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Life Cycle Environmental Impact of High-Strength and Lightweight Pozzolanic Concretes

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A B S T R A C T

This study evaluates the environmental and economic performance of six innovative concrete mixtures using Life Cycle Assessment (LCA) and cost analysis. The concrete types incorporate various industrial and agricultural by-products, including PET waste, steel fibers, nano-silica, pumice, ceramic waste, EAF slag, asbestos cement sheets, and rice husk ash. Using the CML 2001, IMPACT 2002+, and ReCiPe methods, environmental impacts were assessed across key categories, such as global warming potential, toxicity, and resource depletion. Results indicate that conventional concrete had the lowest environmental burden overall, while PET/steel fiber concrete showed the highest impact in most categories. Sensitivity analysis identified cement as the primary contributor to environmental damage, followed by micro-silica in select mixes. The economic analysis identified conventional concrete as the most cost-effective, followed by pumice and PET/steel fiber concretes, which were 19.3% and 69.6% more expensive, respectively. Integrating environmental and cost factors revealed that, despite its relatively low cost, PET/steel fiber concrete contributed the most to CO_2 emissions. These findings support more informed material selection for sustainable construction.

1. Introduction

The construction industry is a major contributor to global environmental degradation, largely due to intensive energy use, raw material extraction, and emissions from material production from cement manufacturing, as concrete is the most widely used construction material [1, 2]. The key challenge is balancing the rising global demand for cement and concrete with the urgent need to reduce CO_2 emissions. In response, sustainable concrete structures have gained growing attention, particularly in countries with stringent environmental regulations. A range of strategies has been developed to minimize the environmental footprint of concrete-based infrastructure. These impacts are closely tied to the composition and properties of the materials used in concrete production. As concrete is central to urban development, it contributes to the high emissions from cities, estimated at 70% of global totals. In line with the Kyoto Protocol, this has driven the development of tools to assess the environmental performance of buildings across their life cycle [3]. To effectively address these environmental challenges in the concrete and construction sectors, it is essential to adopt a comprehensive and scientifically grounded evaluation tool-Life Cycle Assessment (LCA) [4].

Given the complexity of materials, energy flows, and processes involved, a systematic analytical approach like LCA is indispensable. LCA enables the comparison and evaluation of environmental impacts across different product systems using a standardized functional unit [5]. According to ISO guidelines, LCA covers the full "cradle-to-grave" span of a product—from raw material acquisition to production, use, recycling, and final disposal [6]. There are two main LCA approaches: process-based LCA, which tracks detailed inputs and outputs for specific processes and is commonly used in construction, and Economic Input-Output LCA (EIO-LCA), which evaluates impacts at a broader economic level [7]. The LCA methodology, as defined by ISO [8], involves four key phases: goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and

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interpretation. These steps help quantify various environmental parameters, including global warming potential, resource depletion, toxicity, acidification, and more.

LCA highlights material composition as a key factor in environmental impact. Cement, the main binder in concrete, is a major CO_2 emitter due to fuel combustion and limestone decomposition. Smaller emissions also result from electricity use and the release of other gases like NO_x and CH_4 during production [9]. Producing one ton of cement emits about 930 kg of CO_2-mainly from limestone decomposition (500 kg), fuel combustion (350 kg), and electricity use (80 kg). NO_x emissions vary by fuel type and kiln technology, ranging from 1.5–9 kg per ton [10]. To reduce emissions, Portland cement is often partially replaced with pozzolanic materials—natural or artificial substances that react with calcium hydroxide to form cement-like compounds [11]. Enhancing concrete sustainability also involves reducing the use of virgin aggregates, which make up 70–80% of its weight and 60–70% of its volume [12]. Concrete aggregates are classified as natural or artificial. Natural aggregates-mainly sand and gravel-are cost-effective and commonly sourced from deposits or quarries. However, their extraction through mining can significantly damage rivers and ecosystems, highlighting the need to reduce reliance on these materials [13, 14]. To reduce reliance on natural aggregates, recycled or artificial alternatives are used. Recycled aggregates come from construction waste but often have lower quality due to high water absorption and reduced strength. In contrast, artificial aggregates made from industrial by-products like EAF slag and GGBFS offer better performance and help address waste disposal, supporting environmental sustainability [15]. In addition to aggregates, additives—though used in smaller quantities-play a key role in enhancing concrete performance. Concrete additives are generally classified into two main groups: chemical additives and mineral additives [16].

Francesco Colangelo et al. [17], in their study on the LCA of various concrete types containing waste for sustainable construction, assessed the environmental impacts of all samples using the SimaPro software. The environmental damage analysis (including resource use, ecosystem quality, and human health) revealed that human health is the primary area of concern. Demiral et al. [18] conducted a cradle-to-gate life cycle assessment of self-compacting mortars with fly ash and PET waste using SimaPro and the ReCiPe database. The results showed that incorporating recycled materials reduces environmental impacts by conserving natural aggregates and minimizing landfill waste. Asadollahfardi et al. [19] conducted a cradle-to-gate LCA on five concrete types using SimaPro 8.1. Geopolymer concrete showed a 26% lower global warming potential than ordinary concrete, while micro-silica, nano-silica, and micro-nanobubble concretes had increases of 56%, 17%, and 38%, respectively. Overall, ordinary concrete had the lowest environmental impact during production. Billel et al. [20] showed that using natural volcanic pozzolans improved concrete strength, insulation, and reduced density. A 25% substitution of black pozzolan powder was optimal, offering both economic and environmental benefits. Ersan et al. [21] used cradle-to-gate LCA to compare ordinary and lightweight concretes. Lightweight concrete had 13% lower greenhouse gas emissions, and recycled plastic waste proved to be a sustainable alternative to natural aggregates. Shahmansouri et al. [22] found that adding natural zeolite to concrete exposed to aggressive environments reduced global warming potential, with 20% zeolite achieving the lowest impact. Napulano et al. [23] used LCA to compare lightweight concretes and found that those made with recycled aggregates had significantly lower environmental impacts than those with natural aggregates. Valipour et al. [24] found that replacing 30% of cement with natural zeolite in green concrete significantly reduced global warming potential over a 15-year lifecycle in marine environments. Nath et al. [25] showed that replacing 30–40% of cement with fly ash in marine concrete reduced the carbon footprint by up to 23% and energy use by nearly 10%, while also enhancing durability. However, high-strength concrete increased CO_2 emissions due to higher cement content.

To support informed material selection for sustainable and low-carbon construction, this study focuses on the environmental and economic assessment of high-strength and lightweight concrete mixtures incorporating pozzolanic and recycled materials. Six mix designs were developed, including one conventional concrete and five alternatives containing materials such as pumice, PET waste with steel fibers, nano-silica, ceramic waste with electric arc furnace slag (EAFS), and asbestos cement sheets with rice husk ash. A process-based LCA was conducted following ISO 14040/44 standards [26], using a cradle-to-gate system boundary that includes raw material extraction, transportation, and concrete production. In parallel, an economic analysis was performed based on material and energy costs. To evaluate the robustness of the environmental results and identify key contributing factors, a sensitivity analysis was also conducted by varying input quantities. This integrated approach offers a comprehensive basis for assessing the trade-offs between sustainability and cost in concrete mix design.

2. Materials and methods

2.1. Concrete mix designs

Six concrete mixtures were developed and assessed in this study. Table 1 summarizes their compositions and characteristics. These mixes include:

- Conventional concrete: 42 MPa compressive strength, water-to-cement (w/c) ratio of 0.50
- Pumice concrete: 23 MPa compressive strength, w/c ratio of 0.27
- PET/steel fiber concrete: 35 MPa compressive strength, w/c ratio of 0.30
- Recycled fine aggregate with nano-silica concrete: 40 MPa compressive strength, w/c ratio of 0.50
- Ceramic and EAF slag concrete: 40 MPa compressive strength, w/c ratio of 0.40
- Asbestos cement sheet and rice husk ash concrete: Mix details presented in Table 1.

Table 1. Mix design of concrete types.

Material/type of concrete	Asbestos and rice husk ash	Ceramics and EAFS	Nano-Silica	PET and fibers	Pumice	Ordinary
Portland cement	425	448	404.2	477	468.3	430
water	215	215	215	157	126.7	215
gravel	522	445	855.5	1.04	-	845
Pumice aggregate	-	-	-	-	200.7	-
sand	570.7	275	-	95	-	855
Recycled fines	-	-	793.1	-	-	-
Micro-silica	-	-	-	-	46.8	-
Nano-silica	-	-	25.8	-	-	-
plasticizer	2.1	-	0.4	0.92	0.85	-
PET waste	-	-	-	36.7	-	-
Steel fibers	-	-	-	78.5	-	-
Silica fume	-	-	-	53	-	-
Ceramic	-	52	-	-	-	-
Slag	-	445	-	-	-	-
Rice husk ash	75	-	-	-	-	-
Asbestos cement	387.8	-	-	-	-	-

2.2. Life Cycle Assessment (LCA)

This study employed a process-based LCA using the cradle-to-gate approach, in accordance with ISO 14040/44 standards [26]. The LCA was structured into four main phases: goal and scope definition, inventory analysis, impact assessment, and interpretation.

