

Environmental and Performance Assessment of Waste-Based Geopolymer Concrete: A Systematic Review with Meta-Analysis

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Abstract

The growing demand for sustainable infrastructure has accelerated interest in eco-friendly alternatives to Ordinary Portland Cement (OPC). Geopolymer concrete (GPC), synthesised from industrial by-products and activated with alkaline solutions, offers a promising pathway to reduce carbon emissions while utilising diverse waste materials. This systematic literature review, conducted using the PRISMA methodology, analyses 65 relevant studies published in the Indian subcontinent and Southeast Asia over the past decade. The review evaluates agricultural, industrial, construction and demolition (C&D), hazardous, municipal, biogenic, and e-waste as potential substitutes in GPC. Life Cycle Assessment (LCA) was carried out using OpenLCA and ReCiPe Midpoint (H) 2016 indicators to quantify environmental impacts across different compressive strength categories (0–50 MPa and 51–100 MPa). Results indicate substantial reductions in global warming potential, fossil resource scarcity, and terrestrial acidification when incorporating materials such as wood ash, groundnut shell ash, and steel slag, compared to conventional OPC concretes (M40 and M80 grades). Overall, this study highlights the environmental advantages and performance viability of waste-infused geopolymer concrete, emphasising its role in advancing sustainable construction practices.

Keywords: Geopolymer concrete, Waste utilization, Life cycle assessment, Sustainability, Circular economy

ABBREVIATION

POA: Palm Oil ash, BMW: Biomedical waste ash, BCW: Bone china waste, PF: polypropylene fibres, CSF: Crimped steel fibre, TB: Turmeric bulb, GP: Glass powder, CR: Crumb rubber, GF: Glass fibre, SF: Steel fibre, GWP: Glass waste powder, CS: Copper slag, QD: Quarry rock dust/ Quarry dust, LF: Lignocellulosic fibre, SS: Steel slag, BMWA: Bio-medical waste ash, RCA: Recycled coarse aggregate, SBA: Sugarcane bagasse ash, RFA: Recycled fine aggregate, BA: Bamboo ash, GP: Glass powder, A: Alcofine, RHA: Rice husk ash, RGW: Recycled granite waste, GW: Granite waste, AD/ AC: Air dry/ Air curing, OD/ OC: Oven dry/ Oven curing, VPD: Volcanic pumice dust, GSA: Groundnut shell ash, RBA: recycled bricks aggregate, SLS: Sewage sludge, BWSP: Bethamcherla waste stone powder, MHA: Millet husk

ash, WSA: Wheat straw ash, POC: Palm oil clincker, OPS: Oil palm shell, FA: fly ash, GGBS: Ground granulated blast furnace slag, LCWA: Low calcium waste wood ash, WRF: Waste rubber fibre, EW: electronic waste, WGP: Waste glass powder, CR: Crumb rubber, GFRP: Glass fibre reinforce polymer, CFRP: Carbon fibre reinforce polymer, PVA: Polyvinyl alcohol fiber, BR: Bauxite residue, G: Glass, BA: Bottom ash, FS: Foundry sand, EPP: Eco-Processed pozzolan, AAS: Alkaline activated slag, GPC: Geopolymer concrete, WFS: waste foundry sand, GFRC: Glass Fibre Reinforced Concrete, AGF: AR Glass fiber, BF: basalt fibre, COCS: crude oil contaminated sand, HC: Heat curing, LA: Laterite aggregates, PW: plastic waste, BLA: Bamboo leaf ash

