

Life Cycle Assessment of Geopolymer Concrete Based on Municipal Wastewater Sludge versus Ordinary Portland Cement Concrete: Implications for Sustainable Urban Architecture

Alireza Esparham

University of Tehran Faculty of Environment

Nasser Mehrdadi

mehrdadi@ut.ac.ir

Tehran University: University of Tehran <https://orcid.org/0000-0002-1608-2405>

Akbar Baghvand

Tehran University: University of Tehran

Research Article

Keywords: geopolymer concrete, life cycle assessment, sustainable urban architecture, wastewater sludge, ground granulated blast furnace slag, cumulative energy demand

Posted Date: September 30th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10909025/v1>

License: © ⓘ This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Life Cycle Assessment of Geopolymer Concrete Based on Municipal Wastewater Sludge versus Ordinary Portland Cement Concrete: Implications for Sustainable Urban Architecture

Abstract

Ordinary Portland Cement (OPC) concrete accounts for roughly 5–7% of global CO₂ emissions. Geopolymer concrete, synthesized from industrial byproducts and waste-derived aluminosilicate materials, offers a sustainable alternative to conventional concrete for environmentally friendly construction. This study presents a Life Cycle Assessment (LCA) of 1 m³ of geopolymer concrete based on a municipal wastewater sludge-derived aluminosilicate binder combined with ground granulated blast furnace slag (GGBFS), compared with standard OPC concrete of equivalent compressive strength (approximately 80 MPa at 28 days). The analysis was performed in SimaPro V9 using the CML 2001 baseline method for ten impact categories and the Cumulative Energy Demand (CED) method for energy analysis, within the context of the Isfahan metropolitan area, Iran. Geopolymer concrete showed markedly lower environmental impacts than OPC concrete across all ten CML categories. Its Global Warming Potential (GWP) was 73.2% lower than that of OPC concrete (1070.75 kg CO₂ eq/m³), and its cumulative energy demand was 73.0% lower than that of OPC concrete (8958.76 MJ/m³). Sodium silicate and sodium hydroxide were the largest contributors to the environmental burden of geopolymer concrete, while Portland cement and the chemical superplasticizer dominated the burden of conventional concrete. These findings indicate that geopolymer concrete produced from waste-derived precursors is a more environmentally sustainable alternative to OPC concrete, with considerable potential to reduce the environmental footprint of the built environment.

Keywords: geopolymer concrete; life cycle assessment; sustainable urban architecture; wastewater sludge; ground granulated blast furnace slag; cumulative energy demand

1. Introduction

The term 'sustainability' has become embedded in various industries. Multiple explanations for sustainable development exist. However, the definition that has gained the widest acceptance is the provision of resources to present generations without endangering resource availability for future generations (Mensah 2019). Economically sustainable development, social progress, human rights, and sustainable development all harmoniously address environmental protection. In the context of the built environment, sustainable development is called sustainable architecture. However, separating sustainable architecture from its economic, cultural, and social frameworks is a serious problem. Rogers, as cited by O'Rourke, holds that sustainable design is the provision for future generations in a way that does not waste the resources needed by future generations to survive. Within the context of sustainable design of buildings, emphasis is placed on the optimal use of resources and energy, the flexibility of design, and the long-term sustainability of the building. In the same way, the identification of Kims, as cited by O'Rourke, places resource conservation, and life-cycle and human-centered design, as the three pillars upon which sustainable architecture is established (Esparham et al. 2023).

In the past decades, sustainable architecture has become one of the most prominent factors in the design and construction of buildings and cities. In the context of sustainable urban architecture, it is vital to understand the environmental impact and pollution created by different activities in urban environments. Moreover, industrial processes need to comply with environmental goals in order to limit pollutant emissions and decrease the ecological footprint of pollutants (Rahimi et al. 2024). Human population on Earth depends on the amount of natural resources and needs of society. Currently, urban areas consume almost 75% of the world's energy supply and produce 75% of the world's greenhouse gases. Moreover, UN expects that by 2050 around 68% of the world population will live in urban environment. Therefore, any talk about sustainable development needs to take into account direct and indirect environmental impact of urban environment (Ballen Zamora et al. 2021; Esparham et al. 2023).

Urban centers act as crucial nodes that link together vast networks of services in terms of infrastructure. Resilience and robustness in urban infrastructure are some of the basic requirements of sustainable development. However, there have been several environmental problems and issues associated with waste coming from industries operating in peri-urban regions, construction waste, and urban wastewater (Enyew et al. 2026).

Valorization of industrial, municipal, and agricultural wastes into supplementary cementitious materials (SCMs), recycled aggregates, and geopolymeric binders is one of the key features of circular economy-inspired construction. Wastes such as coal fly ash, blast-furnace slag, rice husk ash, and construction and demolition wastes participate in pozzolanic and alkali activation reactions that not only reduce the amount of calcium hydroxide but also increase the formation of C-S-H and C-A-S-H gels (Akintayo et al. 2025). Besides increasing compressive strength and resistance to corrosion by chloride ions and sulfates, this approach is more environmentally friendly than OPC production in terms of reducing the carbon footprint. It has been explained by characterization methods such as isothermal calorimetry, thermogravimetric analysis, and synchrotron X-ray diffraction that allowed optimizing the composition of concrete for equal or better performance compared to traditional concretes and waste diversion from landfills (Barbir et al. 2026; Esparham 2023).

The inclusion of the aforementioned secondary resources in hybrid construction processes and systems provides additional benefits for enhanced environmental performance via multi-level models and life cycle

optimization. The use of computational fluid dynamics (CFD) combined with discrete element modelling (DEM) and machine-learning predictive models enables modelling of mass flow, heat flow, and mechanical properties of the materials that incorporate waste in the form of composites under various environmental stressors (Cai et al. 2026). Recent developments such as nanomaterials treated recycled aggregates, biological stabilizers, and photocatalytic coatings made from titanium dioxide-treated industrial byproducts enable both pollutant capturing (heavy metals, VOCs, and NO_x), as well as the self-cleaning capacity. In comparison to linear approaches, these integrated approaches offer significant improvements in terms of reducing global warming potential, cumulative energy demand, and eutrophication effects, according to ISO-compliant LCA approach (Esparham et al. 2022; Nfor et al. 2026).

The sustainable building materials made of secondary resources are formulated such that their cumulative energy requirement and environmental footprint throughout their life cycle are minimized, through utilization of processes like alkali activation, hydrothermal process and carbonation hardening at lower temperatures. The above-mentioned processes effectively reduce direct and indirect carbon dioxide emissions compared to the conventional high-energy-intensive clinker process, while the binders produced are known to have equivalent or better mechanical strength due to the strong gel network with low Ca/Si ratio and higher degree of cross-linking (Zhang et al. 2025). Durability of these binders is additionally improved by reduction of capillary porosity, pore size distribution and improved interfacial transition zones, which protect the binder from aggressive species such as chlorides, sulfates and CO₂. This can be quantitatively explained with advanced analytical techniques like mercury intrusion porosimetry, nuclear magnetic resonance and nanoindentation, for performance based mixing of sustainable building material (Esparham and Ghalatian 2022; Sivakumar et al. 2023).

The localization of valorization of urban and industrial wastes into secondary construction materials reflects a regional circular economy approach which at once reduces the need for landfilling and saves primary raw materials. Geopolymers and calcium sulfoaluminate cement containing fly ash, bottom ash, slag, and ground recycled concrete exhibit strong capacity to immobilize heavy metals and organic contaminants through physical entrapment and chemical binding in aluminosilicate structure (Aderinto et al. 2026). Multi-criteria decision analysis along with GIS-based logistics modeling for the supply chain minimizes carbon footprint related to transportation while ensuring maximum recovery of resources. Through the combination of end-of-life recycling process and design for disassembly approaches, such materials contribute to closed material loop and significantly reduce environmental impacts, as is confirmed by consequential life cycle assessment (Esparham 2021; Lehmusto et al. 2024).