2.2.1.Goal and scope definition

The primary goal was to evaluate and compare the environmental impacts associated with producing 1 m³ of each concrete type. The cradle-to-gate system boundary includes raw material extraction, transportation, and concrete production. Fig. 1 illustrates the system boundaries applied in this study.

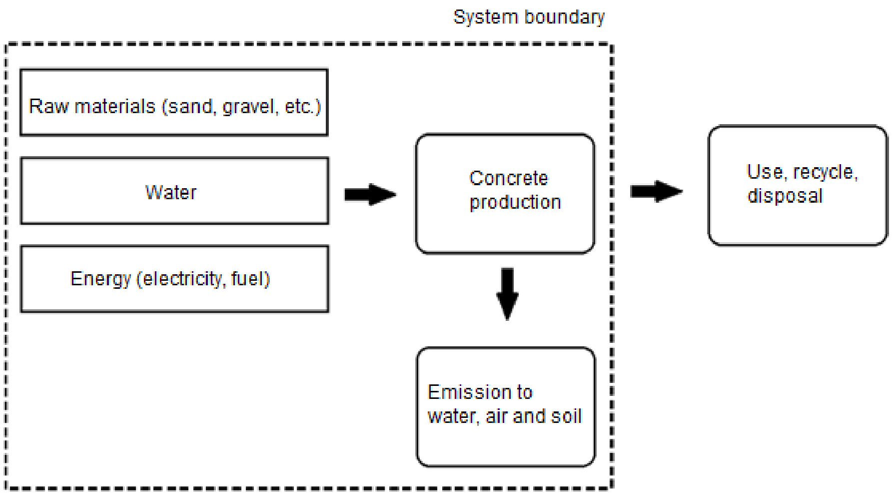

Fig. 1. System boundaries for the production of 1 cubic meter.

2.2.2.Inventory analysis

The life cycle inventory (LCI) data were sourced primarily from the Ecoinvent database and integrated into SimaPro software for analysis. Material quantities and transport distances were carefully recorded for each mix, and energy consumption for production was standardized to 157.9 kWh per m³.

2.2.3.Transportation and energy use

Material transport was modeled using Euro 4 standard trucks with a capacity of 16–32 tons, based on data from the Ecoinvent database integrated into SimaPro. A uniform transport distance of 70 kilometers was assumed for all raw materials. According to

Turner and Collins [27], the CO_2 emission factor for producing and delivering 1 m^3 of concrete, including mixing and transport to a construction site, is 0.0033 kg CO_2. Additionally, emissions related to energy use-such as on-site preparation, access construction, and concrete pumping-were estimated at 0.0094 kg CO_2 per m^3. The energy demand for producing 1 m^3 of ready-mix concrete was taken as 568.6 MJ [28], equivalent to 157.9 kWh, and was applied uniformly across all mix designs in this study.

2.2.4. Software input and mix-specific inventory

Each mix's LCI was entered into SimaPro with full consideration of raw material types, packaging, transport (in tonne-kilometers), and energy use. Tables A-1 through A-6 detail these inventories for all six concrete types.

2.3. Impact assessment and interpretation

The assessment focused on three key areas: human health, ecosystem quality, and resource depletion, following a cradle-to-gate LCA in accordance with ISO 14040/44 [26]. To quantify these impacts, three established methods were applied: CML 2001, ReCiPe, and IMPACT 2002+. These methods offer complementary perspectives by covering both midpoint and endpoint indicators. Midpoint metrics-such as GWP, acidification, and eutrophication-were used to assess specific environmental effects. CML 2001 focuses on these categories, while IMPACT 2002+ extends the analysis to endpoint-level damage, capturing broader implications for human health, ecosystem integrity, climate systems, and resource availability. Impact categories were selected based on their relevance to construction sustainability. This section describes the assessment framework and does not include an interpretation of the results.

2.4. Sensitivity analysis and economic evaluation

Sensitivity analysis was conducted to examine how variations in material quantities affect the environmental outcomes of the LCA [29]. This involved adjusting the volume of all input materials in each concrete mix by ±25%, a standard variation used in LCA studies to reflect typical fluctuations in raw material supply and production conditions. This approach helps assess the robustness of the results and identify parameters with the greatest influence on environmental impact, thereby improving confidence in the findings.

In parallel, an economic evaluation was performed to assess the cost-effectiveness of each concrete mix. The total cost of producing 1 cubic meter of concrete was calculated based on the unit price of all constituent materials and the energy required for production. Energy costs were included using a standard rate per kilowatt-hour. This integrated analysis enabled a comparison of both environmental performance and production costs across the different mix designs.

3. Results

The following section presents the results of the environmental and economic evaluations of the six concrete mixtures. It includes detailed analyses using multiple LCA methods, followed by a sensitivity analysis and cost comparison.

3.1. environmental impact assessment

The results of the evaluation using the CML2001, IMPACT 2002+, and ReCiPe methods for normal concrete, pumice, PET, and fiber concrete, nano-silica concrete, ceramic and EAFS concrete, and asbestos and rice husk ash concrete are presented.

3.1.1. Environmental impact results using the CML 2001 method

The environmental impacts of the six concrete mixtures were assessed using the CML 2001 method, focusing on global warming potential, human toxicity, terrestrial ecotoxicity, and acidification as key midpoint indicators.

As presented in **Table 2**, conventional concrete exhibited the lowest environmental burdens in all categories, including global warming (564.66 kg CO_2 eq), human toxicity (77.38 kg 1,4-DB eq), terrestrial ecotoxicity (0.75 kg 1,4-DB eq), and acidification (1.47 kg SO_2 eq). On the other hand, the PET and fiber concrete mix had the highest values for global warming (939.32 kg CO_2 eq), human toxicity (588.98 kg 1,4-DB eq), terrestrial ecotoxicity (2.22 kg 1,4-DB eq), and acidification (3.11 kg SO_2 eq), reflecting its intensive material and energy inputs.

Table 2. CML 2001-based environmental impact values across four midpoint categories.

Concrete type	Global warming (kg CO_2 eq)	Human toxicity (kg 1,4-DB eq)	Terrestrial ecotoxicity (kg 1,4-DB eq)	Acidification (kg SO_2 eq)
Conventional concrete	564.66	77.38	0.75	1.47
Pumice concrete	736.64	272.8	0.95	2.36
PET and fiber concrete	939.32	588.98	2.22	3.11
Nano-silica concrete	586.09	187.32	0.84	1.97
Ceramic and EAFS concrete	898.72	119.87	1.04	2.09
Asbestos and rice husk ash concrete	706.56	118.06	1.10	2.23

Fig. 2 illustrates the relative share of each concrete type's contribution to total environmental damage in percentage terms. PET and fiber concrete had the highest contributions in all categories: global warming (91.3%), human toxicity (60.2%), and ecotoxicity (57.6%). In contrast, conventional concrete consistently showed the lowest percentage contributions, with values of 54.9%, 8.33%, 19.4%, and 12.9% across the respective categories.