1 Introduction

The demand for sustainable and eco-friendly infrastructure is projected to increase significantly in the coming years. The term “green building” encompasses the use of renewable energy sources, along with strategies such as recycling, reusing, and incorporating environmentally responsible materials in construction. Owing to global environmental protection efforts and growing climate degradation concerns, different categories of waste materials are being explored for effective use in construction to meet sustainability goals [1]. Each year, enormous quantities of waste are generated from industrial, agricultural, mining, and municipal sectors, both in urban and semi-urban regions. The increasing accumulation of waste each year leads to a critical shortage of landfill space and accelerates the depletion of natural resources [2, 3]. Waste dumped in landfills undergoes decomposition, releasing methane and unpleasant odours, which contribute to greenhouse gas emissions. Moreover, leaching of heavy metals contaminates groundwater, causing serious health hazards. Industrial waste discharged into rivers deteriorates water quality and threatens aquatic ecosystems [2, 4]. GPC is synthesized using industrial by-products activated with alkaline solutions. The incorporation of waste materials as fine or coarse aggregates, or as part of the binder phase, provides a promising route for effective waste utilization. When properly cured and designed with appropriate waste materials, GPC exhibits superior mechanical, physical, durability, and chemical properties [5, 6].

This research aims to study the environmental failure behaviour of tension members with non-staggered holes. The purpose of this analysis is to point out the crack initiation pattern of block shear failure of the gusset plate and angle with rivet fasteners under static and cyclic loading. This research aims to study fatigue failure of the gusset plate under cyclic loading and find out the tension members' behaviour. This research aims to conduct a Numerical study on crack growth behaviour and simulate crack propagation in an axially loaded riveted gusseted connection.

2 Methodology

PRISMA method (Preferred Reporting Items for Systematic reviews and Meta-Analyses) has been followed (Fig. 1) in this study. The keywords ("Geopolymer concrete") AND ("waste material" OR "solid waste") have been given as the input under the field of TITLE-ABS-KEY in both the index, i.e., Scopus and ScienceDirect. Initially, 939 articles have been collected. After screening and sorting meticulously, it has come down to 101, which was further finessed to 65. This review has focused on the articles published in the Indian subcontinent and Southeast Asia, or authored by researchers belonging to that region, over the past decade.

The review has been done to have an idea of the contextual regional advancement of sustainable building materials.

