be balanced against the benefits of cement reduction (Xu et al., 2023). Although dry milling is more common, it can generate particulate emissions, posing occupational health risks and regulatory challenges during implementation. Wet milling can reduce these risks but demands greater energy input and water use, creating trade-offs that vary by context (Yao et al., 2021).

Life Cycle Assessment (LCA) is widely regarded as a suitable tool for evaluating the environmental impacts of concrete production, frequently used to assess non-conventional concrete approaches (Jiang et al., 2014; Petek Gursel et al., 2014; Vieira et al., 2016). Given the multifaceted nature of concrete's environmental footprint and the complex trade-offs involved in implementing alternative materials like GP, LCA has emerged as the most comprehensive framework for evaluating environmental performance in construction systems (Guo et al., 2023). In the case of GP concrete, LCA is particularly valuable because it can quantify not only the benefits of cement replacement but also the impacts of upstream glass collection, energy-intensive grinding, and additional transport. These effects may vary significantly depending on regional infrastructure, electricity mix, and logistical efficiencies. Moreover, LCA enables impact comparison across multiple environmental categories, including climate change, human health, resource depletion, and ecosystem quality, offering a more nuanced picture than global warming potential alone.

While numerous studies have explored the pozzolanic behavior, durability, and mechanical properties of waste glass powder in cementitious systems, very few have applied LCA to holistically evaluate its environmental performance. Among those that exist, the majority focus on idealized scenarios in high-income countries with robust recycling infrastructure and efficient energy systems.

These studies often neglect critical parameters such as transportation logistics, energy demand for grinding, particulate emissions during processing, and the real-world inefficiencies of waste glass recovery—factors that are especially relevant in developing regions.

In the specific context of Tehran, where glass waste recycling rates are extremely low and landfill pressures are high, there is a clear need for regionally grounded, scenario-based LCA studies. Existing models tend to generalize assumptions about material sourcing and process efficiencies, overlooking how regional constraints could influence environmental outcomes or undermine the theoretical benefits of cement substitution.

This study adopts a comprehensive cradle-to-gate LCA to evaluate the environmental performance of concrete incorporating recycled waste GP as a partial cement substitute, under conditions specific to Tehran. The LCA framework was selected for its ability to capture the full spectrum of environmental impacts across the material's life cycle, ensuring that improvements in one phase do not result in unintended burdens in another. Both conventional and GP concrete scenarios are assessed based on detailed modeling of raw material extraction, production processes, transportation routes, and on-site delivery. Particular attention is given to realistic factors such as the energy demands of glass milling, landfilling of unrecycled waste, and water consumption.

An important practical concern addressed in the analysis is the extended transportation distance that may be required to source suitable glass or deliver concrete to construction sites—an issue often overlooked in the literature. In addition to direct impact comparison, the study incorporates sensitivity scenarios and Monte Carlo uncertainty simulations to assess how variations in key parameters—such as lifespan extension, particulate emissions, or transport distance—affect the outcomes. This dual focus on methodological rigor and local relevance fills a critical gap in the literature and provides a replicable framework for evaluating waste-derived cement substitutes in resource-constrained settings.

MATERIALS AND METHODS

The study followed a structured procedure to achieve its objectives, adhering to established LCA guidelines (International Organization for, 2006a, 2006b): 1-Goal and Scope: Defined the system boundary, set a functional unit, and determined the level of detail based on the study's objectives. 2-Life Cycle Inventory (LCI): Involved collecting necessary data and constructing an input/output inventory of the processes involved. 3-Life Cycle Impact Assessment (LCIA): Generated additional information to aid in evaluating the LCI results, quantifying the environmental impacts of the data set. 4-Interpretation: Evaluated LCIA results to identify environmental hotspots, validate findings, and assess the influence of various parameters through sensitivity and uncertainty analyses. This structured approach ensured comprehensive evaluation and comparison of two scenarios using LCA methodology.

This study aims to evaluate the environmental benefits and limitations of incorporating GP into concrete, with a focus on identifying key contributors to environmental impacts and assessing sensitive parameters. The functional unit selected for comparison is the production of 1 m^3 of 35 MPa concrete. To ensure a fair assessment, it is essential that both conventional and GP concrete exhibit comparable properties, including strength, durability, and service life. As demonstrated in the references cited in Section 2.3, the two types of concrete are considered functionally equivalent. The system boundaries for both scenarios—conventional and GP concrete—are illustrated in Figure 1.