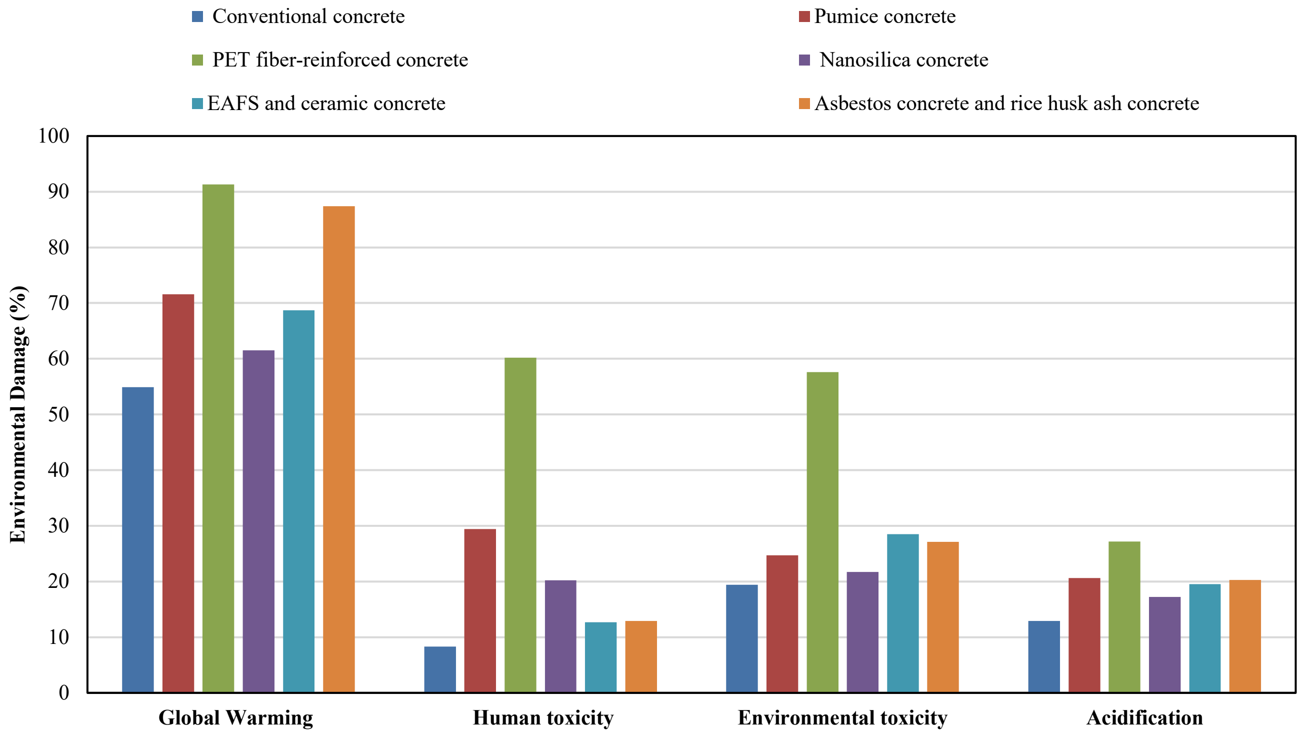

Fig. 2. Percentage contribution of six concrete mixtures to global warming, human toxicity, terrestrial ecotoxicity, and acidification, as assessed by the CML 2001 method.

3.1.2. Environmental impact results using the IMPACT 2002+ method

The environmental performance of the concrete mixtures was further evaluated using the IMPACT 2002+ method, which combines both midpoint and endpoint indicators. This dual-level approach provides a more comprehensive view of environmental damage by considering specific emissions and their broader consequences on human health, ecosystems, climate, and resource availability. As shown in **Table 3**, conventional concrete had the lowest environmental impact across all midpoint categories: global warming (553.26 kg CO_2 eq), ozone layer depletion (0.000031 kg CFC-11 eq), and mineral extraction (4.87 MJ surplus). In contrast, PET and fiber concrete recorded the highest values in global warming (888.98 kg CO_2 eq), ozone layer depletion (0.000053 kg CFC-11 eq), and mineral extraction (37.73 MJ surplus).

Table 3. Characterization results of six concrete mixtures across selected midpoint impact categories using the IMPACT 2002+ method.

Concrete type	Global warming (kg CO_2 eq)	Ozone layer depletion (kg CFC-11 eq)	Mineral extraction (MJ surplus)
Conventional concrete	553.26	0.000031	4.87
Pumice concrete	696.6	0.000044	5.87
PET concrete and fibers	888.98	0.000053	37.73
Nanosilica concrete	605.87	0.000040	5.66
Ceramic concrete and EAFS	884.22	0.000039	13.61
Asbestos concrete and rice husk ash	635.82	0.000038	8.51

Table 4 summarizes the endpoint damage categories including human health (DALY), ecosystem quality, climate change, and resource use. Conventional concrete again had the lowest values in all categories. The PET and fiber concrete had the highest damage across all endpoints: 0.00090 DALY for human health, 265.79 PDF·m²·yr for ecosystem damage, 888.98 kg CO_2 eq for climate change, and 11,837.7 MJ for resource use. Pumice concrete and ceramic/EAFS concrete also exhibited elevated environmental burdens, particularly in climate change and resource categories.

The percentage contribution of each concrete type to total environmental damage is illustrated in Fig. 3. PET and fiber concrete had the highest relative burden in all categories, exceeding 90% in climate change and human health. Pumice concrete also showed substantial impacts: 62.1% in human health and 80.6% in resource depletion. In the ecosystem quality category, asbestos and rice husk ash concrete contributed 22.1%, while ceramic and EAFS concrete showed a strong impact on climate change (89.6%), closely following the PET mix.

Table 4. Damage assessment results of six concrete mixtures across endpoint categories using the IMPACT 2002+ method.

Concrete type	Human health (DALY)	Ecosystem quality (PDF[1]*m^2*yr)	Climate change (kg CO_2 e)	Resources (MJ primary)
Conventional concrete	0.00028	99.17	553.26	4388.20
Pumice concrete	0.00062	193.34	696.68	9542.15
PET concrete and fibers	0.00090	265.79	888.98	11837.70
Nanosilica concrete	0.00036	122.87	568.00	5713.39
Ceramic concrete and EAFS	0.00069	131.68	884.22	5856.81
Asbestos concrete and rice husk ash	0.00039	225.13	637.76	5481.01

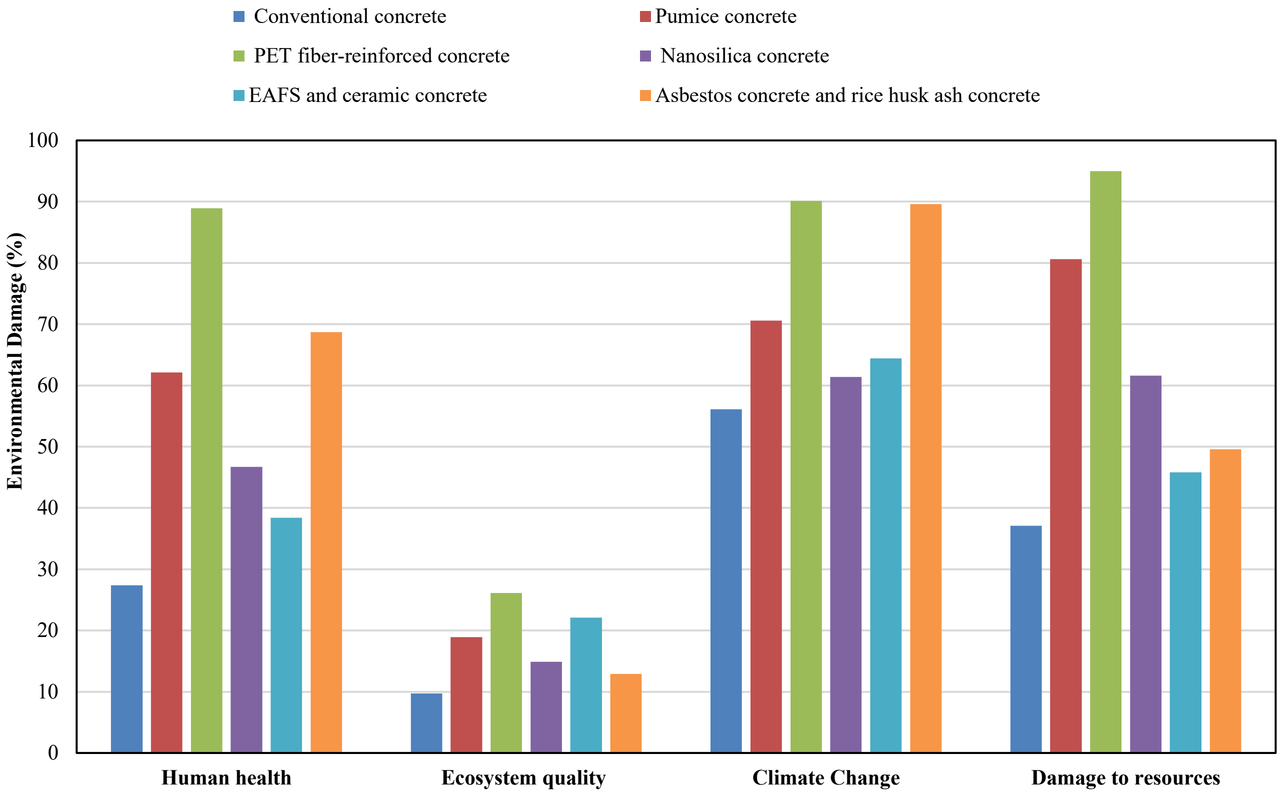

Fig. 3. Relative environmental damage of six concrete types across IMPACT 2002+ endpoint categories (percentage contribution).