Although OPC is widely used in the construction industry, its manufacturing process results in significant environmental effects, including CO₂ emissions. According to research findings, the production of one ton of Portland cement leads to the release of one ton of CO₂. Climate change, which is brought about by global warming, is regarded as one of the most serious environmental problems facing the planet today. Greenhouse gas emissions are the main causes of global warming, as 65% of greenhouse gas emissions are CO₂. Besides, the cement industry contributes to around 5% – 7% of global CO₂ emissions. Considering the environmental effects caused by the cement manufacturing process, sustainable cementitious materials are being developed as an alternative. Geopolymers are considered one of such alternatives to Portland cement (Esparham et al. 2021; Mostafa et al. 2025).

Geopolymers represent three-dimensional amorphous aluminosilicate materials with properties similar to ceramics that can be synthesized and hardened at room temperature. The formation of geopolymers takes place in highly alkaline environment with participation of alkali hydroxide and silicate solutions. In this

case, aluminosilicates react rapidly with dissolution of the silicate ($[\text{SiO}_4]^{4-}$) and aluminate ($[\text{AlO}_4]^{5-}$) tetrahedrons, which then polymerize resulting in rigid three-dimensional network structure. The features of geopolymer materials include fast hardening and rapid strength gain, as well as high 28-day compressive strength up to 100 MPa or higher. In addition, geopolymeric materials possess low permeability (in the range of 10^{-9} – 10^{-10} cm/s), low alkali-induced expansion, and low shrinkage on drying (Sindhunata et al. 2008). Besides, they show good resistance to acidic media, to sulfuric acid attack, to corrosion, and to freezing and thawing cycles. Any silica- and alumina-containing material reacting in the alkaline medium can be considered a geopolymer precursor (Almutairi et al. 2021; Ricciotti et al. 2025).

Different types of waste materials such as mining waste, by-products from power plants, municipal solid wastes, agricultural wastes, and construction and demolition wastes are some of the wastes that can be used in the manufacture of geopolymer materials. Geopolymers can be applied in the manufacturing of concrete products, construction products, fireproof coatings, and insulation. Some of the precursors used in geopolymerization include ground granulated blast furnace slag (GGBFS). This is a waste product from the iron and steel industries. Due to its mainly amorphous nature, GGBFS is one of the best wastes to be used in geopolymers manufacturing (Kheimi et al. 2022; Salimi et al. 2025).

With respect to the environmental performance of geopolymer manufacturing processes vis-à-vis the traditional Portland cement manufacturing processes, the current understanding is limited. Quantitatively speaking, the current literature on the topic offers only rough estimates of the environmental impact, frequently not specifying clear system boundaries, while the majority of research work focuses exclusively on CO₂ emissions. The most common method used in evaluating potential environmental impact is the Life Cycle Assessment (LCA) method, which is a multi-dimensional assessment technique for evaluating products and services throughout the life cycle (Periyasamy and Nagarajan 2024; Sbahieh et al. 2023).

This research seeks to explore the possibility of utilizing industrial by-products/waste products in producing geopolymer concrete through the use of a municipal wastewater sludge aluminosilicate binder combined with GGBFS for developing eco-friendly building materials. The objective is to encourage sustainable urban development by minimizing the emission of greenhouse gases and energy usage through comparison with the environmental performance of ordinary Portland cement concrete through LCA analysis.

2. Methods

2.1. Life Cycle Assessment Framework

Life Cycle Assessment (LCA) is a method used to analyze the materials and associated costs of a product (or process) over its entire life cycle. Analyzing the costs of a product includes the costs of the resources used to make that product, as well as the costs to society based on the waste generated and the possible impacts to health and the environment. The assessment includes interpreting the costs. This method enables the analysis of costs from the very beginning (extraction of resources) to the very end (final disposal). According to the International Organization for Standardization (ISO) 14040 and 14044, there are 4 primary phases in the LCA: defining the goal and scope, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation.

The LCIA phase includes four main interconnected steps: classification, characterization, normalization, and weighting. In classification, the LCI identifies and quantifies the environmental interventions, which are subsequently grouped into impact categories. This is done based on the environmental mechanisms to which interventions contribute. In characterization, contributions to each impact category are expressed in

the same unit and characterized by factors of that category. In normalization, as described in ISO 14042, the scale of each impact category indicator is expressed in relation to a benchmark (e.g., average European or global per capita emissions over a given period). The main goal of normalization is to enhance the clarity and relative importance of each impact category. Weighting is the final optional step, and involves the aggregation of various impact categories. In any LCA, characterization and classification are required steps, while normalization and weighting are discretionary steps that depend on the boundaries of the study.

2.2. Goal and System Boundary Definition

The scope of the LCA in this case will entail the carrying out of an analysis that compares the two types of concrete; namely the geopolymer and the OPC. The main goals include determining the key phases in the life cycle, along with identifying the system with the lesser impact on the environment.

Here, the functional unit that was considered for making comparisons was 1m³ of concrete to provide consistency in comparing both the systems. Both systems were expected to give 80MPa compressive strength after 28 days. Life cycle assessment is a complex methodology which involves large amount of data, so the definition of system boundaries is of great significance in this regard. For the present study, the system boundaries were defined as shown in Figs. 1 and 2, focusing mainly on production process and its upstream processes.

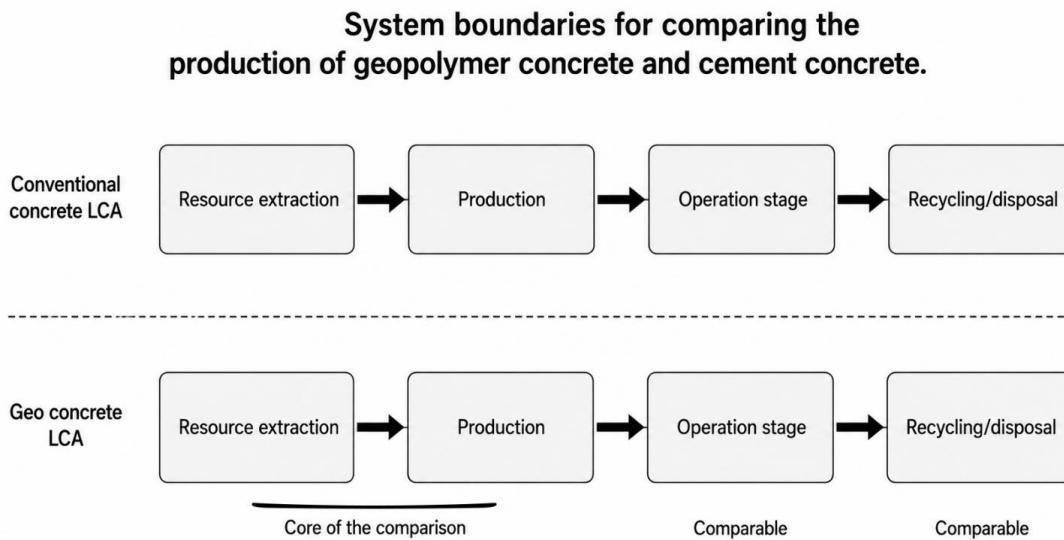


Fig 1. System boundaries for comparing the production of geopolymer concrete and OPC concrete

Even though the transportation of materials does not make a significant contribution to the environmental effects, it is explicitly taken into account in this study's system boundary. The project site is 45 km away from the Isfahan Steel Company, which is where GGBFS is produced primarily. All transportation distances of the materials are assumed according to expert judgement and shown in Table 3.

