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Environmental impact assessment of conventional construction methods in low-rise residential buildings in northern Iran

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Abstracts

The construction sector is among the largest contributors to global environmental degradation due to intensive energy consumption and the depletion of natural resources. In Guilan Province, northern Iran, rapid growth in residential construction has raised concerns about long-term ecological impacts, yet systematic evaluations remain limited. This study addresses this gap by investigating the environmental consequences of residential buildings through the Life Cycle Assessment (LCA) approach. A total of 384 residential building blueprints were manually examined to extract detailed information on material types and quantities. These data were statistically analyzed using SPSS software to identify dominant structural systems and material consumption patterns. Subsequently, the environmental impacts of concrete and steel frame systems were compared with the aid of the OpenLCA software package, considering multiple indicators including greenhouse gas emissions, resource depletion, and air and water pollution. The assessment covered the entire life cycle of building materials, from production to transportation and on-site construction. Results revealed that concrete frames significantly increase CO_2 emissions, contributing to global warming and depletion of non-renewable resources, mainly due to the high environmental cost of cement production. In contrast, steel frame systems were linked to elevated radioactive emissions, such as radon and tritium. Furthermore, transportation—particularly long-distance hauling of construction materials—emerged as a key factor in environmental degradation. These findings highlight the urgent need for integrating sustainability principles into residential construction practices in Guilan Province. Recommendations include promoting the use of local materials, optimizing logistics to reduce transportation distances, and adopting low-energy building technologies.

Keywords: Life Cycle Assessment (LCA); Low-Rise Residential Buildings; Sustainable Construction; Conventional Construction Methods; Energy

1. Introduction

The construction industry is a cornerstone of global economic development, providing essential infrastructure and housing. However, its substantial contribution to environmental degradation and resource depletion has raised concerns, necessitating a shift toward sustainable construction practices. The sector is responsible for nearly 40% of global energy consumption and contributes significantly to greenhouse gas (GHG) emissions, with approximately 38% of total emissions attributed to building-related activities (International Energy Agency, 2020; Izaola et al., 2022). These concerns underscore the need for adopting environmentally friendly construction methods that mitigate adverse ecological impacts while ensuring long-term sustainability. In this regard, quantitative research is essential to identify effective strategies for reducing environmental impacts, for instance through lowering energy consumption. For example, one study demonstrated that changing the type of window glazing could reduce energy use by about 11 to 13% compared to a baseline model (Mirashk-Daghiyan et al., 2021). In addition to the type of materials, the quality of materials also has a significant impact on reducing environmental impacts, and it is only through quantitative studies that the extent of this effect can be determined; for instance, one study showed that, according to a multi-criteria correlation study at a micro scale, physical components of the environment, such as the quality of materials and interior finishes, have a fundamental impact on sustainability; this indicates that quantitative analyses at various scales are an effective approach for optimizing design and reducing energy consumption.(Moztarzadeh & Nikounam Nezami, 2022)

Life Cycle Assessment (LCA) has emerged as a crucial tool for evaluating the environmental footprint of buildings, from raw material extraction to demolition. Research highlights that traditional construction methods relying on concrete and steel contribute extensively to carbon emissions, resource depletion, and environmental pollution (Hamidi & Bulbul, 2014; Gunathilake et al., 2021). Concrete, in particular, has a high embodied

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carbon footprint, with cement production alone accounting for nearly 8% of global CO_2 emissions (Jahandideh et al., 2020). Similarly, steel structures, while offering durability, are associated with significant environmental burdens due to high energy demands in production and raw material extraction.

The importance of regional studies in LCA cannot be overstated, as the environmental performance of construction materials varies based on climatic conditions, local material availability, and transportation requirements. In the Middle East, and particularly in Iran, the lack of region-specific LCA studies has created a knowledge gap (Oladazimi et al., 2021; AbdolkhaniNezhad et al., 2022). Guilan Province in northern Iran represents an ideal case study due to its high humidity, distinct architectural techniques, and high volume of low-rise residential construction. While some studies have assessed the general environmental impact of construction in Iran, there remains a notable absence of detailed LCA analyses focusing on Guilan's specific construction practices.