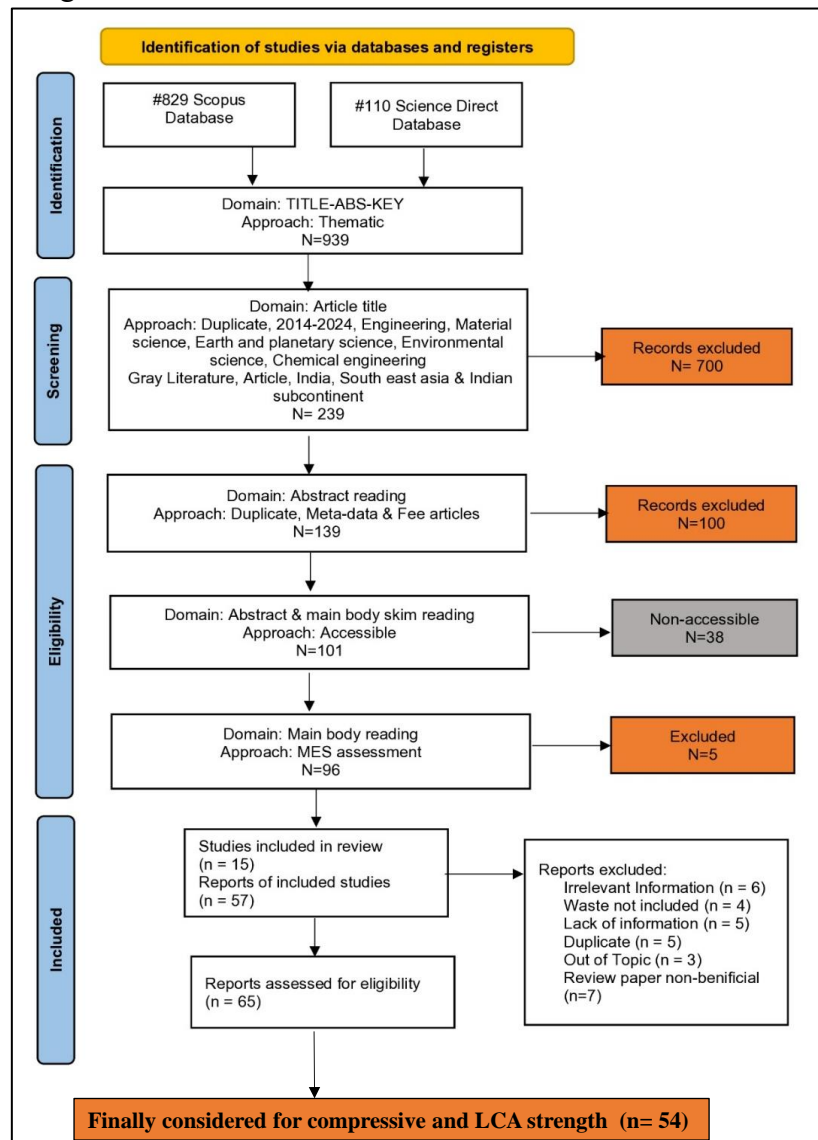


Fig. 1. PRISMA Table (Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020, statement: an updated guideline for reporting systematic reviews. *BMJ* 2021;372:n71. doi: 10.1136/bmj.n71)

2.1 Life-cycle Assessment & Goals

This study aims to evaluate the environmental impacts associated with the utilisation of various types of waste materials in concrete production to minimise the overall environmental footprint. The system boundary is confined to the defined study area, where emissions resulting from the incorporation of different waste types were considered as key parameters. The environmental assessment was conducted by the guidelines outlined in ISO 14040:2006 and ISO 14044:2006 for life cycle assessment (LCA).

The primary objective of this study is to evaluate the potential environmental impacts of using various waste materials as substitutes in concrete production, aiming to achieve the same compressive strength as conventional concrete. The assessment encompasses two

compressive strength categories: low to moderate strength (0–50 MPa) and high strength (51–100 MPa) concrete.

Case 1 (0–50 MPa): Alternative materials incorporated include glass powder, plastic waste, rice husk ash, turmeric bulb, and wood ash.

Case 2 (51–100 MPa): The waste materials evaluated are rice husk ash, groundnut shell ash, and steel slag.

The functional unit (FU), critical for standardizing the life cycle assessment (LCA), is defined as 1 m³ of concrete for each waste material considered in the mix. The study also accounts for the specific characteristics of each waste material, including residue fractions and compositional properties.

2.2 Life-cycle Assessment & Goals

Inventory analysis represents a critical phase of the life cycle assessment (LCA) process, involving the quantification of input and output data related to the incorporation of waste materials in concrete production. In this study, the analysis focuses on calculating the quantities of each waste material required to produce 1 m³ of concrete mix. These data serve as the basis for constructing system models for each type of waste-based concrete.

The LCA was performed using OpenLCA version 2.1 (2024), with background data sourced from the Ecoinvent database (version 3.8, 2021). Environmental impact assessment was carried out using the ReCiPe Midpoint (H) 2016 impact assessment method, which evaluates 18 midpoint environmental indicators. These include key categories such as Global Warming Potential, Terrestrial Acidification, Eutrophication, Ozone Formation, and Water Consumption, among others.

For Case 1, the environmental performance of waste-based concretes was benchmarked against conventional M40 concrete, while in Case 2, comparisons were made with M80 concrete, both representing typical conventional concrete mixes for their respective strength categories.