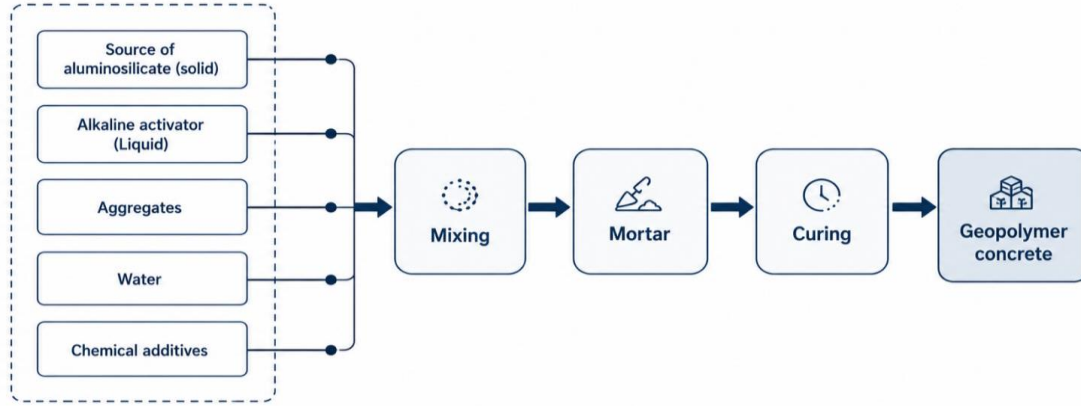


Fig 2. System boundaries for comparing geopolymer compositions

2.3. Life Cycle Inventory (LCI)

The development of life cycle inventories in this study was done using data from various sources. The key data sets used for the raw materials, auxiliary materials, and semi-finished products have been taken from the Ecoinvent database, which is available in SimaPro V9 software. This database, compiled by the Swiss Centre for Life Cycle Inventories together with ETH Zurich, is considered to be one of the most comprehensive life cycle inventory databases in the world. It consists of over 10,000 processes related to various industrial sectors such as energy generation, transport, building sector, chemicals, agriculture, and waste.

The main precursor for geopolymer production in this research is the ground granulated blast furnace slag (GGBFS), which was produced at Isfahan Steel Company. Chemical composition of GGBFS, measured using X-ray Fluorescence technique (XRF), is summarized in Table 1. Design of geopolymer and conventional concretes with 80 MPa compressive strength after 28 days of curing is shown in Table 2.

Table 1. Chemical composition (wt.%) of the ground granulated blast furnace slag (GGBFS) used as the primary geopolymer precursor, determined by X-ray fluorescence (XRF) analysis

SiO ₂	Al ₂ O ₅	CaO	Fe ₂ O ₅	MgO	K ₂ O	Na ₂ O	MnO	Cl
34.4	11.2	37.0	0.6	9.8	0.68	0.60	1.58	0.002

Table 2. Mix proportions of geopolymer concrete and Ordinary Portland Cement (OPC) concrete (kg/m³) for a 28-day compressive strength of approximately 80 MPa

Material	OPC Concrete (kg/m ³)	Geopolymer Concrete (kg/m ³)
Portland cement	410	–
Municipal wastewater sludge-based binder (solid aluminosilicate source)	–	400
Sodium silicate solution (37 wt.%)	–	120
Sodium hydroxide solution (50 wt.%)	–	80
Superplasticizer	8	8
Deionized water	103	10
Coarse aggregate	1026	850
Fine aggregate	810	850
Total	2357	2318

Energy used in making concrete is determined from the period taken by the mixer machine in operation and energy consumption by the machine, to give a total of 0.75 kWh consumed per m³ of concrete. The CO₂ emissions for the calculation will be in accordance with Turner et al(2013) where the emission factor for making concrete is estimated to be 0.0033 kg CO₂/m³, while that for finishing and curing is 0.009 kg CO₂/m³.

In order to include the transportation-related environmental aspects in the LCA, EURO 3 diesel trucks with the capacity of 16-32 tons and greater than 32 tons were selected depending upon the materials. The transportation distance of all components was assumed according to expert opinion and is illustrated in Table 3.

Table 3. Transportation distances and modes for raw materials used in the production of geopolymer concrete and OPC concrete within the Isfahan metropolitan area, Iran

Material	Distance (km)	Transport Mode
Ground granulated blast furnace slag (GGBFS)	45	EURO 3 diesel lorry, 16–32 t
Portland cement	120	EURO 3 diesel lorry, >32 t
Sodium silicate solution	350	EURO 3 diesel lorry, >32 t
Sodium hydroxide solution	350	EURO 3 diesel lorry, >32 t
Coarse aggregate (crushed gravel)	30	EURO 3 diesel lorry, 16–32 t
Fine aggregate (sand)	30	EURO 3 diesel lorry, 16–32 t
Superplasticizer	200	EURO 3 diesel lorry, >32 t
Tap water	5	EURO 3 diesel lorry, 16–32 t

2.4. LCIA Methods

The process of impact assessment determines the possible impacts on the environment based on the inputs and outputs identified in the LCI. By using different models for the environment for the mechanisms of impacts, LCI results are converted into environmental impact indicators. In this research, two complementary LCIA approaches were used based on SimaPro V9, which included CML 2001 and Cumulative Energy Demand (CED) (Singal et al. 2023).

2.4.1. CML 2001 Method

The CML 2001 method, designed by the Institute of Environmental Sciences of Leiden University, offers a range of impact categories and characterization factors for the life cycle impact assessment. The CML method in its original form, which is employed in this work, assesses ten impact categories: abiotic resource depletion (fossil fuels), global warming potential (GWP 100a), ozone depletion, human toxicity, ecotoxicity in freshwater aquatic environment, ecotoxicity in marine aquatic environment, ecotoxicity in terrestrial environment, photochemical oxidation formation potential, acidification, and eutrophication. This method is especially relevant for the assessment of construction materials in the context of sustainable architecture (Gabathuler 2006; Mahmud et al. 2023).

2.4.2. CED Method

CED approach was chosen to assess energy implications in the life cycles of both systems. CED is the sum of all energy used during the entire life cycle of a product in terms of extraction, processing, manufacturing, and disposal of products. Seven energy categories can be defined using CED approach, including two types of non-renewable energy (fossil and nuclear) and five renewable sources of energy (biomass, hydro power, wind, solar, and geothermal energy). Energy consumption of the cement industry and concrete manufacturing industry is high on a global scale, and therefore one of the major tasks of sustainable architecture is efficient energy consumption of building materials (Mahmud et al. 2023).

3. Results and Discussion

In this section, the results obtained from SimaPro V9 are analyzed using both the CML 2001 and CED impact assessment methods. Results are first presented and discussed in terms of the relative contribution of each material input across different impact categories. Subsequently, the outcomes for each system are reported in tabular form, followed by a comparative analysis between geopolymer concrete and conventional OPC concrete.

3.1. Geopolymer Concrete System: CML 2001 Method

Table 4 gives the life cycle impact assessment outputs for the production of 1 m³ of geopolymer concrete, employing the CML 2001 baseline method. Fig. 3 gives a graphical representation of this data. The model is built with the following input data per cubic meter of concrete: electricity, superplasticizer, packaging, sodium hydroxide, sodium silicate, water, aggregates, aluminosilicate (GGBFS combined with municipal wastewater sludge-derived binder), and a polymer.

Table 4. Life cycle impact assessment (LCIA) results for the production of 1 m³ of geopolymers concrete using the CML 2001 baseline method, including contribution analysis of individual life cycle inputs

Impact Category	Unit	Total	Sodium Hydroxide	Sodium Silicate	Lorry >32 t	Lorry 16–32 t	Crushed Gravel	Sand	Superplasticizer	WW Sludge	Tap Water	Electricity	Cement Packaging
Abiotic Depletion (Fossil Fuels)	MJ	2362.37	714.67	870.51	58.17	35.31	41.14	38.25	210.23	361.84	0.006	7.12	25.13
Global Warming Potential	kg CO ₂ eq	286.81	126.24	89.32	5.18	2.40	4.54	3.96	4.69	47.69	0.0004	0.61	2.18
Ozone Layer Depletion	kg CFC-11 eq	9.90×10 ⁻⁶	4.78×10 ⁻⁶	4.89×10 ⁻⁷	6.36×10 ⁻⁷	1.17×10 ⁻⁷	3.18×10 ⁻⁷	2.15×10 ⁻⁷	7.12×10 ⁻⁷	2.36×10 ⁻⁶	2.73×10 ⁻¹⁰	5.88×10 ⁻⁶	2.22×10 ⁻⁷
Human Toxicity	kg 1,4-DB eq	211.34	49.13	81.62	3.63	0.51	3.33	2.83	6.41	61.52	0.000457	0.185	2.16
Freshwater Aquatic Ecotoxicity	kg 1,4-DB eq	165.29	50.42	58.37	0.215	0.316	3.42	0.834	3.42	47.32	0.000382	0.061	0.924
Marine Aquatic Ecotoxicity	kg 1,4-DB eq	333816	105239	126290	917	1001	4190	3001	6191	83316	0.754	410.4	3261
Terrestrial Ecotoxicity	kg 1,4-DB eq	0.8939	0.2318	0.2411	0.00512	0.00315	0.0154	0.0341	0.0664	0.2633	3.31×10 ⁻⁶	0.00039	0.0332
Photochemical Oxidation	kg C ₂ H ₄ eq	0.11083	0.0217	0.0324	0.00056	0.00039	0.00098	0.00065	0.00421	0.0442	7.32×10 ⁻⁸	8.58×10 ⁻⁵	0.00561
Acidification	kg SO ₂ eq	1.7118	0.4891	0.8363	0.01972	0.01769	0.03153	0.03248	0.03815	0.2262	2.36×10 ⁻⁶	0.00213	0.01851
Eutrophication	kg PO ₄ ³⁻ eq	0.5314	0.2312	0.1651	0.00486	0.00312	0.00845	0.00692	0.00762	0.0987	2.44×10 ⁻⁶	0.00081	0.00447