3.1.3. Environmental impact results using the recipe method

The environmental burdens of the concrete mixes were also evaluated using the ReCiPe 2016 method, which integrates midpoint impacts into aggregated endpoint damage categories: human health, ecosystems, and resources. This method enables direct comparison across different environmental dimensions in a unified damage framework.

As presented in **Table 5**, conventional concrete consistently exhibited the lowest environmental damage across all categories, with the smallest values for human health (0.0009 DALY), ecosystems (0.00000051 species·yr), and resource use (USD 33.03). In contrast, PET and fiber concrete showed the highest impact on human health (0.0022 DALY), while asbestos and rice husk ash concrete resulted in the greatest damage to ecosystems (0.00000041 species·yr) and resources (USD 69.32). These outcomes reflect the influence of high embodied energy, waste processing, and additive-intensive mix designs in alternative concretes.

Table 5. Endpoint damage results for six concrete mixes based on the ReCiPe 2016 method.

Concrete type	Human health (DALY)	Ecosystems (species.yr)	Resources (USD2013)
Conventional concrete	0.0009	0.0000051	33.03
Pumice concrete	0.0015	0.0000031	44.5
PET concrete and fibers	0.0022	0.0000040	53.06
Nanosilica concrete	0.0011	0.0000026	39.85
Ceramic concrete and EAFS	0.0016	0.0000033	38.47

[1] Potentially Disappeared Fraction

Asbestos concrete and rice husk ash	0.0012	0.0000041	69.32

Fig. 4 illustrates the percentage contribution of each mix to total environmental damage in the three endpoint categories. PET and fiber concrete dominated the human health category with a 64.5% share, while asbestos/rice husk ash concrete had the highest impact on ecosystems (62%) and resource use (97%). As expected, conventional concrete contributed the least across all categories, reinforcing its comparatively lower environmental burden under the ReCiPe method.

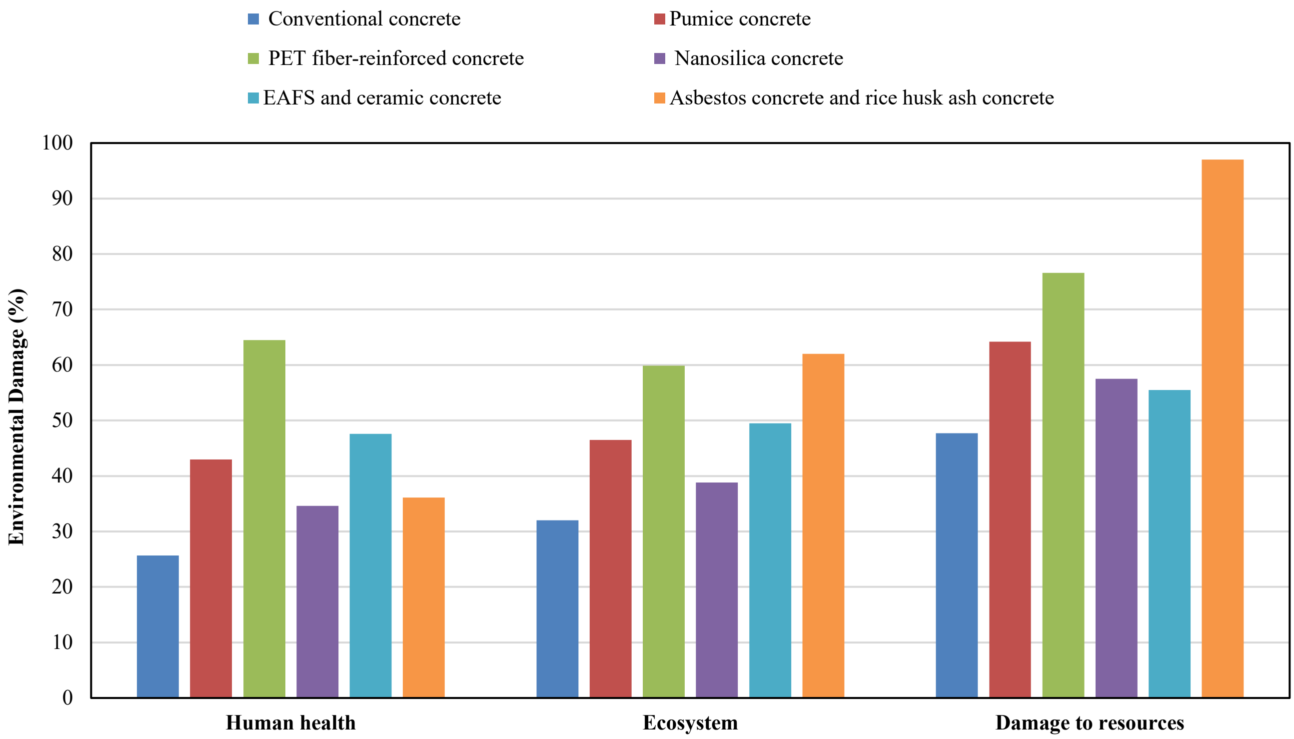

Fig. 4. Relative contribution of six concrete types to ReCiPe 2016 endpoint impact categories (in percentage).

3.2. Sensitivity analysis

To assess the robustness of the life cycle assessment results, a sensitivity analysis was conducted using the IMPACT 2002+ method by applying a ±25% variation in key input materials for each concrete mix. The IMPACT 2002+ method was used for this analysis, as it includes both midpoint and endpoint indicators, allowing for a comprehensive view of environmental effects. The aim was to identify which components had the greatest influence on overall environmental damage across four key categories: human health, ecosystem quality, climate change, and resource use.

3.2.1. Conventional concrete

As shown in Fig. 5, varying the cement content by ±25% had a clear impact across all damage categories. A 25% increase led to a 16.5% rise in climate change potential, while a 25% decrease reduced it by 19.8%. These results confirm cement as the most influential contributor to environmental impacts in this mix.

3.2.2. Pumice concrete

According to Fig. 6, the micro-silica content showed the highest sensitivity. A 25% increase led to rises of 16.3% in human health damage and 15.6% in resource use. In contrast, changes in pumice content produced minimal environmental variation, indicating its relatively low impact.

3.2.3. Pet and fiber concrete

As illustrated in Fig. 7, both micro-silica and PET significantly influenced environmental outcomes. Increasing micro-silica led to 10.5% more human health damage and 11.9% more resource use. Additionally, a 25% increase in cement caused a substantial 11.7% increase in climate change impact.

3.2.4. Nano-silica concrete

Fig. 8 highlights cement as the dominant factor in this mix, with a 25% increase resulting in a 10.5% rise in human health damage and 12.2% in ecosystem degradation. Nano-silica showed moderate sensitivity, while electricity consumption had the greatest effect on the resource use category.

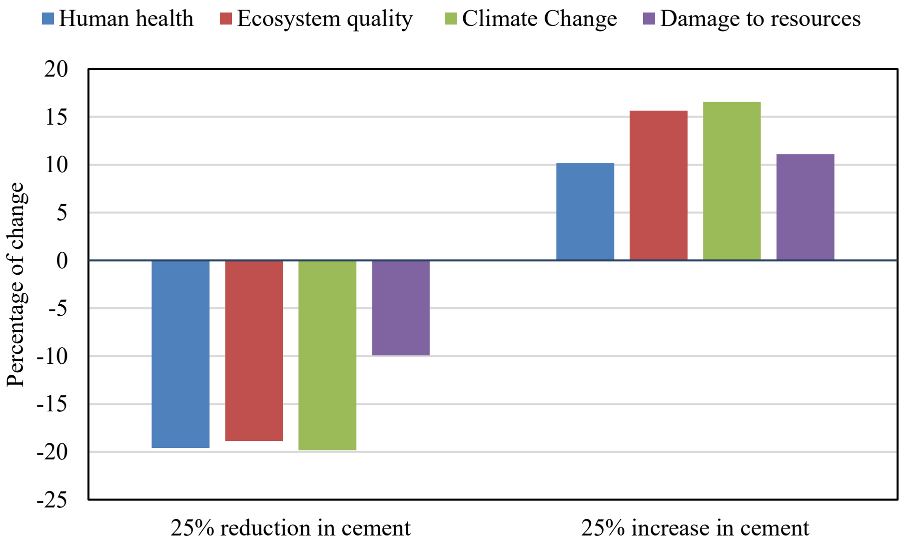

Fig. 5. Sensitivity analysis of conventional concrete under ±25% input variation using the IMPACT 2002+ method.