In both scenarios, concrete production includes all relevant processes and sub-processes, beginning with the extraction of raw materials in quantities specified by the mix design presented in Table 1 (a formulation proposed by Du and Tan (Du & Tan, 2014)), and ending with the delivery of concrete to a designated construction site in Tehran. This site was strategically selected for its proximity to raw material sources, allowing for an effective evaluation of transportation's impact on environmental indicators and their sensitivity to distance within this hypothetical setting.

Glass waste is collected from local waste collection stations and transported via 20-ton lorries to the Aradkooh waste processing plant, where it is crushed and ground into GP. Meanwhile, cement is produced at the Tehran Cement Production Facility. Both GP and cement are then delivered to the Pasargad Concrete Mixing Factory, where the concrete is prepared. The final product is transported to the construction site, assumed to be the University of Tehran due to its central location in the city. Figure 2 shows the distribution of waste collection stations, while Figure 3 illustrates the locations of the key facilities involved in the production and delivery process.

In the conventional concrete scenario (CC Scenario), glass waste is disposed of in landfills. Conversely, in the GP scenario, the glass waste is transported to a hypothetical facility where it is processed into GP. To assess the environmental impact of transportation, an existing MRF facility's

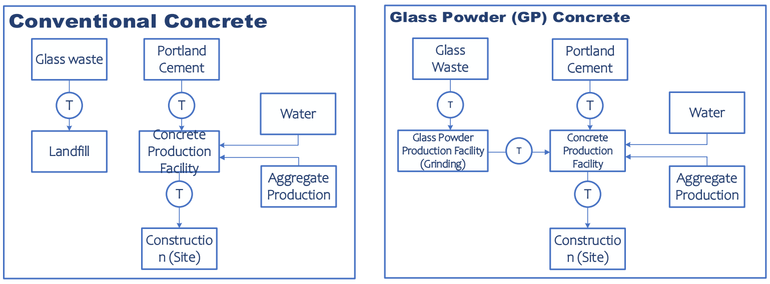

Fig. 1. System boundaries and essential processes of the main scenarios

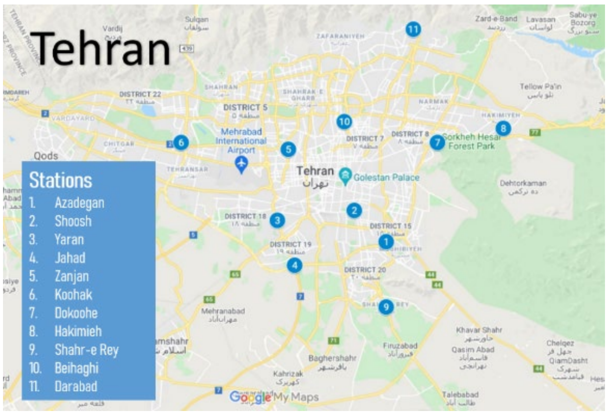

Fig. 2. Locations of the waste collection stations in Tehran (Google.Maps)

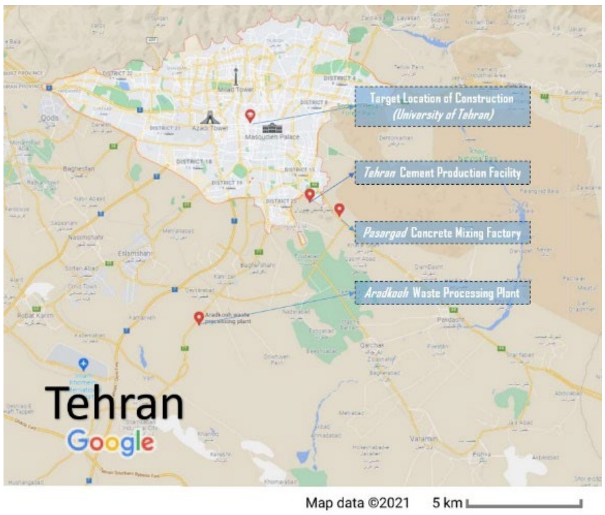

Fig. 3. Locations of the facilities involved in the production of concrete and the target location of the end product (Google. Maps)

location, reasonably distant from glass waste collection points, was chosen as the ideal location for this hypothetical facility. Hence, the environmental impacts associated with glass production are attributed to its initial use. However, the study also considers the impacts of the glass conversion process to GP, transportation, and the necessary infrastructure.