Studies have shown that green walls on building facades act as natural insulation, mitigating thermal fluctuations by creating an insulating air gap; such findings underscore the importance of conducting region-specific research to quantify the effectiveness of material selection and facade strategies in reducing environmental impacts(Fallahi & Ayvazian, 2016). This study aims to address these research gaps by conducting a comprehensive LCA of conventional concrete and steel structures in Guilan Province. By employing OpenLCA and DesignBuilder software for environmental and energy performance analysis, this research provides empirical insights into the GHG emissions, energy consumption, and material sustainability of different construction methods. The findings will contribute to the development of regional sustainability strategies while enhancing the body of knowledge on LCA applications in construction within the Middle East.

2. Research Methodology

This study employs a quantitative and analytical approach to assess the environmental impacts of conventional construction methods in low-rise housing within Guilan Province. The research follows the principles of Life Cycle Assessment (LCA) to systematically evaluate the environmental footprint of construction materials and processes, from raw material extraction to end-of-life disposal. Independent variables in this study are the construction structural systems (concrete frame and steel frame), while dependent variables are environmental impact indicators such as Global Warming Potential (GWP), acidification, eutrophication, fossil fuel depletion, ozone depletion, and human toxicity. Mediating variables include transportation distances, construction logistics, and material sourcing. To ensure a representative dataset, 384 blueprints of low-rise residential buildings were selected based on Morgan's sampling table. These blueprints were obtained from 35 engineering offices across 11 administrative districts of Guilan Province to account for the diversity of construction practices in the region. The selection process was conducted through random stratified sampling, ensuring that the number of samples per city corresponded to the volume of construction activity in each area. Cities with higher construction frequencies, such as Anzali and Rasht, contributed proportionally more samples, while areas with lower construction activity, such as Shaft, had fewer samples. Also the diversity of architectural offices in each city, so that different styles and construction practices were adequately represented. This sampling strategy ensured that the dataset accurately reflected the construction landscape of the province. The study covers constructions from year 1402, defining the temporal scope of the research.

Following the selection of sample buildings, the system boundaries and functional unit were precisely defined. The study considered the entire life cycle of construction materials, encompassing raw material extraction, transportation, construction, and demolition. The functional unit was set as a 99.99 m² low-rise residential unit, which was determined based on statistical analysis of the collected blueprints. This standardization allowed for a meaningful comparison of environmental impacts across different construction methods .Subsequently, a Life Cycle Inventory (LCI) analysis was conducted to quantify the inputs and outputs associated with the construction processes. The LCI process involved collecting data on material consumption, energy use, and emissions at various stages of the life cycle. The study utilized the Ecoinvent database version ecoinvent_371_consequential_lci_20210105, which provides a comprehensive dataset for modeling the environmental impacts of building materials. Additionally, the TRACI (Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts) method, developed by the U.S. Environmental Protection Agency (EPA), was applied to assess key impact categories, including Global Warming Potential (GWP), acidification, eutrophication, fossil fuel depletion, ozone depletion, and human toxicity.

For environmental impact assessment, OpenLCA version 1.10.3 software was employed to simulate and analyze the life cycle impacts of construction materials and processes. The selection of OpenLCA was based on its open-source framework, flexibility, and compatibility with the Ecoinvent database, making it an ideal tool for conducting region-specific LCA studies. OpenLCA software simulated and analyzed life cycle impacts. The outputs of OpenLCA were validated by cross-checking with literature values and internal consistency checks. SPSS software was used for statistical analysis of blueprint data, and its outputs were validated using standard statistical tests (e.g., normality checks and descriptive analysis). To validate the data used in OpenLCA software, the official OpenLCA 2 manual was consulted, which explains data quality management and methods for verifying the accuracy of LCA model results (Greendelta, 2022). Additionally, comparative studies among different LCA software have shown that LCA results may vary

depending on the chosen software, and OpenLCA provides reliable and scientifically robust outputs (Majeau-Bettez et al., 2017).
The analysis followed a structured process, beginning with data integration and normalization, followed by impact modeling using the TRACI method, and concluding with interpretation of results to compare the environmental performance of different construction practices in Guilan Province .By integrating a rigorous LCA framework with region-specific data, this study provides empirical insights into the environmental footprint of low-rise residential construction in Guilan. The findings contribute to the development of sustainable construction strategies tailored to the unique climatic and material conditions of the region, addressing existing gaps in regional LCA studies within Iran and the broader Middle East.