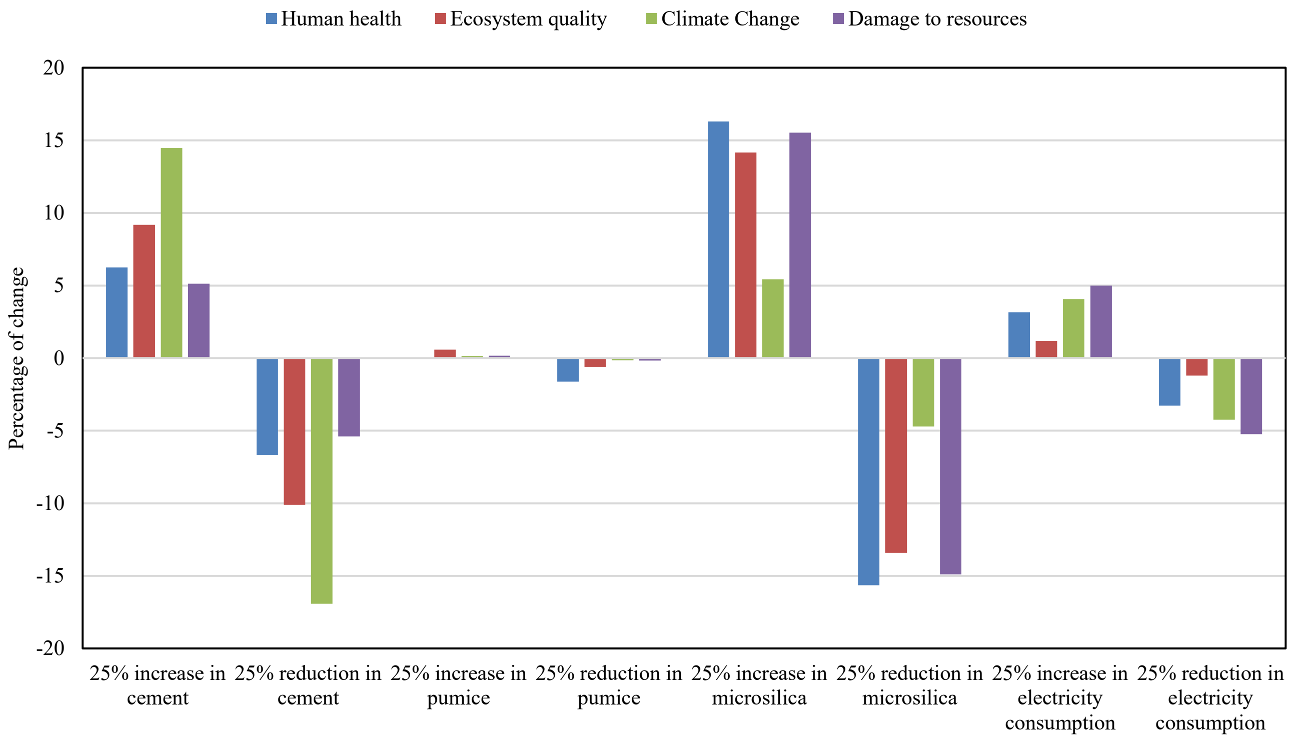

Fig. 6. Sensitivity analysis of pumice concrete under ±25% input variation using the IMPACT 2002+ method.

3.2.5. Asbestos and rice husk ash concrete

Fig. 9 shows that both cement and electricity considerably influenced climate change and human health categories. Notably, rice husk ash had the largest effect on ecosystem damage, with an 11.9% increase observed when its content was increased.

3.2.6. Ceramic and EAF slag concrete

According to Fig. 10, a 25% increase in ceramic waste led to a 12.2% rise in human health damage. Cement again drove increases in both climate change and ecosystem categories, while electricity variation significantly affected resource consumption.

3.2.7. Cross-verification of results using BEES and IPCC methods

To ensure the validity and robustness of the environmental impact results, the findings from the CML 2001 and IMPACT 2002+ methods were cross-verified using two supplementary approaches: BEES (Building for Environmental and Economic Sustainability) and the IPCC method for GWP. These additional methods were selected due to their widespread use and methodological distinctions, which allow for independent validation of key results.

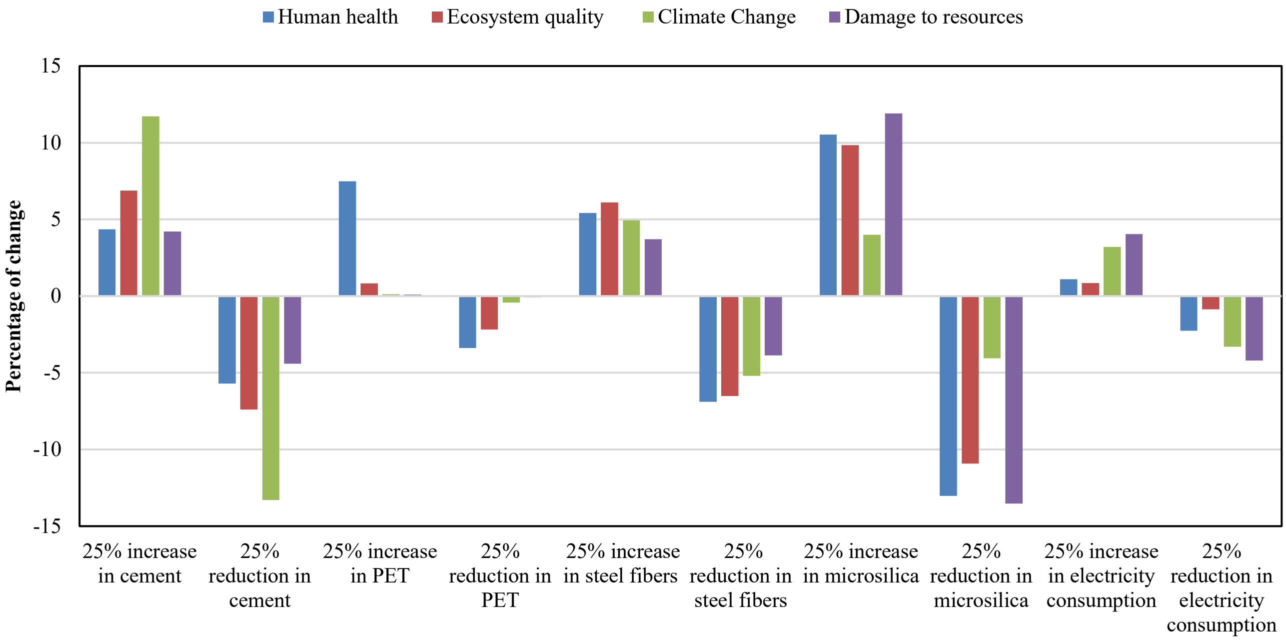

Fig. 7. Sensitivity analysis of PET and fiber-reinforced concrete under ±25% input variation using the IMPACT 2002+ method.

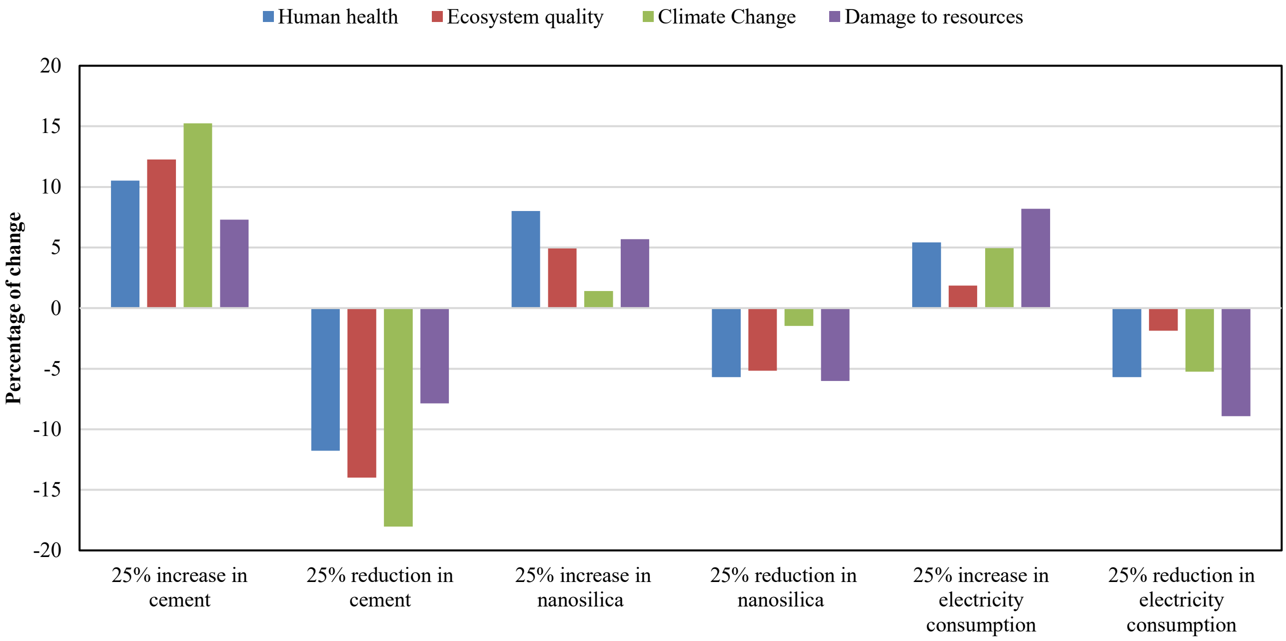

Fig. 8. Sensitivity analysis of nano-silica concrete under ±25% input variation using the IMPACT 2002+ method.