In this study, the environmental impacts of chemical admixtures in both conventional and GP concrete were not included. In Tehran's everyday construction practices, these admixtures are not used, and their environmental effects are considered negligible. Similar studies have also concluded that the environmental impacts of these chemical admixtures are minimal, as their mass constitutes less than 1% of the concrete's total mass (Flower & Sanjayan, 2007; Jiang et al., 2014). While it's suggested that soaking GP in tap water for six hours could enhance the mechanical properties of GP concrete (Google. Maps), this study does not incorporate such enhancements.

The information regarding waste collection stations was sourced from Tehran's comprehensive waste management plan (Elaqra et al., 2021). Additional data about these stations was provided by Tehran's municipality. Transportation distances were calculated using Google Maps, with precise location markers for all intended sites. Several studies have demonstrated that finer glass particles exhibit higher pozzolanic reactivity, with GP particle sizes needing to be smaller than 100 micrometers to achieve the desired reactivity (Waste Management Organization of Tehran, 2020). Moreover, according to research by Du and Tan (Shi & Zheng, 2007), a particle size distribution of GP similar to cement can be effective.

The validity of the chosen functional unit relies on the assumption that GP concrete can achieve comparable compressive strength and durability to conventional 35 MPa concrete. Regarding compressive strength, studies indicate that replacing up to 30% of cement with GP initially may result in a slight decrease in strength at seven days, but leads to higher strength at 28 days (Shi & Zheng, 2007) and 91 days (Shi & Zheng, 2007). Over time, GP concrete can continue to gain strength at a faster rate than conventional concrete due to its higher pozzolanic reactivity (Shayan & Xu, 2006). In terms of durability, research by Omran and Tagnit-Hamou (Omran & Tagnit-Hamou, 2016), Jain et al. (Jain et al., 2020), and others cited in section 1 demonstrate that GP concrete exhibits improved characteristics in the pore network due to GP particles filling voids and the transformation of (C-H) to (C-S-H). This enhances durability by reducing susceptibility to chloride-ion penetration and improving resistance to freeze-thaw cycles compared to conventional concrete. Therefore, the assumption made in this study may be conservative for the GP scenario and optimistic for conventional concrete, given the potential advantages of GP concrete in strength and durability.

To estimate the electricity required for converting waste glass powder into GP with the desired particle size, data from Jiang et al. (Jiang et al., 2014), based on experiments by Shao et al. (Shao et al., 2000), were utilized. According to Jiang et al. (Jiang et al., 2014), longer grinding durations and higher electricity consumption result in smaller GP particles. However, the optimal procedure appears to be when 20% of the particles achieve the desired size. The process of converting waste glass powder into GP can also result in the emission of particulates (Dynan et al., 2023), which pose health risks to on-site workers. To calculate the emissions of these particulates, guidelines provided by the Environmental Protection Agency of the United States were employed (Hottle et al., 2022; United States Environmental Protection, 2004; Xing et al., 2022). The resource use and emissions for Portland cement, sand, gravel, transportation, electricity, water, admixtures, and infrastructure in both scenarios were modeled using the Ecoinvent 3.2 database. Detailed LCI information can be found in the supplementary materials (Table S1).

This paper employed an innovative approach in selecting the appropriate methodology for its analysis. Initially, a preliminary LCA was conducted using the Eco-indicator 99 H method to identify key midpoint indicators with the highest relative impact, focusing on climate change, respiratory inorganics, and fossil fuel after normalization. Subsequently, following ILCD recommendations for LCIA methods, the IMPACT 2002+ (Jolliet et al., 2003) V2.14 method was carefully chosen and applied.

The LCIA interpretation involves conducting a comparative analysis of the main scenarios using the IMPACT 2002+ method. Major contributors to each environmental indicator are identified through a contribution analysis. To ensure the stability and robustness of this interpretation, sensitivity and Monte Carlo uncertainty analyses are performed.

The initial sensitivity analysis involved switching the life cycle impact method to ReCiPe (Goedkoop et al., 2009). This choice was based on the distribution of impact scores between IMPACT 2002+ and ReCiPe; IMPACT 2002+ emphasizes resource consumption in its LCI scores, whereas ReCiPe prioritizes human health and does not include climate change implications in its inventory (Stavropoulos et al., 2016). The diverse approaches in life cycle assessment were the primary reason for selecting ReCiPe for sensitivity analysis.