3 Results and discussions

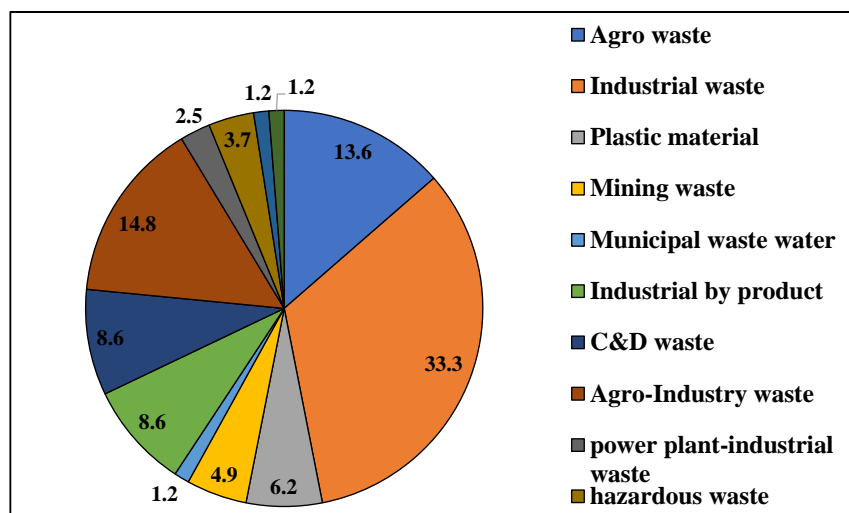


Fig. 2. Waste found throughout the review

Agricultural wastes are the by-products of agriculture/crop residue, or leftover materials. Agro-waste has its sub-branch known as agro-industrial waste, aquatic agriculture, animal waste, food processing waste, forestry waste, etc. The branches found by reviewing the articles were

agro & agro-industrial waste like turmeric bulb, lignocellulose fibre, palm oil ash, etc. This type of waste occupies 28.4% of the pie chart of waste mentioned in Fig.2.

Industrial waste is the unwanted or residual material and by-products that are generated while manufacturing any product. Industrial waste was divided into many sub-branches, known as mining waste, packaging waste/plastic waste, mining waste, food processing and beverage waste, etc. The branches that were found by reviewing the articles were industrial waste, mining waste, industrial by-products, power plant industrial waste, like carbon fibre, polypropylene fibres, bauxite residue (red mud RM), etc. This type of waste occupies 55.5% of the pie chart of waste mentioned in Fig.2.

C&D Waste (construction & demolition waste) is generated on-site during the construction and demolition of a building; it is also known as “rubbish”. The C&D waste that has been extracted from the review is recycled fine & coarse aggregate, recycled granite waste, etc. This type of waste occupies 8.6% of the pie chart of waste mentioned in Fig.2.

Hazardous waste that poses a threat to human life, animals & environment due to its chemical, biological, or physical properties. The waste that was extracted from the articles is biomedical waste ash and crude oil-contaminated sand. This type of waste occupies 3.8% of the pie chart of waste in Fig.2.

Biogen waste refers to the organic matter that can decompose naturally through biological processes. The waste that was extracted from the articles is coral coarse aggregate. This type of waste occupies 1.2% of the pie chart of waste mentioned in Fig.2.

Municipal wastewater, also known as sewage, consists of liquid waste released from homes. It is a thick, slimy substance that is found in the drain. The waste extracted from the articles is laterite that was created from Sewage sludge. This type of waste occupied 1.2% of the pie chart of waste mentioned in Fig.2.

E-waste (electronic waste) is derived from dismantled electronic parts, such as a silicon board, a broken TV remote, etc. This type of waste occupies 1.2% of the pie chart of waste mentioned in Fig.2.

3.1 Physical properties of waste and compressive strength

Table 1. Summary of the chemical composition of fly ash from selected literature sources

Waste	Length (mm)	Diameter/ thickness (mm)	Elastic modulus (GPa)	Tensile strength (MPa)	Density (kg/m ³)	Specific gravity	Water absorption (%)	Bulk density (kg/m ³)	Fineness modulus	Ref no.
CSF	30	0.45	-	800	7950	-	-	-	-	[8]
TB	-	-	-	-	-	2.13	12.1	-	-	[9]
CR	-	-	-	-	-	0.5	-	-	2.36	[10]
PVA	6	0.024	40	1600	-	-	<1	-	-	[11]
LA	-	-	-	-	-	2.54	14.28	-	-	[12]
SSL	-	-	-	-	-	1.5	44	730	-	[13]
SF	30	0.6	-	1260	7.91	-	-	220	-	[14]

RFA	-	-	-	7500	1410	-	-	-	-	[15]
CS	-	-	-	-	-	3.2	-	-	-	[16]
LF	12	-	-	7700	0.91	-	-	-	-	[17]
CSF	25	0.5	200	11.3	7.8	-	-	-	-	[18]
GF	-	-	82	2500	2540	2.4	-	-	-	[19]
SS	-	-	-	-	-	-	2	1935	-	[20]
LCWA	-	-	-	-	-	1.7	-	-	9	[21]
RCA	-	-	-	-	-	2.635	2.7	1353	7.4	[22]
CR	38	-	-	28.1	-	0.54	-	-	2.36	[23]
PF	45	0.8	-	570-660	-	0.91	85	-	-	[24]
SF	-	0.55	-	1345	-	-	-	-	-	[25]
CS	-	-	-	-	-	3.9	0.4	2195	3.39	[26]