Tables 6 and 9 present the environmental impact results of five concrete types across acidification, eutrophication, global warming potential, and human toxicity. Among them, micro-silica concrete exhibited the highest impact in all categories, particularly in acidification and human toxicity.

Table 7 presents a comparison of global warming potential values derived from the CML 2001 and IMPACT 2002+ methods against those obtained from the BEES model. The results show a high level of agreement across all concrete types, with percentage differences generally below 5%. The largest deviation was observed for the asbestos and rice husk ash concrete mix, at 7.43%. Despite differences in modeling assumptions and units of measurement, the close alignment across methods confirms the reliability and robustness of the life cycle assessment results and indicates that the relative environmental ranking of the concrete mixes is not significantly influenced by the choice of assessment model.

Further validation was performed using the IPCC method, which focuses on climate-related emissions. As shown in Table 8, global warming results from CML 2001 and IPCC show excellent agreement with differences ranging from 0.04% to 0.20%. This confirms the robustness of the findings and indicates that the results are not sensitive to the choice of impact assessment model. These outcomes are consistent with prior research by Asadollahfardi et al. [19], who also reported minimal variation across methods when evaluating the environmental impacts of different concrete types.

Overall, these comparisons further confirm that methodological differences between IPCC and CML-IA have minimal impact on the outcome, supporting the robustness and consistency of the LCA results across evaluation methods.

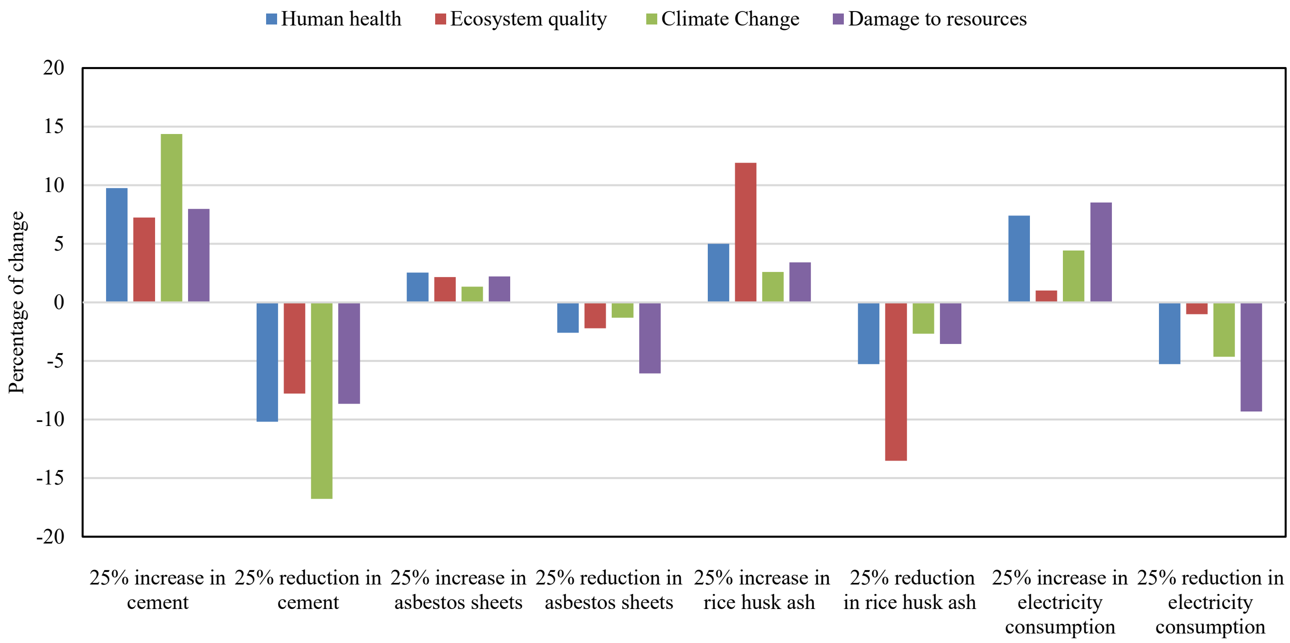

Fig. 9. Sensitivity analysis of asbestos and rice husk ash concrete under ±25% input variation using the IMPACT 2002+ method.

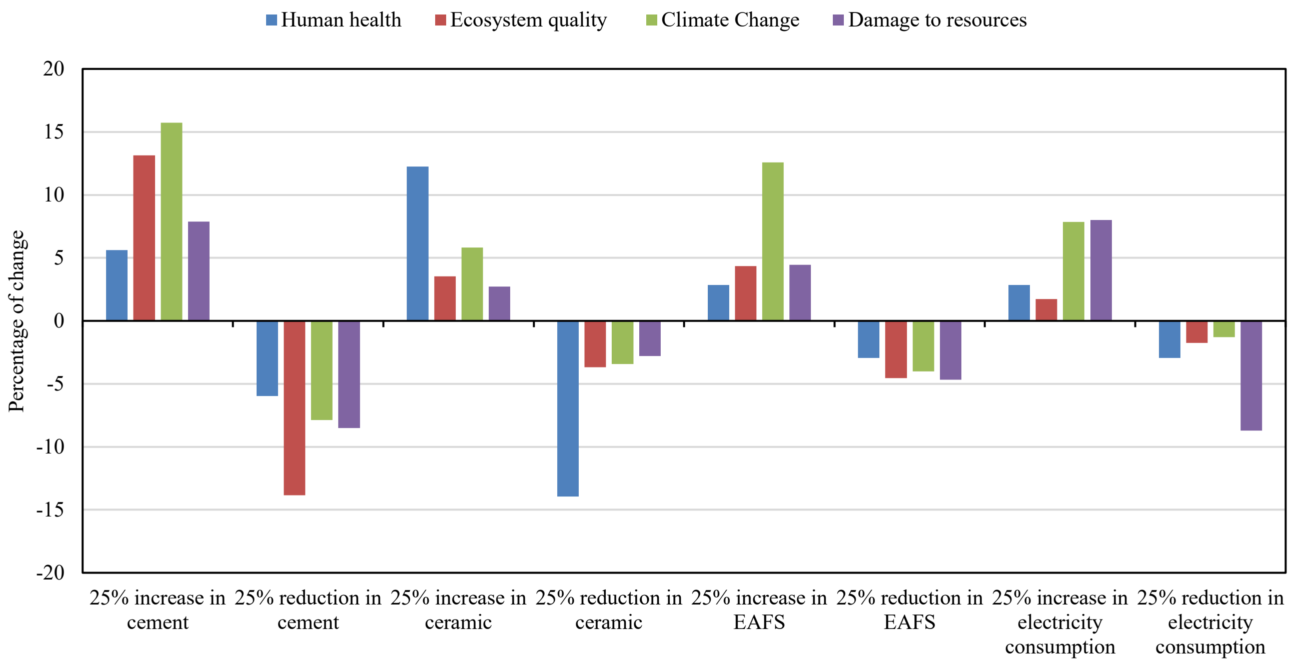

Fig. 10. Sensitivity analysis of ceramic and EAFS concrete under ±25% variation in inputs using the IMPACT 2002+ method.

Table 6. Global warming potential of six concretes: CML 2001 vs. BEES (with % difference).

Concrete type	Global warming for IMPACT (kg CO_2 eq)	Global warming for BEES (g CO_2 eq)	Difference(%)
Conventional concrete	564.66	559251.34	0.96
Pumice concrete	736.64	720658.20	2.19
PET and fiber concrete	939.32	918354.18	2.26
Nano-silica concrete	586.09	578172.58	1.36
Ceramic and arc slag concrete	898.06	891765.86	0.78
Asbestos and rice husk ash concrete	706.56	684874.99	3.12

Table 9 presents the environmental impact results of five concrete types across acidification, eutrophication, global warming potential, and human toxicity. Among them, micro-silica concrete exhibited the highest impact in all categories, particularly in acidification and human toxicity.