To identify the most influential parameters in the model, several assumptions were adjusted and additional scenarios were developed. These modifications were applied to the life cycle inventory (LCI) of the GP scenario to further explore the environmental impacts under varying conditions.

Four key parameters were selected to construct the sensitivity scenarios. First, the distance between the concrete mixing factory and the construction site was altered to evaluate how concrete transportation affects environmental indicators. In practice, more distant facilities within Tehran could also be used for mixing and manufacturing (Scenario 1). A second concern involves the limited availability of facilities capable of processing waste glass into GP—an issue expected to persist in the near future. This constraint may require GP to be transported over long distances, particularly from other cities. To reflect this, Scenario 2 assumes a 500 km freight lorry transportation distance for GP, using Isfahan as a representative source.

Third, the potential release of harmful particulates during glass grinding poses health and environmental concerns for on-site workers. While dry grinding is common, alternative procedures like wet grinding could significantly reduce or eliminate such emissions. Scenario 3 evaluates the environmental impact of GP production under the assumption of zero particulate emissions. Lastly, although Section 2.3 cites studies suggesting a 30% increase in the lifespan of GP concrete (Deschamps et al., 2018), this study adopts a more conservative estimate of a 20% increase to maintain a realistic impact projection (Scenario 4).

To quantify uncertainty in the input data, a pedigree matrix approach was used. Each data point in the life cycle inventory was evaluated on a scale from 1 (best) to 5 (worst), based on its reliability, completeness, and relevance across temporal, geographical, and technological dimensions. These scores were then used to calculate the geometric standard deviation of a lognormal data distribution (Muller et al., 2016). A Monte Carlo simulation with 10,000 iterations was conducted to comprehensively assess the uncertainty in the LCA results. This method allowed for a robust evaluation of how variations in input parameters could influence the overall outcomes.

RESULTS AND DISCUSSION

Figure 4 presents the comparative environmental impacts of producing 1 m^3 of conventional concrete versus GP concrete under the main study scenarios. It also details the contribution of individual life cycle

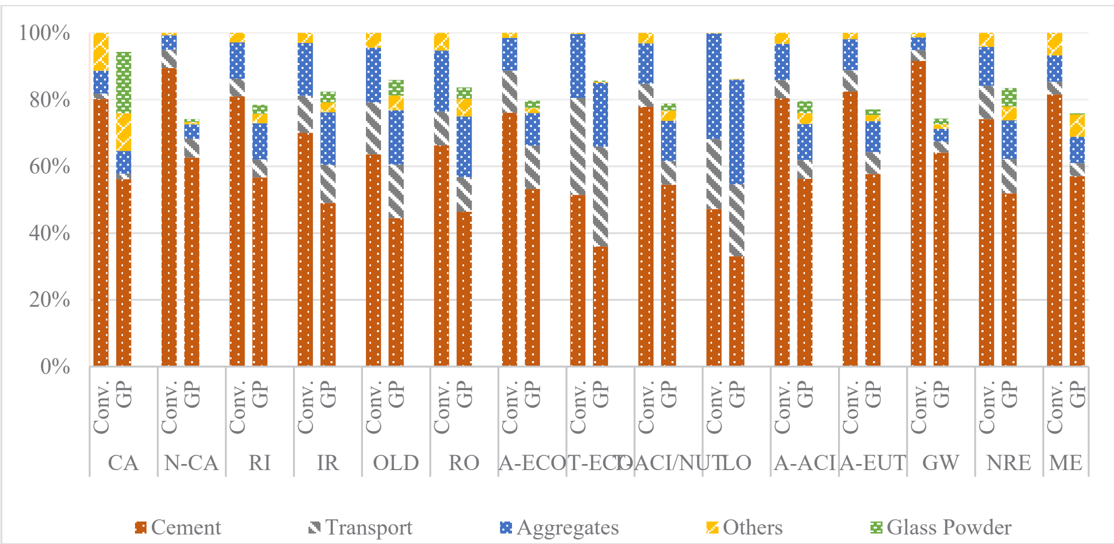

Fig. 4. Midpoint results of the Conv. concrete vs. the GP concrete via IMPACT 2002+ method

stages and material inputs within each scenario. Supplementary Table S4 provides the corresponding numerical data.

The categories “Cement” and “Aggregates” capture the environmental burdens associated with the extraction and production of core concrete constituents. “Transportation” includes the movement of glass waste from collection points to the Aradkooh waste processing facility (in both scenarios), the transfer of GP from Aradkooh to the mixing plant (GP scenario), and the delivery of cement and final concrete to the construction site. “Glass Powder” refers to the milling process required to convert glass waste into GP, while “Other” includes minor inputs such as water, electricity, lubricants, and synthetic rubber used during casting.