3. Results and Discussion

A statistical analysis of the selected samples was conducted to evaluate their representativeness. Given the non-normal distribution of variables, a proportion test was employed to verify the research hypothesis, and the analytical results are summarized in Table 1. To ensure the validity of the reported averages, a significance test was performed to determine whether these values accurately represent their respective variable groups.
The hypothesis testing framework was structured as follows: the null hypothesis (H_0) assumed that the examined variable was not a suitable representative of the building characteristics, whereas the alternative hypothesis (H_1) posited that it was an appropriate representative. The significance test results indicated that building orientation, window dimensions, building width, and length were statistically valid representatives of their respective categories. However, for variables such as occupancy area and roof slope, the most frequently occurring values were found to be the most appropriate representatives rather than the computed averages.

Table 1
Analytical statistics of case examples of low-rise buildings in Guilan province

Hypothesis (H_0 / H_1)	**Max**	**Min**	**Standard Deviation**	**Mean**	**Variable**
$\mathbf{H_1}$ (Significant)	40.00	-45.00	1.1	13.38	Building Orientation (° relative to North)
$\mathbf{H_1}$ (Significant)	46.00	11.00	5.22	30.73	Window-to-Wall Ratio (WWR) (m²)
$\mathbf{H_0}$ (Not Significant)	224.00	70.00	30.12	112.83	Building Occupancy Area (m²)
$\mathbf{H_1}$ (Significant)	**11.00**	**7.15**	0.5781	**9.24**	Building Width (m)
$\mathbf{H_1}$ (Significant)	**14.08**	**8.00**	0.8431	**10.74**	Building Length (m)
$\mathbf{H_0}$ (Not Significant)	38.00	25.00	1.35	29.92	Roof Slope (°)
$\mathbf{H_0}$ (Not Significant)	-	-	0.33	1.88	Structural System (Concrete = 1, Steel = 2)
$\mathbf{H_0}$ (Not Significant)	-	-	0.35	1.14	Façade Material (Travertine = 1, Other = 2)

To ensure the statistical validity of the selected variables, hypothesis testing was conducted using a proportion test, given the non-normal distribution of the dataset. The null hypothesis (H_0) assumed that a variable's mean value was not a suitable representative of its category, whereas the alternative hypothesis (H_1) posited that it was. The results indicated that variables such as building orientation, window-to-wall ratio (WWR), building width, and building length were statistically significant representatives of their respective categories.
However, for roof slope and building occupancy area, the mean value did not show statistical significance in the proportion test, meaning it lacked the necessary representativeness for these variables. Instead, the most frequently occurring value (mode) was found to be a more reliable representative, as it better reflected the dataset's distribution pattern. This adjustment ensures that the selected values more accurately depict real-world architectural trends in the region rather than being skewed by outlier data points.
Additionally, key architectural variables such as roof type, exterior walls, and structural materials were examined to provide a comprehensive understanding of the region's building characteristics. The analysis indicated that 37.8% of buildings had gable roofs, while 62.2% featured hipped roofs, with an average slope of 29.99%. This preference for hipped roofs is likely due to their superior resistance to high humidity and precipitation, which are common climatic conditions in Guilan Province .Regarding building height, 89.1% of the case study buildings were single-storey, while only 10.9% had two storeys. This predominance of single-storey structures aligns with the region's traditional architectural patterns and the availability of land.
The study also found that no dominant building orientation was statistically evident. However, on average, 38.5% of the buildings were oriented southward, suggesting that orientation was primarily influenced by land parcel layouts and access routes rather than passive solar design considerations .From a structural perspective, 88% of buildings utilized concrete frames, which is expected given their ease of construction and cost-effectiveness for low-rise buildings. Similarly, 85.7% of the sample cases used travertine stone for façade cladding, indicating a regional preference for this material due to its availability and aesthetic qualities.