From the stress analysis result, the maximum stress concentration has been determined and shown below. To locate the hot-spot stress, a static analysis has been performed over the gusset-angle jointed connection. A 2D model is considered in Fig. 2, 3, and 4 due to the complexity of the model. In spite of rivets, fasteners are considered for modelling. An edge surface loading is applied at the top edge of the angle.

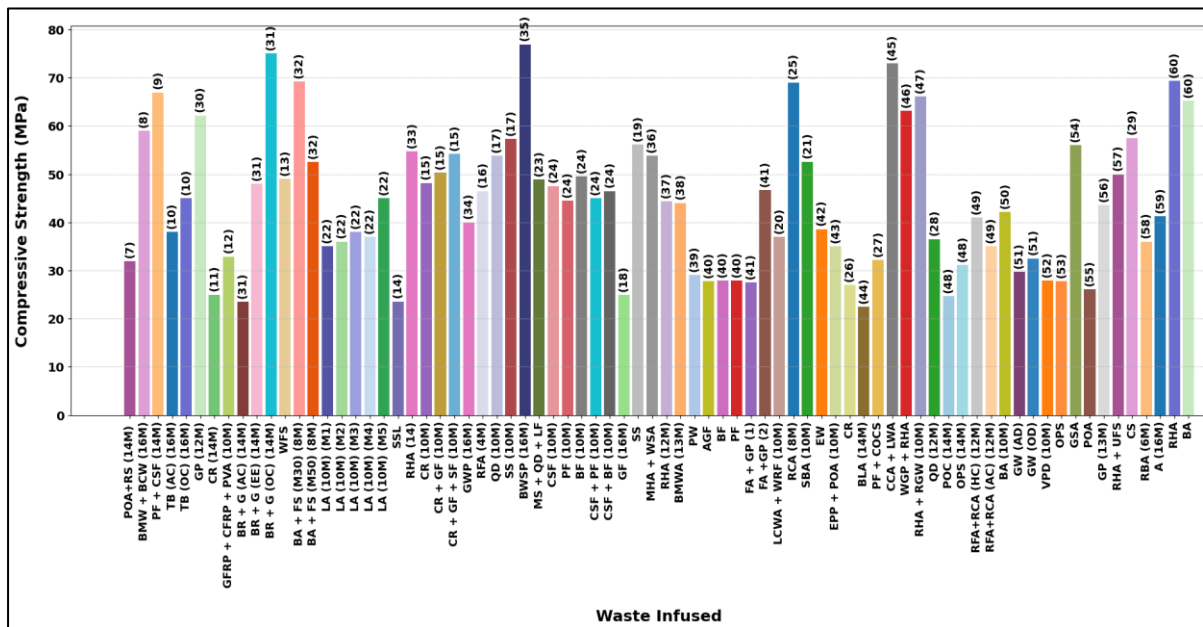


Fig. 3. Compressive strength

The performance of geopolymer concrete depends on the physical properties of its constituent materials, such as fly ash, GGBS, metakaolin, and the physical and chemical properties of the waste. Table 1 represents the physical properties of waste. The chemical characteristics of these key components play a crucial role in the reactivity and sustainability of geopolymer concrete. Table 1 represents the physical

properties of waste material, which enhances the mechanical properties because of their physical existence, such as bulk density, specific gravity, fibre or powder form, etc.

3.2 Life Cycle Impact

This section presents the environmental impact of concrete mixes incorporating various waste materials, based on LCA using the ReCiPe Midpoint H (2016) method. The results are categorised into two cases based on compressive strength and are shown in Tables 2 and 3.