Initial results demonstrate that GP concrete consistently reduces environmental impact across all measured indicators. The most substantial improvement is observed in the global warming (GW) category, where emissions decrease by 25.7%. In contrast, the smallest reduction occurs in the carcinogens (CA) category, with only a 5.8% decline. Cement production is the dominant contributor in nearly all impact categories, responsible for 91.59% of GW and 89.45% of non-carcinogens (N-CA) in the conventional scenario. In categories where cement has the highest burden—such as GW, N-CA, respiratory inorganics (RI), and mineral extraction (ME)—substituting it with GP results in marked improvements. However, in categories with lesser cement contribution, such as terrestrial ecotoxicity (T-ECO), respiratory organics (RO), and land occupation (LO), reductions are more modest. The limited improvement in the CA category, despite cement’s 80.18% contribution, is attributed to additional particulate emissions from the glass grinding process.

Aggregates also exert a notable influence on LO and T-ECO, contributing 31.67% and 19.18%, respectively, in the conventional scenario. These impacts show minor declines in the GP scenario, reflecting slight adjustments in the mix design. Transportation emerges as a key factor in categories like T-ECO and LO, accounting for 29% and 21% of the impacts, respectively. Although the total mass-distance increases marginally in the GP scenario (see Table S3), this effect is not visually prominent in Figure 4.

Collectively, these findings highlight the disproportionate environmental burden associated with cement production and support the theoretical assertion that decarbonization strategies in concrete must prioritize binder replacement over marginal process optimizations. This reinforces existing LCA literature that positions binder substitution as the most impactful intervention point. The observed variation across impact categories also underscores the importance of multidimensional environmental evaluation, as reliance on a single metric (e.g., CO_2) may obscure trade-offs in toxicity or land use. Such insights contribute to a broader theoretical understanding of material substitution by revealing that the environmental efficacy of SCMs like GP is not absolute but context- and category-dependent.

Figure 5 presents a comparative assessment of the environmental impacts of conventional and GP concrete, based on IMPACT 2002+ endpoint indicators. Detailed numerical data for each endpoint category are provided in Table S4 of the supplementary materials. As with the midpoint results, the figure confirms that cement production remains the dominant contributor to the overall environmental burden—most notably in global warming, where it accounts for over 91% of the impact. Transportation and aggregate extraction also make significant contributions, particularly to ecosystem quality, with respective shares of 19% and 25% in the conventional scenario, and 22% and 30% in the GP scenario.

In terms of resource use, cement continues to exert the largest impact, though transportation and aggregate sourcing remain important contributors, representing 10% and 11% in the conventional case, and 12% and 14% in the GP scenario, respectively. Notably, nearly all resource use—up to 99.9%—is associated with non-renewable energy (NRE), reflecting the heavy fossil fuel dependency of cement production. While the impact of mineral extraction processes (e.g., sand, gravel, limestone) may appear secondary, their contribution is likely underrepresented in current models, potentially leading to an overemphasis on fuel related impacts. This observation suggests that refining inventory datasets for mineral sourcing could improve the resolution of LCA studies in this domain.

With respect to human health, RI dominate the impact profile, contributing nearly 91% of the total