Table 2
Summary of these statistics

storey	Orientation	Occupancy Area(m^2)	Length(m)	Width(m)	Roof Type	Roof Slope	Exterior Wall	Structure	Facade
1	1.1E	99.99	10.74	9.24	Hipped roof	30%	Clay brick	Concrete	Travertine

In the Life Cycle Assessment (LCA) method, the system boundary and level of detail are determined based on the study's subject and objectives. In this research, the defined system boundary encompasses the structural skeleton, exterior walls, and the structural roof of low-rise residential buildings in Guilan Province .The primary purpose of establishing these boundaries is to ensure a consistent basis for comparison between different material options and to facilitate the identification of optimized, environmentally friendly alternatives. By limiting the scope to fundamental structural components, the study isolates the critical environmental impacts of various construction methods without the influence of secondary factors such as interior finishes or temporary site works . Table 2 provides a summary of the key architectural and structural characteristics of the analyzed buildings, offering a quantitative overview that serves as a foundation for the subsequent environmental impact assessment.

Table 3
System Overview

Objective	**Environmental impact assessment of different residential construction methods**
Application	Guidelines for decision-making on sustainable residential construction methods
Functional Unit	A 99.99 m^2 one-storey residential building
System Boundary	Skeleton, exterior walls, and structural roof of low-rise residential buildings in Guilan Province

To comprehensively evaluate the environmental impacts of low-rise residential buildings in Guilan Province, as previously discussed, this study compares steel-frame and concrete-frame construction methods using openLCA software. These two structural systems were selected due to their prevalence in regional construction and their distinct material compositions, which influence various environmental impact categories For this purpose, a detailed inventory of the inputs and outputs associated with each construction method was compiled. This inventory includes the materials used, energy consumption, and resulting emissions, ensuring a systematic comparison of both structural approaches. The summarized data are presented in Table 3, providing a foundational dataset for the subsequent life cycle impact assessment (LCIA).

Table 4
inventory of the inputs and outputs of concrete and steel frame system

Structural System	Input	Amount	Unit	Output	Output Amount
Concrete	Cement	13793.9	kg	Concrete beams & columns	6.5 m^3
	Water	10403.32	L	Water	1,721.3 L
	Sand	48135.88	kg	External clay brick wall	39.94 m / 108 m^2 / 21.6 m^3
	Gravel	16379	kg	Internal clay brick wall	15.31 m / 42 m^2 / 42 m^3
	Rebar & stirrup	2813.45	kg		
	Clay brick	3724	kg		
	Polystyrene insulation	514.35	kg		
Metal	IPE20	1782.816	kg	Steel beams & columns	
	Rebar	1445.45	kg	Water	1,721.3 L
	Cement	8582.4	kg	External clay brick wall	39.94 m / 108 m^2 / 21.6 m^3
	Sand	34734.88	kg	Internal clay brick wall	15.31 m / 42 m^2 / 42 m^3
	Water	6895.52	L		
	Clay brick	37.24	kg		
	Polystyrene insulation	514.35	m^3		

Inputs

Flow	Category	Amount	Unit
cement mortar	239:Manufacture of non-me...	8582.40000	kg
clay brick - IR	239:Manufacture of non-me...	3724.00000	kg
polystyrene, general purpose	201:Manufacture of basic ch...	514.35000	kg
sand	081:Quarrying of stone, san...	3.47349E4	kg
Steel rebar	Materials production/Metal...	1445.45000	kg
Steel sections	Materials production/Metal...	1782.81600	kg
tap water	360:Water collection, treat...	6895.52000	kg
transport, freight, light commercial v...	492:Other land transport/49...	5567.98162	t*km

Fig. 1. Inventory analysis for concrete frame residential building

Inputs

Flow	Category	Amount	Unit
cement mortar	239:Manufacture of non-me...	1.37939E4	kg
clay brick - IR	239:Manufacture of non-me...	3724.00000	kg
gravel, round	081:Quarrying of stone, san...	4.81359E4	kg
polystyrene, general purpose	201:Manufacture of basic ch...	514.35000	kg
sand	081:Quarrying of stone, san...	1.63790E4	kg
Steel cold rolled coil	Materials production/Metal...	2813.45000	kg
Steel rebar	Materials production/Metal...	2813.45000	kg
tap water	360:Water collection, treat...	1.04033E4	kg
transport, freight, light commercial v...	492:Other land transport/49...	5261.80915	t*km

Fig. 2. Inventory analysis for steel frame residential building

In figures 1 and 2, the inventory regarding both options can be seen in the Openlca software.
After analyzing Table 4, which details the inputs and outputs of concrete and steel frame systems, the inventory analysis conducted using OpenLCA software provides further insights into the environmental impact of these construction methods. The software-generated figures illustrate how material consumption contributes to various environmental burdens, offering a comprehensive visualization of the life cycle inventory (LCI) results. These analyses facilitate a deeper understanding of the role of each material in pollutant emissions and ecological impacts. Subsequently, Table 5 presents the life cycle impact assessment (LCIA) results using the TRACI method, comparing key environmental impact categories between the two structural systems.