Table 2. Environmental impacts of concrete mixes (Case 1: 0–50 MPa)

Impact category	Reference unit	M40 OPC	Glass Powder	Plastic Waste	Rice Husk Ash	Turmeric Bulb	Wood Ash
Fine particulate matter formation	kg PM2.5 eq	0.3290	0.0795	0.0802	0.0968	0.0991	0.0693
Fossil resource scarcity	kg oil eq	51.2143	15.0833	15.2197	18.5399	16.9392	13.0043
Freshwater ecotoxicity	kg 1,4-DCB	6.7965	0.9697	0.9788	1.2026	3.6486	0.8306
Freshwater eutrophication	kg P eq	0.0522	0.0058	0.0059	0.0072	0.0113	0.0050
Global warming	kg CO2 eq	450.7620	45.9417	46.3558	56.4318	56.2920	39.7263
Human carcinogenic toxicity	kg 1,4-DCB	9.3628	2.6463	2.6703	3.2565	4.9979	2.2980
Human non-carcinogenic toxicity	kg 1,4-DCB	214.1808	32.1410	32.4374	39.9067	95.4158	27.4753
Ionizing radiation	kBq Co-60 eq	9.5606	0.7803	0.7875	0.9625	1.1185	0.6727
Land use	m ² a crop eq	13.1917	4.8962	4.9242	5.4803	3.6720	4.7379
Marine ecotoxicity	kg 1,4-DCB	9.6160	1.6700	1.6721	2.0664	5.2370	1.4647
Marine eutrophication	kg N eq	0.0058	0.0005	0.0005	0.0006	0.0013	0.0005
Mineral resource scarcity	kg Cu eq	2.5230	0.2297	0.1834	0.2628	0.8631	0.3282
Ozone formation, Human health	kg NOx eq	0.9171	0.2612	0.2634	0.3159	0.2669	0.2293
Ozone formation, Terrestrial ecosystems	kg NOx eq	0.9296	0.2661	0.2683	0.3219	0.2737	0.2336
Stratospheric ozone depletion	kg CFC11 eq	0.0001	0.0000	0.0000	0.0000	0.0000	0.0000
Terrestrial acidification	kg SO2 eq	0.7462	0.1636	0.1651	0.1995	0.2017	0.1425
Terrestrial ecotoxicity	kg 1,4-DCB	1114.650 3	663.256 4	669.563 0	825.602 2	784.233 8	563.388 8
Water consumption	m ³	0.8733	0.1086	0.1096	0.1345	0.3040	0.0935

In Case 1, the environmental performance of alternative waste materials used in concrete production was compared with conventional M40 concrete across key impact categories, including global warming potential, fossil resource scarcity, terrestrial acidification, ozone formation (human health), and land use. The results indicate a significant reduction in environmental impacts when waste materials are used as a partial replacement of cement. Conventional M40 concrete exhibited the highest global warming potential (450.76 kg CO₂

eq), whereas wood ash showed the lowest (39.73 kg CO₂ eq), followed by glass powder (45.94 kg CO₂ eq) and plastic waste (46.36 kg CO₂ eq). A similar trend was observed in fossil resource scarcity, where conventional concrete recorded 51.21 kg oil eq, while wood ash and glass powder contributed only 13.00 and 15.08 kg oil eq, respectively. Terrestrial acidification and ozone formation impacts were also considerably lower for waste-based mixes, with wood ash again showing the least contribution in both categories. In terms of land use, turmeric bulb had the lowest impact (3.67 m²a crop eq), reflecting the sustainability of agricultural waste integration. Overall, wood ash emerged as the most environmentally favourable material, consistently yielding the lowest impact across multiple categories, while all alternative materials demonstrated substantial potential for reducing the ecological footprint of concrete

Table 3. Environmental impacts of concrete mixes (Case 2: 51–100 MPa)