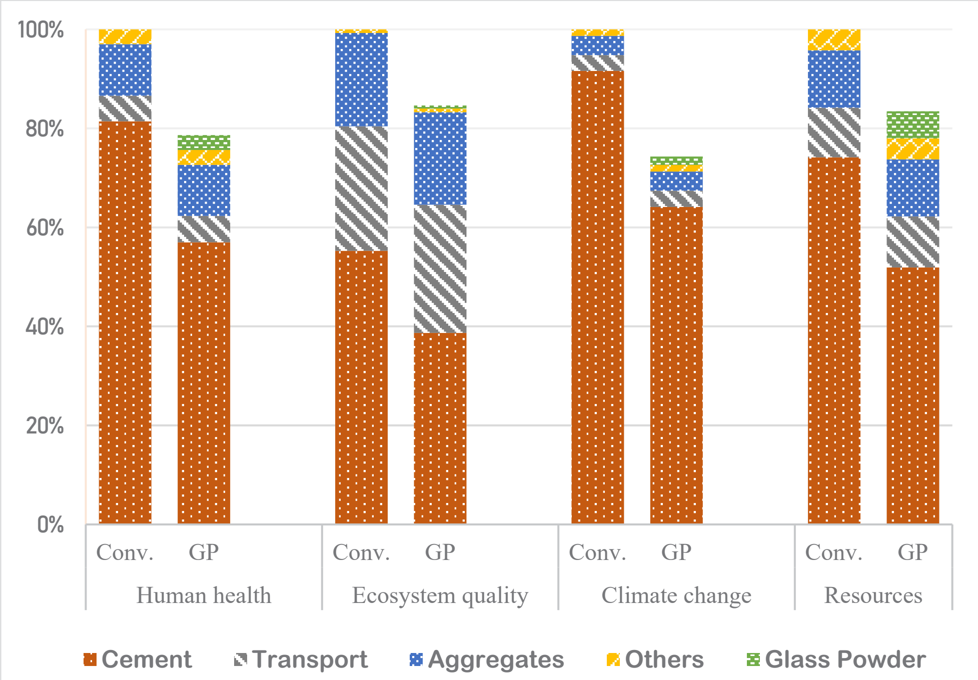

Fig. 5. The endpoint results of Conv. concrete vs. the GP scenarios using IMPACT 2002+

burden across both scenarios. N-CA and CA follow, accounting for less than 6% and around 3%, respectively. Other human health-related indicators—including ionizing radiation (IR), ozone layer depletion (OLD), and RO—together make up less than 0.1% of the impact. Approximately half of the RI impact originates from clinker production, which involves high-temperature fuel combustion that emits pollutants such as CO_2, nitrogen oxides (NO_x), sulfur dioxide (SO_2), and fine particulates ($PM_{2.5}$).

The production of clinker, central to cement manufacturing, is a major source of both greenhouse gases and air pollutants. It requires temperatures reaching up to 1450°C, leading to the release of substantial quantities of CO_2 and precursor compounds for acid rain (e.g., NO_x and SO_2). RI is particularly critical from a public health perspective, primarily driven by emissions of nitrogen oxides (0.778 kg $PM_{2.5}$ eq) and fine particulates (0.0732 kg $PM_{2.5}$ eq) per functional unit, with sulfur dioxide contributing an additional 0.0275 kg $PM_{2.5}$ eq. These findings support the broader theoretical understanding that cement's health-related externalities—especially those tied to air quality degradation—are as critical as its climate impacts.

From a theoretical standpoint, these results underscore the need to consider multiple environmental dimensions—beyond just carbon emissions—when evaluating sustainable alternatives to conventional concrete. The disproportionate influence of a single process (clinker production) across multiple endpoint categories highlights the systemic leverage points for reducing environmental and health burdens in the construction sector.

Using the ReCiPe method (Figure S2), GP concrete consistently demonstrates significantly lower environmental impact potential across all indicators compared to conventional concrete. ReCiPe was selected in part due to its strong emphasis on human health impacts, making it particularly relevant to this study's objectives. When comparing human health outcomes across methods, ReCiPe confirms that GP concrete results in noticeably reduced impacts. For ecosystem quality, ReCiPe estimates GP concrete to have only 75% of the impact associated with conventional concrete—an even greater improvement than the 85% reduction calculated using the IMPACT 2002+ method. In terms of resource use, both methods yield similar results, with only a 3% difference between them.

The study also conducted sensitivity analyses across four scenarios to evaluate the influence of