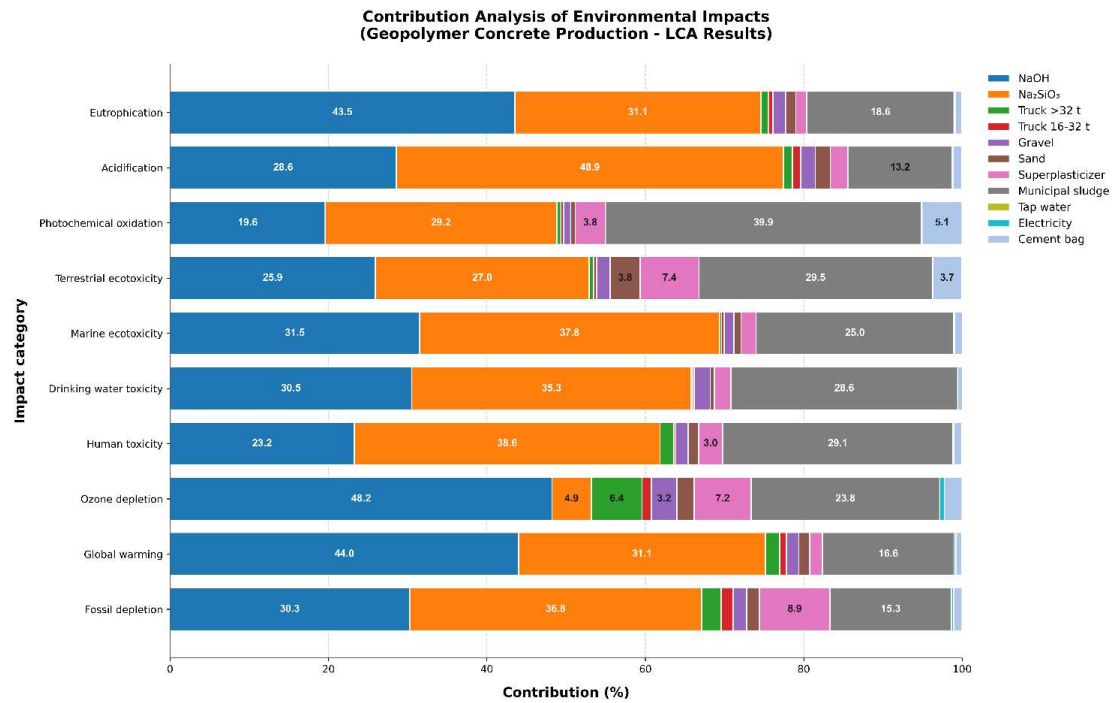


Fig. 3 Life Cycle Assessment results for the production of 1 m³ of geopolymer concrete using the CML 2001 baseline method — contribution of individual inputs to each impact category

The aluminosilicate precursor (from wastewater materials) most significantly impacts photochemical oxidation, scoring 39.88% (0.0442 kg C₂H₄ eq) among a total 0.11083 kg C₂H₄ eq. 15.32% and 16.63% are contributions to abiotic depletion (fossil fuels) and global warming, respectively. The lowest contribution from the aluminosilicate precursor is in the category of terrestrial ecotoxicity shown at 0.00037%. Electricity consumption in the geopolymer concrete system has a negligible environmental impact across all categories, with contributions consistently below 0.6%. Sodium silicate exhibits its highest contribution in the acidification category (48.85%), with a value of 0.8363 kg SO₂ eq out of a total of 1.7118 kg SO₂ eq. Its lowest relative contribution is observed in the ozone layer depletion category (4.94%). Sodium hydroxide exhibits its highest environmental burden in the ozone layer depletion category (48.23%), with a value of 4.776×10^{-6} kg CFC-11 eq out of a total of 9.902×10^{-6} kg CFC-11 eq. Its lowest contributions are observed in the photochemical oxidation category (19.58%) and human toxicity (23.25%), respectively. The superplasticizer contributes 8.90% to abiotic resource depletion (fossil fuels), while its impact in other categories remains below 7.5% of the respective totals. Sand and crushed gravel exhibit consistently minor environmental contributions across all impact categories, generally remaining below 4% in each category. Cement packaging shows its highest relative contribution in the photochemical oxidation category (5.06%), while its contributions in all other categories remain below 1.08%. Transportation of raw materials also demonstrates minimal environmental impact across all categories, with contributions typically below 4%.

3.2. Conventional OPC Concrete System: CML 2001 Method

Table 5 and Fig. 4 show the LCIA results using the CML 2001 baseline method for producing 1 m³ of conventional OPC concrete. Portland Cement has the highest contribution to global warming potential with 75.76%. This is equivalent to 811.12 kg CO₂ eq. Relative to the 1070.75 kg CO₂ eq for the entire process. Following global warming potential, the highest contribution by Portland Cement is to terrestrial ecotoxicity

at 64.45%, and then to acidification with 60.42%. The smallest relative contribution of Portland cement is in human toxicity at 21.64%. The superplasticizer's environmental impact is highest in the human toxicity category (73.55%, 214.86 kg 1,4-DB eq, of 292.13 kg 1,4-DB eq). The second most significant impact is freshwater aquatic ecotoxicity (63.71%, 164.11 kg 1,4-DB eq, of 257.61 kg 1,4-DB eq). The superplasticizer shows its lowest contribution in the global warming potential category (22.11%).

Electricity consumption and tap water usage exhibit negligible environmental impacts across all categories, each contributing less than 0.3%. Transportation, sand, crushed gravel, and cement packaging also show minimal environmental contributions across all impact categories, generally remaining below 4%.

Table 5. Life cycle impact assessment (LCIA) results for the production of 1 m³ of Ordinary Portland Cement (OPC) concrete using the CML 2001 baseline method, including contribution analysis of individual life cycle inputs