Table 7. Global warming potential of six concretes: IMPACT 2002+ vs. BEES (with % difference).

Concrete type	Global warming for IMPACT (kg CO_2 eq)	Global warming for BEES (g CO_2 eq)	Difference(%)
Conventional concrete	553.6	559251.36	1.08
Pumice concrete	696.6	720658.44	3.33
PET and fiber concrete	888.9	918354.18	3.22
Nano-silica concrete	605.8	578172.38	4.61
Ceramic and arc slag concrete	882.2	891764.56	0.85
Asbestos and rice husk ash concrete	635.8	684874.35	7.43

Table 8. Comparison of global warming potential for six concrete types using CML 2001 and IPCC methods (% difference).

Concrete type	Global warming for CML (kg CO_2 eq)	Global warming for IPCC (g CO_2 eq)	Difference(%)
Conventional concrete	564.6	564.89	0.04
Pumice concrete	736.6	737.62	0.13
PET and fiber concrete	939.3	940.58	0.13
Nano-silica concrete	586.09	586.5	0.07
Ceramic and arc slag concrete	898.72	899.04	0.07
Asbestos and rice husk ash concrete	706.56	707.99	0.20

Table 9. Environmental impact indicators for five concrete types (acidification, eutrophication, GWP, human toxicity).

Concrete type	Acidification (kg SO_2 eq)	Eutrophication (kg PO_4^{3-} eq)	Global warming potential (kg CO_2 eq)	Human toxicity (kg 1.4-DB eq)
Concrete with ordinary Portland cement	0.84	0.159	386.44	35.68
Microsilica	1.55	0.572	605.32	182.52
Geopolymer	1.11	0.183	286.85	72.35
Micro-nano bubbles	0.89	0.175	424.17	37.45
Nanosilica	0.96	0.185	453.31	41.04

In Table 10, global warming potential values obtained from the IPCC and CML-IA (World 2000) methods were compared. The results show negligible differences for most concrete types-just 0.6% for ordinary Portland cement, nano-silica, and micro-nanobubble concretes. Slightly higher differences were observed for geopolymer (0.9%) and micro-silica (2.4%) concretes.

Table 10. CML-IA vs. IPCC: Global warming potential for five concretes (% difference).

Concrete type	Global warming for CML (kg CO_2 eq)	Global warming for IPCC (kg CO_2 eq)	Difference(%)
Concrete with ordinary Portland cement	388.84	386.44	0.6
Microsilica	619.73	605.32	2.4
Geopolymer	289.54	286.85	0.9
Micro-nano bubbles	426.72	424.17	0.6
Nanosilica	456.08	453.31	0.8

3.3. Economic analysis of concrete mixes

To complement the environmental analysis, an economic assessment was conducted using life cycle costing based on current Iranian market prices for raw materials. The cost per cubic meter of each concrete type was calculated from material quantities and unit prices (Table 11).

The estimated costs are as follows:

- Conventional Concrete: 9,854,800 IRR
- Pumice Concrete: 11,999,646 IRR
- PET & Fiber Concrete: 20,446,668 IRR
- Nano-silica Concrete: 242,695,148 IRR

- Ceramic & EAFS Concrete: 34,386,450 IRR
- Asbestos & Rice Husk Ash Concrete: 104,029,586 IRR

Table 11. Unit prices of raw materials used in concrete mix designs (based on the Iranian market).

Raw materials used	Unit	Price (I.R Rial)	Raw materials used	Unit	Price (I.R Rial)
Cement	kg	13600	Pumice	kg	2830
Sand	kg	2200	Ceramics	kg	22500
Sand	kg	2200	Electric arc furnace slag	kg	56170
PET waste	kg	185400	Asbestos cement sheets	kg	87270
Steel fibers	kg	520000	Rice hull ash	kg	800000
Microsilica	kg	54000	Lubricant	L	952570
Nanosilica	kg	9000000	-	-	-

Conventional concrete is the most cost-effective option, mainly due to its reliance on widely available and low-cost materials. In contrast, nano-silica concrete has the highest cost, driven by the high price of nanosilica and other specialized additives like microsilica and steel fibers. Other mixes, such as those containing rice husk ash, asbestos sheets, ceramics, and slag, also show elevated costs due to the expensive or limited availability of their components. While these alternatives may offer environmental or performance benefits, their high economic cost can limit practical application, highlighting the trade-off between sustainability and affordability in material selection.

3.4. Integrated environmental–economic evaluation

Given the critical role of both environmental and economic factors in material selection, an integrated assessment was performed to support more informed decision-making. As shown in Fig. 11, conventional concrete emerges as the most balanced option, offering both the lowest production cost and GWP. Nano-silica concrete demonstrates relatively low CO_2 emissions, suggesting environmental benefits; however, its extremely high cost significantly reduces its economic attractiveness. On the other hand, PET fiber-reinforced concrete, while economically moderate, exhibits the highest GWP, making it environmentally less favorable. Alternatives such as pumice concrete and EAFS-ceramic concrete offer more balanced profiles with moderate emissions and reasonable costs. These findings emphasize the importance of evaluating both impact categories jointly, as no single concrete mix optimizes all performance criteria simultaneously.

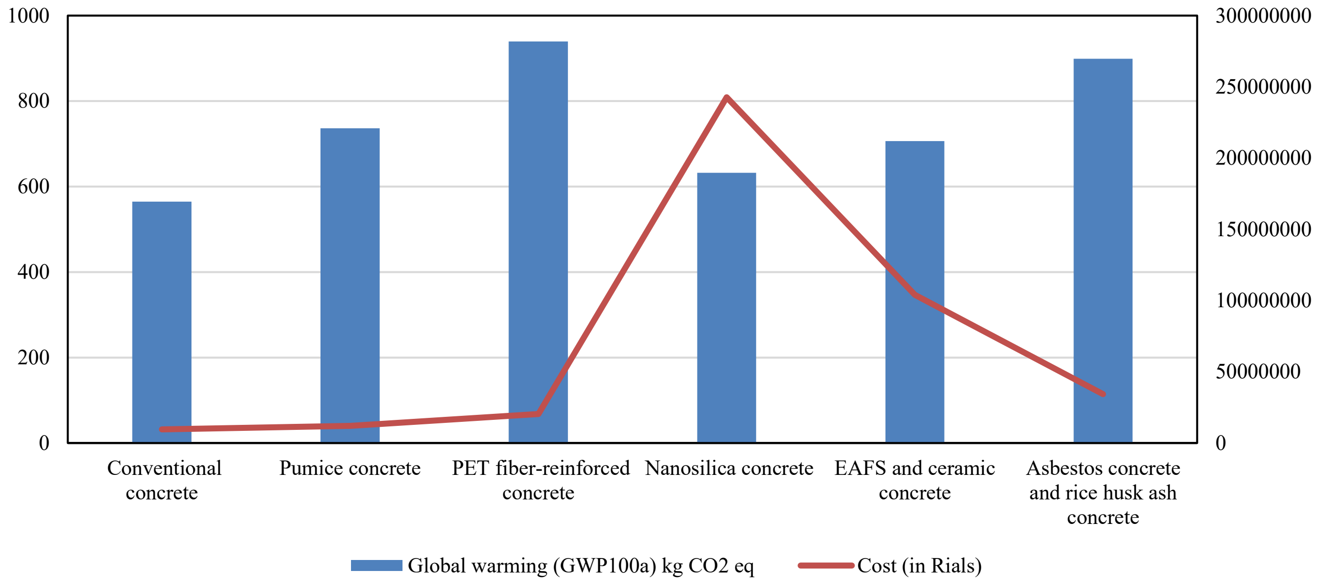

Fig. 11. Economic and environmental assessment of CO2 emissions based on the CML method.

3.5. Research limitations

A key limitation of this study is that some of the proposed concrete mix designs were not implemented at full scale in real-world construction, limiting the availability of accurate performance data, particularly regarding service life. As a result, a cradle-to-gate system boundary was adopted, focusing exclusively on the environmental impacts associated with raw material extraction, processing, and concrete production. Additionally, due to limited transparency and restricted access to emission data from domestic manufacturing facilities in Iran, the life cycle assessment relied on European and international datasets and standards. While this approach provides a consistent methodological framework, it may not fully capture region-specific variations in environmental performance.

4. Conclusion

This study assessed the environmental and economic performance of six concrete mixtures using LCA and cost analysis. The results consistently identified conventional concrete as the most environmentally and economically favorable option. It showed the lowest impacts across key categories such as global warming, human toxicity, ecotoxicity, and acidification, as confirmed by the CML, IMPACT 2002+, and ReCiPe methods.