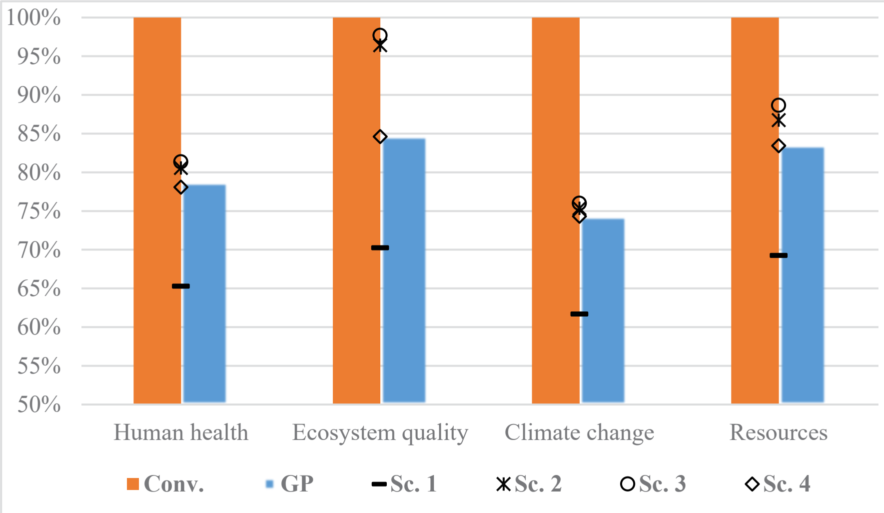

Fig. 6. Endpoint of the Conv. concrete vs the GP concrete scenarios; GP concrete - extended lifespan (Scenario 1), distant supplier for the GP (Sc. 2), remote target location (Sc. 3), GP concrete without particulate emission (Sc. 4)

key parameters. Scenario 1 assumed an extended service life for GP concrete, which resulted in lower environmental impacts across all endpoint indicators (Figure 6). Scenario 2 assessed the effect of particulate emissions generated during the grinding of waste glass, which were found to have a minimal effect on total impact scores but raised occupational health concerns, emphasizing the importance of proper safety and environmental controls. Scenarios 3 and 4 explored the consequences of increased transportation distances and the hypothetical elimination of particulate emissions, respectively. While most indicators remained stable, some category-specific impacts were affected.

A closer analysis of Scenarios 2 and 3 reveals that although extended transportation distances do not significantly alter climate change indicators, they substantially increase impacts on ecosystem quality—effectively offsetting much of the environmental benefit achieved through cement substitution. In Scenario 2, transporting GP 500 km by freight lorry raised the ecosystem quality impact to 96% of that associated with conventional concrete. Similarly, Scenario 3, which modeled an additional 30.9 km of concrete transport, brought this value up to 98%. Resource use also increased modestly, reaching 87% and 89% for Scenarios 2 and 3, respectively, due to additional fuel consumption. This rise in transportation-related energy consumption, slightly elevated climate change impact scores by approximately 1.5%.

These findings reinforce the theoretical principle that material substitution strategies in sustainable construction must account not only for the properties of the substitute material but also for the logistical and infrastructural context in which it is implemented. They also suggest that environmental trade-offs can shift across impact categories depending on transportation intensity, highlighting the importance of system-wide assessments in low-carbon material design.

Among all evaluated scenarios, Scenario 1, which assumes a 20% extension in the lifespan of GP concrete, clearly emerges as the superior option from an environmental standpoint. Compared to both the baseline GP scenario and conventional concrete, Scenario 1 demonstrated the lowest overall environmental impact across all endpoint categories. As shown in Figure 6, this extended lifespan proportionally reduces the functional unit's impact, as environmental burdens such as cement use, transportation, and energy consumption are amortized over a longer service life. This effect was most evident in the categories of climate change and resource use, where Scenario 1 reduced impacts by an additional 15–20% compared to the baseline GP scenario. Importantly, this improvement does not introduce new environmental trade-offs—unlike Scenarios 2 and 3, where increased transportation distances substantially elevated ecosystem quality and resource use impacts, nearly offsetting the gains

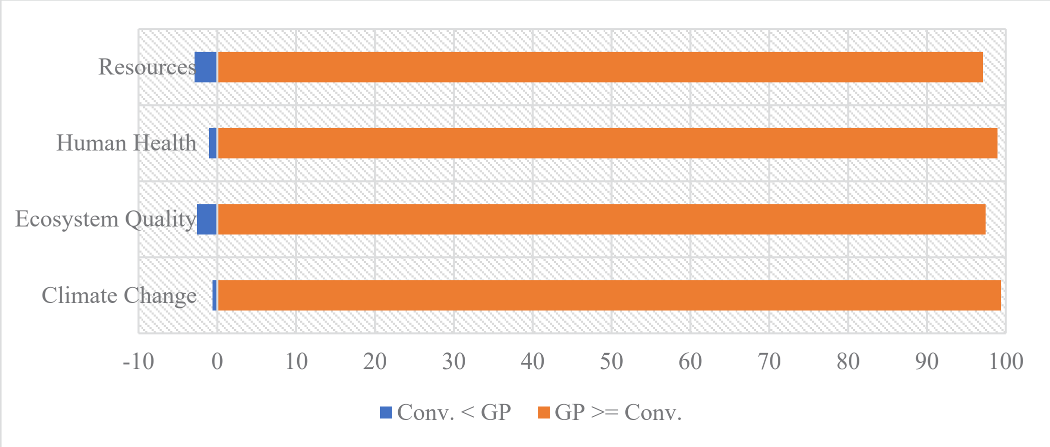

Fig. 7. Results of the Monte Carlo Analysis on the IMPACT 2002+ endpoint indicators (confidence interval: 95%; 10000 iterations).