Impact Category	Unit	Total	Portland Cement	Lorry >32 t	Lorry 16–32 t	Crushed Gravel	Sand	Superplasticizer	Tap Water	Electricity	Cement Packaging
Abiotic Depletion (Fossil Fuels)	MJ	6991.27	2713.56	70.25	30.62	58.71	32.15	4025.40	0.052	4.39	56.13
Global Warming Potential	kg CO ₂ eq	1070.75	811.12	5.23	4.13	5.52	2.15	236.75	0.0074	0.679	5.155
Ozone Layer Depletion	kg CFC-11 eq	2.318×10 ⁻⁵	1.094×10 ⁻⁵	8.56×10 ⁻⁷	4.32×10 ⁻⁷	7.35×10 ⁻⁷	4.54×10 ⁻⁷	9.32×10 ⁻⁶	2.86×10 ⁻⁹	5.34×10 ⁻⁸	3.78×10 ⁻⁷
Human Toxicity	kg 1,4-DB eq	292.13	63.22	3.70	0.636	4.12	2.61	214.86	0.00415	0.0825	2.898
Freshwater Aquatic Ecotoxicity	kg 1,4-DB eq	257.61	84.73	0.411	0.212	3.893	0.731	164.11	0.00513	0.0073	3.514
Marine Aquatic Ecotoxicity	kg 1,4-DB eq	458840	223153	1460	722	5835	2986	218130	10.35	30.64	6512
Terrestrial Ecotoxicity	kg 1,4-DB eq	1.1466	0.7389	0.0083	0.0056	0.0278	0.0233	0.2864	5.26×10 ⁻⁷	8.45×10 ⁻⁵	0.0562
Photochemical Oxidation	kg C ₂ H ₄ eq	0.1124	0.0465	0.0005	0.0003	0.0018	0.0006	0.0614	7.31×10 ⁻⁵	6.38×10 ⁻⁵	0.0011
Acidification	kg SO ₂ eq	1.8602	1.1240	0.0256	0.0064	0.0332	0.0199	0.6338	2.27×10 ⁻⁵	0.000528	0.0167
Eutrophication	kg PO ₄ ³⁻ eq	1.1765	0.5265	0.0062	0.0030	0.0153	0.0059	0.6122	2.12×10 ⁻⁵	6.20×10 ⁻⁵	0.0073

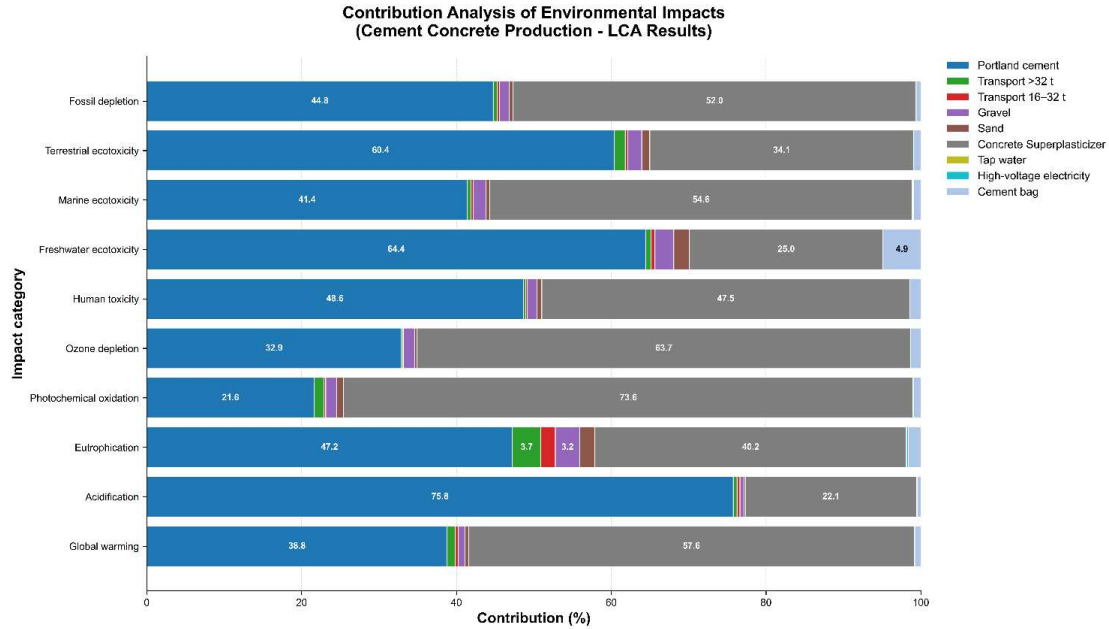


Fig. 4 Life Cycle Assessment results for the production of 1 m³ of OPC concrete using the CML 2001 baseline method — contribution of individual inputs to each impact category

3.3. Comparative Analysis: Geopolymer Concrete vs. OPC Concrete (CML 2001 Method)

Fig. 5 presents the normalized LCIA results obtained using the CML 2001 baseline method, enabling direct comparison between the two concrete systems across all ten environmental impact categories. Normalization was performed to harmonize units across categories and to clarify their relative significance within each system. From the above comparison of the two concrete systems, it is evident that the traditional OPC concrete system is more influential in terms of all the environmental impact categories than the geopolymer concrete system. In case of the traditional concrete system, the global warming potential category has the highest influence with a percentage of 78.87% out of the sum ($1070.75 / (1070.75 + 286.81)$) and abiotic resource depletion (fossil fuels) having 74.74% ($6991.27 / (6991.27 + 2362.37)$).

However, the geopolymer concrete system exhibits its maximum relative contribution in the category of photochemical oxidation (49.66%) and minimum relative contribution in the category of global warming potential (21.13%). These results have been proven by findings published by Bajpai et al(2014) which prove significant differences between environmental impacts of geopolymer and traditional concrete systems. Moreover, the results of environmental impact assessments of both concrete systems depend on the mix design and types of materials used.

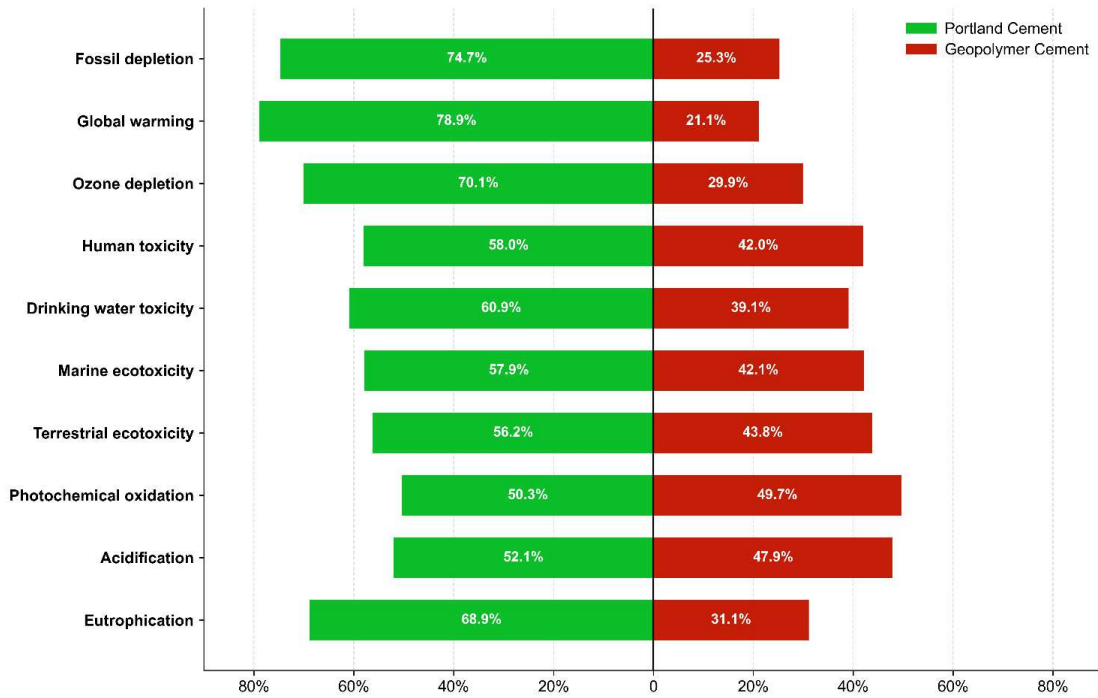


Fig. 5 Normalized CML 2001 comparison of the environmental impact contributions of geopolymer concrete (wastewater sludge-based) and OPC concrete for the production of 1 m³

3.4. Geopolymer Concrete System: Cumulative Energy Demand (CED) Method

LCA results of the GPC system using the CED method are shown in Table 6 and Fig. 6. The total cumulative energy demand of one m³ geopolymer concrete based on WW derived AS precursor is 2416.27 MJ. It consists of fossil (1971.82 MJ – 81.61 %), nuclear (180.16 MJ – 7.46 %), renewable energy resources [biomass: 121.71 MJ (5.05 %); wind, solar, geothermal: 22.73 MJ (0.94 %); hydropower: 119.51 MJ (4.92 %)] altogether 263.95 MJ (10.93 %).