Among the alternative mixes, PET/steel fiber concrete exhibited the highest environmental burden-particularly in terms of CO_2 emissions and human health impacts-despite being relatively cost-effective. In contrast, nano-silica concrete, though environmentally competitive, was economically impractical due to the high cost of its components. Cement was found to be the most influential contributor to environmental damage across all mixes, with a 25% increase in content-raising impacts by up to 16%. Microsilica also showed notable influence, particularly in the PET and pumice-based mixes. The integrated analysis demonstrated that no single mix optimized all performance aspects. However, pumice concrete and ceramic/EAFS concrete provided moderate emissions with acceptable costs, offering more balanced alternatives. Ultimately, the findings highlight the trade-offs between environmental benefits and economic feasibility, emphasizing the need for context-specific mix selection in sustainable construction.

Statements & declarations

Author Contributions

Mohammad-Amin Dashab: Conceptualization, Investigation, Methodology, Formal analysis, Resources, Writing - Original Draft, Writing - Review & Editing.

Mostafa Kazemi: Conceptualization, Methodology, Project administration, Supervision, Writing - Review & Editing.

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Declarations

The authors declare no conflict of interest.

Data availability

The data presented in this study will be available on interested request from the corresponding author

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Appendix

Table A- 1. LCA input data for conventional concrete in SimaPro, including materials, transport, energy, and CO_2 emissions.

Input process	Unit	Amount	Raw materials, process and emission
Cement, Portland {RoW}| market for | APOS, U	kg	430	Portland cement
Tap water {RoW}| market for | APOS, U	L	215	Water
Gravel, crushed {RoW}| market for gravel, crushed | APOS, U	kg	845	Gravel
Sand {RoW}| gravel and quarry operation | APOS, U	kg	855	Sand
Packing, cement {RoW}| processing | APOS, U	kg	430	Cement packaging
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	30.1	Cement transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	59.1	Gravel transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	59.8	Sand transportation
Electricity, medium voltage | market for | APOS, U	KWh	157.9	Concrete production energy

Carbon dioxide	kg	0.0033	Factory carbon dioxide emissions
Carbon dioxide	kg	0.0094	Carbon dioxide emissions from workshop activities for concrete production

Table A- 2. LCA input data for pumice aggregate in SimaPro, including materials, transport, energy, and CO_2 emissions .

Input process	Unit	Amount	Raw materials, process and emission
Cement, Portland {RoW}| market for | APOS, U	kg	468.3	Portland cement
Tap water {RoW}| market for | APOS, U	L	126.7	Water
Pumice {GLO}| market for | APOS, U	kg	200.7	Pumice
Sand {RoW}| gravel and quarry operation | APOS, U	kg	784.5	Sand
Ferrosilicon {GLO}| market for | APOS, U	kg	46.8	Microsilica
Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO}| market for | APOS, U	kg	0.85	Lubricant
Packing, cement {RoW}| processing | APOS, U	kg	468.3	Cement batching
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	32.8	Cement transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	14.0	Pumice transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	54.9	Sand transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	3.3	Microsilica transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	0.06	Pumice transportation
Electricity, medium voltage {IR}| market for | APOS, U	KWh	157.9	Concrete production energy
Carbon dioxide	kg	0.0033	Factory carbon dioxide emissions
Carbon dioxide	kg	0.0094	Carbon dioxide emissions from workshop activities for concrete production

Table A- 3. LCA input data for PET and steel fibers in SimaPro, including materials, transport, energy, and CO_2 emissions.

Input process	Unit	Amount	Raw materials, process and emission
Cement, Portland {RoW}| market for | APOS, U	kg	477	Portland cement
Tap water {RoW}| market for | APOS, U	L	157	Water
Gravel, crushed {RoW}| market for gravel, crushed | APOS, U	kg	1.04	Gravel
Sand {RoW}| gravel and quarry operation | APOS, U	kg	95	Sand
Ferrosilicon {GLO}| market for | APOS, U	kg	53	Microsilica
Waste polyethylene terephthalate, for recycling, sorted {RoW}| market for waste polyethylene terephthalate, for recycling, sorted | APOS, U	kg	36.7	PET waste
Steel fibers	kg	78.5	Steel fibers
Packing, cement {RoW}| processing | APOS, U	kg	477	Cement packaging
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	33.4	Cement transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	0.07	Gravel transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	6.6	Sand transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	3.7	Microsilica transport
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	2.6	PET waste transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	5.5	Steel fiber transportation
Electricity, medium voltage {IR}| market for | APOS, U	KWh	157.9	Concrete production energy
Carbon dioxide	kg	0.0033	Factory carbon dioxide emissions
Carbon dioxide	kg	0.0094	Carbon dioxide emissions from workshop activities for concrete production

Table A- 4. LCA input data for nanosilica pozzolan in SimaPro, including materials, transport, energy, and CO_2 emissions.

Input process	Unit	Amount	Raw materials, process and emission
Cement, Portland {RoW}| market for | APOS, U	kg	404.2	Portland cement

Tap water {RoW}| market for | APOS, U	L	215	Water
Gravel, crushed {RoW}| market for gravel, crushed | APOS, U	kg	855.5	Gravel
RC Sand	kg	793.1	Recycled sand
Nanosilica	kg	25.8	Nano-silica
Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO}| market for | APOS, U	kg	0.4	Lubricant
Packing, cement {RoW}| processing | APOS, U	kg	404.2	Cement packaging
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	28.3	Cement transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	599	Gravel transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	55.5	Transportation of recycled sand
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	1.8	Nano-Silica Transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	0.03	Lubricant transportation
Electricity, medium voltage {IR}| market for | APOS, U	KWh	157.9	Concrete production energy
Carbon dioxide	kg	0.0033	Factory carbon dioxide emissions
Carbon dioxide	kg	0.0094	Carbon dioxide emissions from workshop activities for concrete production

Table A- 5. LCA input data for ceramic waste and EAFS in SimaPro, including materials, transport, energy, and CO_2 emissions.

Input process	Unit	Amount	Raw materials, process and emission
Cement, Portland {RoW}| market for | APOS, U	kg	448	Portland cement
Tap water {RoW}| market for | APOS, U	L	215	Water
Gravel, crushed {RoW}| market for gravel, crushed | APOS, U	kg	445	Gravel
Sand {RoW}| gravel and quarry operation | APOS, U	kg	275	Sand
Ceramic tile {GLO}| market for | APOS, U	kg	52	Ceramic
Electric arc furnace slag	kg	445	EAFS
Packing, cement {RoW}| processing | APOS, U	kg	448	Cement packaging
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	31.4	Cement transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	31.1	Gravel transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	19.2	Sand transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	3.6	Ceramic transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	31.1	EAFS transportation
Electricity, medium voltage {IR}| market for | APOS, U	KWh	157.9	Concrete production energy
Carbon dioxide	kg	0.0033	Factory carbon dioxide emissions
Carbon dioxide	kg	0.0094	Carbon dioxide emissions from workshop activities for concrete production

Table A- 6. LCA input data for asbestos cement corrugated sheets and rice husk ash waste in SimaPro, including materials, transport, energy, and CO_2 emissions.

Input process	Unit	Amount	Raw materials, process and emission
Cement, Portland {RoW}| market for | APOS, U	kg	425	Portland cement
Tap water {RoW}| market for | APOS, U	L	215	Water
Gravel, crushed {RoW}| market for gravel, crushed | APOS, U	kg	522	Gravel
Sand {RoW}| gravel and quarry operation | APOS, U	kg	570.2	Sand
Asbestos, crysotile type {GLO}| market for | APOS, U	kg	387.2	Asbestos cement sheet
Rice husk ash (RHS)	kg	75	Rice husk ash
Plasticiser, for concrete, based on sulfonated melamine formaldehyde {GLO}| market for | APOS, U	kg	2.1	Lubricant
Packing, cement {RoW}| processing | APOS, U	kg	425	Cement packaging

Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	29.7	Cement transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	36.5	Gravel transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	39.9	Sand transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	27.2	Asbestos cement sheet transportation
Transport, freight, lorry 16-32 metric ton, EURO4 {RoW}| transport, freight, lorry 16-32 metric ton, EURO4 | APOS, U	tkm	5.2	Rice husk ash transportation
Electricity, medium voltage {IR}| market for | APOS, U	KWh	157.9	Concrete production energy
Carbon dioxide	kg	0.0033	Factory carbon dioxide emissions
Carbon dioxide	kg	0.0094	Carbon dioxide emissions from workshop activities for concrete production