from cement substitution. Furthermore, the enhanced performance of Scenario 1 is both technically justified and realistic, as supported by multiple experimental studies cited in Section 2.3, which report superior long-term durability and strength development for GP concrete due to its pozzolanic reactivity and densified microstructure. Monte Carlo simulation results (Figure 7) further reinforce the robustness of this scenario, with over 99% of iterations confirming lower impacts for GP concrete. Taken together, these findings provide strong evidence that Scenario 1 represents the most environmentally favorable and technically feasible pathway for sustainable concrete production using glass powder as a partial cement substitute.

Figure 7 presents the results from a Monte Carlo analysis with 10,000 model runs, indicating the probability of GP concrete having a lower environmental impact compared to conventional concrete across various endpoint indicators. In a significant majority of runs, GP concrete demonstrates a lower environmental burden. Specifically, for the climate change indicator, over 99.4% of runs show GP concrete with a lower impact. This percentage decreases slightly to 97.1%, 98.9%, and 97.4% for resource use, human health, and ecosystem quality indicators, respectively.

CONCLUSION

This study provides strong evidence that integrating ground waste GP as a pozzolanic substitute for cement in concrete can significantly reduce the environmental burden associated with conventional concrete production. The LCA results confirm that GP concrete outperforms conventional concrete across all evaluated impact categories, with the most substantial improvement observed in climate change (a 25.7% reduction in CO_2 emissions). Other notable reductions include 21.3% in human health impacts, 15.4% in ecosystem quality, and 16.6% in resource use. These findings reinforce the theoretical premise that binder substitution—rather than marginal process improvements—is the most effective leverage point for decarbonizing the concrete industry.

From a theoretical perspective, this study contributes to a more nuanced understanding of material substitution in sustainable construction. It demonstrates that the environmental performance of SCMs like GP is highly context-dependent, shaped not only by the intrinsic properties of the material but also by logistical factors such as transportation distance, processing energy, and local infrastructure. This reinforces recent calls in LCA literature to move beyond generalized claims of sustainability and focus on region-specific assessments that account for systemic constraints.

On a practical level, the findings highlight several actionable insights. First, the environmental benefits of GP concrete can be significantly compromised by long-distance transportation or inefficient grinding operations. Therefore, localizing GP production facilities and improving glass waste collection and sorting systems are essential to maximizing its advantages. Second, the study underscores the importance of regulatory and market incentives for glass waste valorization, as current economic conditions and informal recycling practices in cities like Tehran hinder widespread adoption.

Key lessons learned from this research include the realization that environmental benefits do not scale linearly with material substitution. In some scenarios, small logistical inefficiencies (e.g., transporting GP from distant cities) nearly nullified the gains achieved through cement reduction. Additionally, while GP concrete performed well in most categories, the increase in particulate emissions during glass grinding introduced new health-related burdens—demonstrating that sustainability interventions can carry trade-offs that must be critically evaluated. This study is not without limitations. First, the scope was restricted to a cradle-to-gate system boundary, excluding use-phase and end-of-life impacts. Second, the GP concrete mix design was validated based on laboratory data; its long-term field performance under Tehran's specific environmental conditions remains to be studied. Third, the LCI data for glass grinding and waste logistics were modeled using best available estimates, which may vary in actual industrial implementations. Finally, mineral depletion impacts were not included in the IMPACT 2002+ method used here, which may underrepresent the total environmental footprint.

Despite these constraints, the study offers a replicable framework for evaluating alternative SCMs under realistic conditions in infrastructure-limited regions. Future research should extend the system boundary to a full life cycle, incorporate economic cost modeling, and explore decentralized glass milling systems to assess the viability of distributed GP production. In doing so, this line of research can better support decision-makers in urban planning, waste management, and green construction policy.

GRANT SUPPORT DETAILS

The present research did not receive any financial support.

CONFLICT OF INTEREST

The authors declare that there is not any conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/ or falsification, double publication and/or submission, and redundancy has been completely observed by the authors.

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LIFE SCIENCE REPORTING

No life science threat was practiced in this research.

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