The most energy intensive subprocesses in the GPC production system are sodium silicate (681.80 MJ of fossil energy; 785.29 MJ total), sodium hydroxide (536.13 MJ of fossil energy; 673.34 MJ total), and aluminosilicate waste precursor (398.91 MJ of fossil energy; 472.11 MJ total across all energies). In contrast, the least energy consumptive processes are tap water (~0.056 MJ total) and on-site electricity (7.21 MJ total).

Table 6. Cumulative Energy Demand (CED) results for the production of 1 m³ of municipal wastewater sludge-based geopolymer concrete

Impact Category	Unit	Total	NaOH	Na₂SiO₃	Lorry >32 t	Lorry 16–32 t	Gravel	Sand	Superplasticizer	WW Sludge	Tap Water	Electricity	Packaging
Non-renewable – Fossil	MJ	1971.82	536.13	681.80	30.94	20.18	31.83	19.73	231.48	398.91	0.000102	5.48	15.34
Non-renewable – Nuclear	MJ	180.16	72.651	32.52	0.3442	0.02187	33.26	13.158	5.81	18.214	0.0312	0.04163	4.11
Non-renewable – Biomass	MJ	0.332	0.0237	0.0331	0.0435	0.03256	0.0200	0.0005	0.00061	0.167	0.000217	0.00033	0.0092
Renewable – Biomass	MJ	121.71	14.56	50.25	0.2193	3.328	1.56	1.126	0.8138	6.46	0.000115	0.0248	43.37
Renewable – Wind, Solar, Geothermal	MJ	22.73	12.25	5.38	0.0612	0.4126	0.52	0.249	0.5385	2.126	0.000408	0.975	0.2196
Renewable – Hydropower	MJ	119.51	37.73	15.31	0.3584	0.0312	9.33	5.214	3.771	46.234	0.0245	0.691	0.815



Fig. 6 Cumulative Energy Demand (CED) heat map showing the distribution of fossil, nuclear, and renewable energy (hydropower, wind, geothermal, and solar) for the production of 1 m³ of geopolymer concrete

3.5. Conventional OPC Concrete System: Cumulative Energy Demand (CED) Method

The CED results for the production of 1 m³ of conventional OPC concrete are presented in Table 7 and illustrated in Fig. 7. The total cumulative energy demand amounts to 8958.76 MJ. Fossil energy contributes with 6448.50 MJ (71.98%), while nuclear energy is responsible for 1681.50 MJ (18.77%). Renewable energy sources including biomass (329.12 MJ), wind/solar/geothermal (37.69 MJ), and hydropower (461.46 MJ) make up for the remaining 828.27 MJ (9.25%).

Among the conventional concrete production system's most energy-intensive subprocesses are Portland cement production (total: 4234.13MJ) and superplasticizer production (total: 4051.82MJ), while among its least energy-consuming are tap water supply (approximately 0.51MJ total) and on-site electricity consumption (11.18MJ total).

Table 7. Cumulative Energy Demand (CED) results for the production of 1 m³ of Ordinary Portland Cement (OPC) concrete

Impact Category	Unit	Total	Portland Cement	Lorry >32 t	Lorry 16–32 t	Gravel	Sand	Superplasticizer	Tap Water	Electricity	Packaging
Non-renewable – Fossil	MJ	6448.50	2837.12	98.397	42.512	68.161	41.63	3286.73	0.0757	10.743	63.13
Non-renewable – Nuclear	MJ	1681.50	924.31	0.126	0.4865	45.281	21.312	682.13	0.2984	0.311	7.212
Non-renewable – Biomass	MJ	0.5203	0.278	0.0500	0.0300	0.0341	0.00057	0.0750	0.000412	0.000372	0.0518
Renewable – Biomass	MJ	329.12	48.125	0.2642	0.0796	4.163	0.8975	41.39	0.0368	0.02748	234.135
Renewable – Wind, Solar, Geothermal	MJ	37.69	26.713	0.0932	0.0499	0.6675	0.3465	9.354	0.000368	0.000297	0.4682
Renewable – Hydropower	MJ	461.46	398.361	0.4897	0.0189	17.32	9.76	32.11	0.0941	0.0970	3.2135

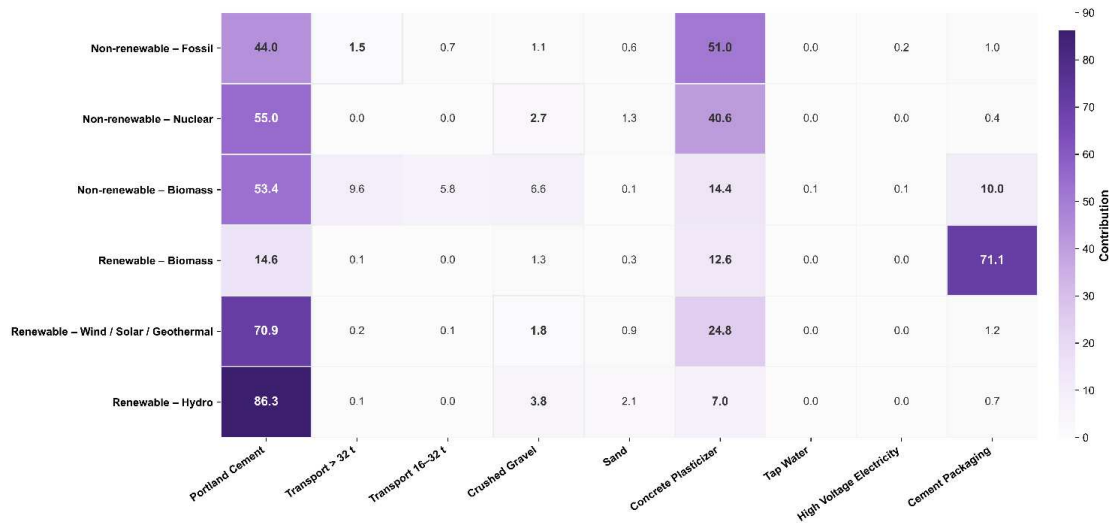


Fig. 7 Cumulative Energy Demand (CED) heat map showing the distribution of fossil, nuclear, and renewable energy for the production of 1 m³ of OPC concrete

3.6. Comparative Analysis: Geopolymer Concrete vs. OPC Concrete (CED Method)

Comparative CED results of geopolymer concrete (waste water derived Aluminosilicate precursor) & conventional OPC are shown in Fig. 8. The total cumulative energy demand for production of 1m³ GPC is 2416.27 MJ, which is 73.03% lower compared to 8958.76MJ required for OPCC.

This dramatic drop aligns with findings reported in the literature. Salas et al. [full reference to be supplied by the author] reported that the cumulative energy demand of zeolite geopolymer concrete (for 28 day compressive strengths of 5, 5.5, and 15 MPa) was approximately 46%, 37.3%, and 27% lower, respectively, relative to conventional concrete with a 28 day compressive strength of 15 MPa. Similarly, Sproehm et al. [full reference to be supplied by the author] report a 35% reduction in cumulative energy demand of geopolymer concrete versus Portland cement-based concrete at similar strength levels. The greater drop seen here (73.03%) could be due to using waste-derived binder(s), particularly the mixture of MWSL and GGBFS, which have much lower upfront energy burdens than standard binders. Additionally, our higher target 28 day compressive strength (approx. 80 MPa) also plays a role.