Impact category	Reference unit	M80 OPC	Rice Husk Ash	Groundnut Shell Ash	Steel Slag
Fine particulate matter formation	kg PM2.5 eq	0.4088	0.0720	0.0619	0.0609
Fossil resource scarcity	kg oil eq	62.6228	14.1151	10.9727	11.0894
Freshwater ecotoxicity	kg 1,4-DCB	8.6977	0.9348	0.6585	0.6847
Freshwater eutrophication	kg P eq	0.0674	0.0056	0.0040	0.0041
Global warming	kg CO ₂ eq	583.768	42.8948	33.5888	33.8777
Human carcinogenic toxicity	kg 1,4-DCB	11.4901	2.4863	1.9082	1.9354
Human non-carcinogenic toxicity	kg 1,4-DCB	273.506	31.1125	21.6150	22.5631
Ionizing radiation	kBq Co-60 eq	12.4545	0.7390	0.5527	0.5647
Land use	m ² a crop eq	15.7608	3.2009	5.9271	5.0237
Marine ecotoxicity	kg 1,4-DCB	12.2067	1.6143	1.1386	1.1737
Marine eutrophication	kg N eq	0.0074	0.0005	0.0003	0.0003
Mineral resource scarcity	kg Cu eq	3.3232	0.2236	0.1949	0.1544
Ozone formation, Human health	kg NO _x eq	1.1248	0.2313	0.2125	0.2055
Ozone formation, Terrestrial ecosystems	kg NO _x eq	1.1397	0.2357	0.2163	0.2093
Stratospheric ozone depletion	kg CFC11 eq	0.0000	0.0000	0.0000	0.0000
Terrestrial acidification	kg SO ₂ eq	0.9335	0.1489	0.1264	0.1247
Terrestrial ecotoxicity	kg 1,4-DCB	1236.9912	647.2539	436.9864	460.2331
Water consumption	m ³	1.1235	0.1042	0.0747	0.0773

In Case 2, the environmental performance of high-strength concrete incorporating rice husk ash, groundnut shell ash, and steel slag was assessed against conventional M80 concrete. The findings reveal a significant reduction in environmental burdens across all key impact categories. The global warming potential of M80 concrete was the highest at 583.77 kg CO₂ eq, while steel slag and groundnut shell ash presented substantially lower values at 33.88 kg CO₂ eq and 33.59 kg CO₂ eq, respectively, marking a reduction of over 90%. Similarly, fossil resource scarcity dropped from 62.62 kg oil eq for M80 concrete to 10.97–14.12 kg oil eq for waste alternatives, with groundnut shell ash demonstrating the greatest efficiency. Terrestrial

acidification was also markedly reduced, with steel slag exhibiting the lowest value (0.1247 kg SO₂ eq) compared to 0.9335 kg SO₂ eq in M80 concrete. Regarding ozone formation impacting human health, conventional concrete recorded 1.12 kg NO_x eq, whereas the waste-based alternatives ranged between 0.205–0.231 kg NO_x eq, highlighting a significant decrease in air pollutant formation. In terms of land use, all alternatives required less area than M80 concrete, with rice husk ash showing the lowest land occupation (3.20 m²a crop eq). Overall, groundnut shell ash and steel slag demonstrated the most favourable environmental profiles, consistently achieving the lowest values in nearly every impact category, emphasising their suitability for sustainable high-strength concrete production.

These findings from both Case-1 and Case-2 clearly demonstrate the environmental advantages of incorporating waste materials in concrete across different strength grades. The consistent reduction in global warming potential, fossil resource use, and other key impact categories highlights the sustainability potential of these alternatives. Waste materials such as wood ash, groundnut shell ash, and steel slag emerge as highly effective in minimising the ecological footprint of concrete production. This supports their broader application in green construction practices.

4. Conclusion

This study systematically reviewed the waste materials in enhancing the sustainability of geopolymer concrete within the regional context of India and Southeast Asia. The findings clearly frames the integration of diverse waste streams, including agricultural residues, industrial by-products, and recycled aggregates—not only improves resource efficiency but also significantly reduces the environmental footprint of concrete production. Life Cycle Assessment results confirm that alternatives such as wood ash, groundnut shell ash, and steel slag can achieve more than 80–90% reductions in global warming potential and fossil resource use compared to conventional OPC mixes. These outcomes underscore the feasibility of adopting waste-infused GPC as a mainstream construction material capable of addressing pressing environmental concerns while meeting mechanical performance requirements. However, future research should focus on large-scale experimental validation, durability studies, and policy integration to accelerate the transition toward greener construction technologies.

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