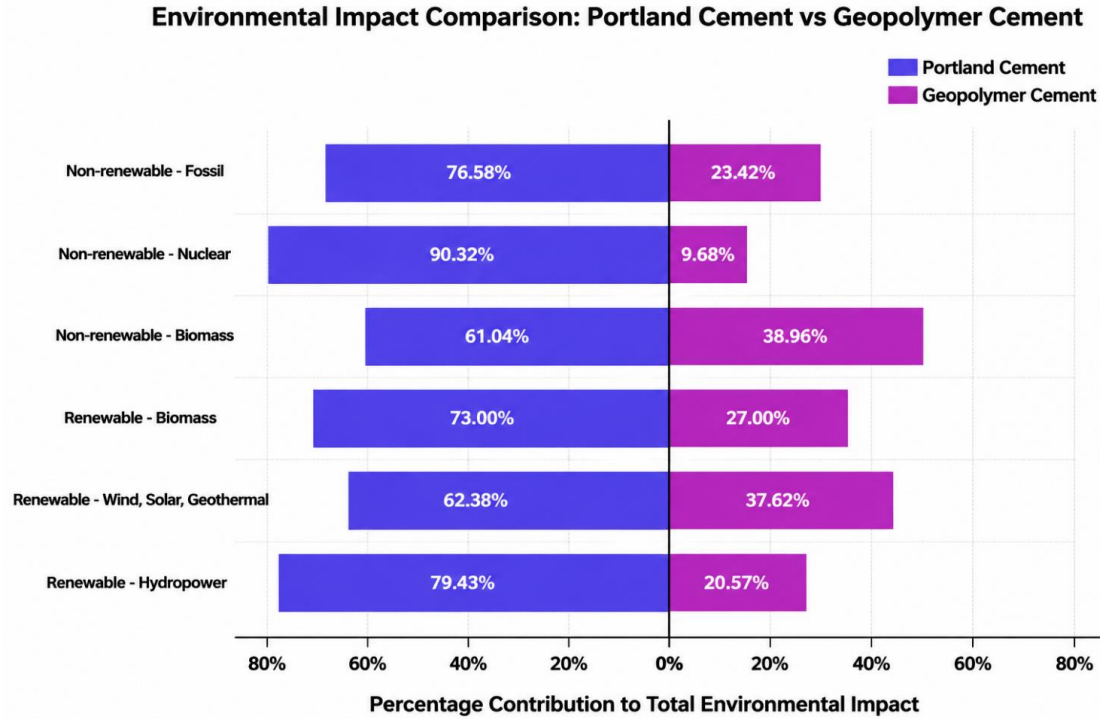


Fig. 8 Comparison of the Cumulative Energy Demand (CED) for the production of 1 m³ of geopolymer concrete (municipal wastewater sludge-based) and OPC concrete

4. Conclusions

This study used LCA to assess and compare the environmental profile of geopolymer concrete based on a municipal wastewater sludge-derived aluminosilicate binder and conventional OPC concrete for production of 1 m³ concrete at approximately equivalent 28 day compressive strength of about 80MPa. LCA was performed using SimaproV9 with CML2001 baseline and CED method including raw material extraction, processing and transportation within the Isfahan metropolitan area, Iran.

Results showed that the GPC system has significantly lower environmental burdens than OPC across all ten CML 2001 impact categories: geopolymer system contributes 25.26% of combined system total for abiotic resource depletion (fossil fuels); 21.13% global warming potential; 29.93% ozone layer depletion; 41.98% human toxicity; 39.08% freshwater aquatic ecotoxicity; 42.11% marine aquatic ecotoxicity; 43.81% terrestrial ecotoxicity; 49.66% photochemical oxidation; 47.92% acidification; 31.11% eutrophication (all are geopolymer system's share of combined geopolymer +OPC concrete, confirming geopolymer as less impactful in all cases) (Abbasali 2025; Sorathiya et al. 2025).

The conventional OPC concrete system demonstrated much larger environmental impacts throughout each of these impact categories. The largest relative dominance of the OPC system was recorded in the GWP category, where OPC concrete accounted for 78.87% of the total combined (equating to 1070.75 kg CO₂ eq/m³ versus 286.81 kg CO₂ eq/m³ for GPC). This suggests that traditional concrete leaves far greater negative impacts on climate, aquatic environments, terrestrial systems, and human health than does geopolymer concrete (Cong et al. 2024; Kim et al. 2016).

With regard to energy, the overall cumulative energy requirement of the geopolymer concrete system (2416.27 MJ/m³) was 73.03% lower compared to the conventional OPC concrete system (8958.76 MJ/m³). Sodium silicate and sodium hydroxide solutions were found to be the main culprits of the geopolymer concrete's footprint whilst Portland cement and the chemical superplasticizer dominated conventional OPC concrete's footprint (Bellum et al. 2025; Oyebisi et al. 2019).

As a whole, geopolymer concrete produced using recycled aluminosilicates appears to be an environmentally friendly and promising alternative to traditional OPC concrete, with considerable potential for decreasing the construction industry's impact on the environment and achieving the goals of sustainable urban architecture. Energy efficiency and reduction of environmental impact throughout the life cycle of the buildings and structures is among the main goals of sustainable architecture; it has been proven by the present results that geopolymer concrete helps reach these goals much better than OPC concrete does. Still, additional research is needed in order to make improvements in production technology and decrease the environmental costs associated with the use of activators (especially sodium silicate) (Ngayakamo and Ikotun 2026; Zaland et al. 2026).

Declarations

Funding: No funding was received to assist with the preparation of this manuscript.

Competing interests: The authors have no relevant financial or non-financial interests to disclose.

Ethics approval: Not applicable.

Consent to participate: Not applicable.

Data availability: The datasets generated and analysed during the current study are available from the corresponding author on reasonable request.

Author contributions: A. Esparham , N. Mehrdadi and A. Baghvand conceived and designed the study.

References

- Abbasali Saffar. (2025). Life Cycle Assessment of the Geopolymer Concrete Containing Fly Ash, Metakaolin and Zeolite. *The International Journal of Multiphysics*, 19(1), 185 - 197. <https://doi.org/10.52783/ijm.v19.1698>
- Aderinto, G. E., Kolade, A. S., Ikotun, B. D., Ikotun, J. O., Katte, V. Y., & Oyejobi, D. O. (2026). Geopolymerization of mine tailings for pavement applications: Properties, limitations and future directions. *International Journal of Pavement Research and Technology*, 1-30. <https://doi.org/10.1007/s42947-026-00781-y>
- Akintayo, B. D., Babatunde, O. M., Akintayo, D. C., & Olanrewaju, O. A. (2025). Transforming industrial waste into low-carbon cement: A multi-criteria assessment of supplementary cementitious materials for sustainable concrete design. *Recycling*, 10(6), 211. <https://doi.org/10.3390/recycling10060211>
- Almutairi, A. L., Tayeh, B. A., Adesina, A., Isleem, H. F., & Zeyad, A. M. (2021). Potential applications of geopolymer concrete in construction: A review. *Case Studies in Construction Materials*, 15, e00733. <https://doi.org/10.1016/j.cscm.2021.e00733>
- Ballen Zamora, S. A., Medina Campos, L., & Ortega Morales, J. A. (2021). Sustainable architecture and construction. In *Industry, Innovation and Infrastructure* (pp. 1038-1048). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-319-95873-6_120
- Barbir, D., Dabić, P., & Weber, I. (2026). Advanced Characterization of Eco-Friendly Cement Composites: Hydration Kinetics, Microstructure, and Mechanical Performance. *Buildings*, 16(9), 1829. <https://doi.org/10.3390/buildings16091829>
- Bajpai, P. K., Singh, I., & Madaan, J. (2014). Development and characterization of PLA-based green composites: A review. *Journal of Thermoplastic Composite Materials*, 27(1), 52-81. <https://doi.org/10.1177/0892705712439571>
- Bellum, R. R., Durga, C. S. S., Meeravali, K., Kumar, N. S. V., Chaitanya, B. K., & Venkatesh, C. (2026). A comprehensive review of geopolymer concrete: applications, properties, and future directions. *Silicon*, 18(3), 807-843. <https://doi.org/10.1007/s12633-025-03532-z>
- Cai, Z., Lu, M., Li, Z., Liu, X., & Wang, J. (2026). Review of the CFD Simulations of High-Viscosity Fluid Mixing in Mixers. *Processes*, 14(11), 1696. <https://doi.org/10.3390/pr14111696>
- Cong, P., Du, R., Gao, H., & Chen, Z. (2024). Comparison and assessment of carbon dioxide emissions between alkali-activated materials and OPC cement concrete. *Journal of Traffic and Transportation Engineering (English Edition)*, 11(5), 918-938. <https://doi.org/10.1016/j.jtte.2023.07.011>
- Esparham, A. (2021). Investigation of the effects of nano silica particles and zeolite on the mechanical strengths of metakaolin-based geopolymer concrete. *International Journal of Innovation in Engineering*, 1(4), 82-95. <https://doi.org/10.59615/ijie.1.4.82>
- Esparham, A. (2023). Investigation the Properties of Geopolymers for Use as Sustainable Materials. *Basparesh*, 13(1), 65-77.
- Esparham, A., & Ghalatian, F. (2022). The features of geopolymer concrete as a novel approach for utilization in green urban structures. *J. Compos. Compd*, 4(11), 89-96. <https://doi.org/10.52547/jcc.4.2.4>
- Esparham, A., Moradikhou, A. B., Andalib, F. K., & Avanaki, M. J. (2021). Strength characteristics of granulated ground blast furnace slag-based geopolymer concrete. *Advances in concrete construction*, 11(3), 219-229. <https://doi.org/10.12989/acc.2021.11.3.219>
- Esparham, A., Moradikhou, A. B., & Jamshidi Avanaki, M. (2022). Investigating the Environmental Properties and Energy Consumption of Geopolymer Concrete as A Sustainable Material. *Advance Researches in Civil Engineering*, 4(2), 44-53. <https://doi.org/10.30469/arce.2022.157272>

- Esparham, A., Vatin, N. I., Kharun, M., & Hematibahar, M. (2023). A study of modern eco-friendly composite (geopolymer) based on blast furnace slag compared to conventional concrete using the life cycle assessment approach. *Infrastructures*, 8(3), 58. <https://doi.org/10.3390/infrastructures8030058>
- Fentahun, E. F., Kassaw, A. S., Bauer, T., Fischer, T., Reinfried, M., & Gernot, S. (2026). Towards Sustainable Urban Development: A Systematic Review of Challenges in Urban Infrastructure Planning and Development in the Global South. *Land*, 15(6), 966. <https://doi.org/10.3390/land15060966>
- Gabathuler, H. (2006). The CML story: how environmental sciences entered the debate on LCA. *The International Journal of Life Cycle Assessment*, 11(Suppl 1), 127-132. <https://doi.org/10.1065/lca2006.04.021>
- Kheimi, M., Aziz, I. H., Abdullah, M. M. A. B., Almadani, M., & Abd Razak, R. (2022). Waste material via geopolymerization for heavy-duty application: A review. *Materials*, 15(9), 3205. <https://doi.org/10.3390/ma15093205>
- Kim, T., Tae, S., & Chae, C. U. (2016). Analysis of environmental impact for concrete using LCA by varying the recycling components, the compressive strength and the admixture material mixing. *Sustainability*, 8(4), 389. <https://doi.org/10.3390/su8040389>
- Lehmusto, J., Tesfaye, F., Karlström, O., & Hupa, L. (2024). Ashes from challenging fuels in the circular economy. *Waste Management*, 177, 211-231. <https://doi.org/10.1016/j.wasman.2024.01.051>
- Mahmud, M. A. P., Farjana, S. H., Lang, C., & Huda, N. (2023). Environmental impacts of solar-PV and solar-thermal plants. *Green Energy*, 47-72.
- Mensah, J. (2019). Sustainable development: Meaning, history, principles, pillars, and implications for human action: Literature review. *Cogent social sciences*, 5(1), 1653531. <https://doi.org/10.1080/23311886.2019.1653531>
- Mostafa, A., Khater, H. M., Gharieb, M., & Anwar, M. (2025). Sustainable cement production: minimizing CO2 by optimizing efficiency with LC3. *Discover Applied Sciences*, 7(7), 684. <https://doi.org/10.1007/s42452-025-07298-2>
- Nfor, N. E., Khan, M. S., Sarwar, R., Bilal, M., Khan, A., Tasqueeruddin, S., ... & Riaz, N. (2026). Ag/TiO₂-functionalized photocatalytic concrete for visible-light photocatalytic degradation of reactive black 5: Experimental optimization, mechanistic insights and machine learning modeling. *Journal of Science: Advanced Materials and Devices*, 101170. <https://doi.org/10.1016/j.jsamd.2026.101170>
- Ngayakamo, B. H., & Ikotun, B. D. (2026). Geopolymer concrete for sustainable construction exploring materials properties challenges and future prospects. *Discover Concrete and Cement*, 2(1), 46. <https://doi.org/10.1007/s44416-026-00089-x>
- Oyebisi, S., Ede, A., Olutoge, F., Ofuyatan, O., & Alayande, T. (2019, May). Building a sustainable world: Economy index of geopolymer concrete. In *10th International Structural Engineering and Construction Conference (ISEC-10)* (pp. 20-25).
- Periyasamy, L., & Nagarajan, V. (2024). Transforming waste into sustainable building materials: properties and environmental impacts of geopolymer concrete with recycled concrete aggregates. <https://doi.org/10.30955/gnj.005518>
- Rahimi, H., Behzadfar, M. and Abdollahzadeh Taraf, A. (2024). Recognizing the theory of sustainable urban design in peri-urban areas. *International Journal of Nonlinear Analysis and Applications*, 15(8), 181-193. <https://doi.org/10.22075/ijnaa.2023.31250.4594>
- Ricciotti, L., Frettoloso, C., Franchino, R., Pisacane, N., & Aversa, R. (2025). Geopolymer materials: cutting-edge solutions for sustainable design building. *Sustainability*, 17(16), 7483. <https://doi.org/10.3390/su17167483>

- Salimi, M., Payan, M., Hosseinpour, I., Arabani, M., & Ranjbar, P. Z. (2025). Geopolymer stabilization of construction and demolition waste using water treatment sludge and silica fume for pavement applications. *Journal of Materials Research and Technology*, 37, 1834-1849. <https://doi.org/10.1016/j.jmrt.2025.06.096>
- Sbahieh, S., McKay, G., & Al-Ghamdi, S. G. (2023). Comprehensive analysis of geopolymer materials: Properties, environmental impacts, and applications. *Materials*, 16(23), 7363. <https://doi.org/10.3390/ma16237363>
- Sindhunata, Provis, J. L., Lukey, G. C., Xu, H., & van Deventer, J. S. (2008). Structural evolution of fly ash based geopolymers in alkaline environments. *Industrial & engineering chemistry research*, 47(9), 2991-2999. <https://doi.org/10.1021/ie0707671>
- Singal, S. K., Goel, V., Nautiyal, H., & Papantonis, D. E. (2023). Chapter 10-Environmental impacts of small hydropower system. *Small hydropower: design and analysis*. Elsevier, 259-269.
- Sivakumar, P. P., Villagrán-Zaccardi, Y. A., Lapauw, T., Gruyaert, E., Matthys, S., & De Belie, N. (2023). Durability performance of hybrid binder concretes containing non-ferrous slag and recycled aggregates. *Sustainability*, 15(8), 6338. <https://doi.org/10.3390/su15086338>
- Sorathiya, D. R., Khoker, P., & Sain, R. (2025). Study on the effect of geopolymer concrete in reducing carbon footprint. *Momentum International Journal of Civil Engineering (MIJCE)*, 1(1), 7-13. <https://doi.org/10.64123/mijce.v1.i1.2>
- Turner, L. K., & Collins, F. G. (2013). Carbon dioxide equivalent (CO₂-e) emissions: A comparison between geopolymer and OPC cement concrete. *Construction and building materials*, 43, 125-130. <https://doi.org/10.1016/j.conbuildmat.2013.01.023>
- Zaland, S., Wang, J., Li, K., Sadat, S. I., & Akhunzada, K. (2026). Geopolymers as a sustainable alternative to Portland cement: Synthesis, durability, applications, environmental impacts, and cost analysis. *Renewable and Sustainable Energy Reviews*, 225, 116157. <https://doi.org/10.1016/j.rser.2025.116157>
- Zhang, L., Zhu, D., Marani, A., Nehdi, M. L., Wang, L., Yang, G., & Zhang, J. (2025). Toward sustainable construction: Comprehensive utilization of coal gangue in building materials. *Case studies in construction materials*, 23, e04930. <https://doi.org/10.1016/j.cscm.2025.e04930>

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [ArticleEspHighlights.pdf](#)