Table 5
Environmental impacts of samples in each impact category

Impact Category	Reference Unit	Steel Frame Sample	Concrete Frame Sample	Difference (%)
Acidification	kg SO_2 eq	24.979	29.447	+17.88%
Carcinogenics	CTUh	0.0001875	0.000212	+13.06%
Ecotoxicity	CTUe	55064.828	60250.219	+9.41%
Eutrophication	kg N eq	11.431	14.588	+27.61%
Fossil fuel depletion	MJ surplus	12894.722	13523.459	+4.88%
Global warming	kg CO_2 eq	6993.550	8166.862	+16.78%
Non-carcinogenics	CTUh	0.001152	0.00131	+13.72%
Ozone depletion	kg CFC-11 eq	0.0006484	0.000711	+9.66%
Respiratory effects	kg PM2.5 eq	4.695	5.660	+20.52%
Smog	kg O_3 eq	481.767	574.936	+19.34%

Table 5 provides a comparative analysis of the environmental impacts of steel and concrete structural systems across multiple categories. The most pronounced disparity is found in the ecotoxicity category, where the concrete frame exhibits 5,185.391 CTUe more impact than the steel frame, highlighting its significantly higher environmental burden. Likewise, the fossil fuel depletion and global warming potential categories show substantial differences, with the concrete system exceeding the steel system by 628.737 MJ and 1,173.312 kg CO_2 eq, respectively. These figures underscore the greater resource consumption and greenhouse gas emissions associated with concrete structures. In contrast, the carcinogenics category shows the smallest variation, with a negligible difference of 0.0000245 CTUh, indicating that both structural types have a nearly identical impact in this regard. Similarly, ozone depletion and respiratory effects exhibit relatively minor discrepancies, suggesting that these aspects are less affected by the choice of structural material.

Overall, the findings demonstrate that the concrete frame system has higher environmental impacts in most categories, particularly in global warming, eutrophication, and acidification. These results highlight the critical importance of selecting sustainable construction materials to mitigate environmental harm and promote more eco-friendly building practices.

Table 6
Flows with the highest contribution in the air pollution category

Flow UUID	**Flow**	**Subgroup**	**Unit**	Concrete Frame Emissions	Steel Frame Emissions	**Difference (%)**
4ac6979b-55f2-42ae-8d7e-37846e92506c	Radon-222	Low population density, long-term	kBq	**18,092.71**	**27,575.68**	**+52.4%**
349b29d1-3e58-4c66-98b9-9d1a076efd2e	Carbon dioxide, fossil	Unspecified	kg	**4,779.63**	**0**	N/A
bd64a010-0115-47ca-942f-cbdac1d26b87	Noble gases, radioactive	Low population density	kBq	**0**	**4,916.409**	High

The results of the Life Cycle Assessment (LCA) indicate that both concrete and steel structural systems contribute to environmental pollution, albeit with notable differences in the type and magnitude of emissions. Findings suggest that concrete structures contribute more significantly to carbon dioxide (CO_2) emissions, with levels 16.78% higher than those of steel structures. This disparity is primarily attributed to the extensive use of cement, as concrete frames release 1,173.31 kg more CO_2 per functional unit compared to steel frames. The data highlight a 52.4% higher release of radon-222 in steel structures compared to concrete structures, with emissions reaching 27,575.68 kBq for steel frames versus 18,092.71 kBq for concrete frames. Radon is a radioactive gas and a known carcinogen, with potential health risks in poorly ventilated environments (EPA, 2016). In contrast, due to its mineral composition and lower porosity, concrete emits comparatively lower radon levels .

Conversely, concrete structures exhibit higher emissions of sulfur dioxide (SO_2) and particulate matter (PM2.5). The results indicate that concrete structures contribute 17.88% more to acidification, 27.61% more to eutrophication, and 19.34% more to smog formation than steel structures. These emissions are largely due to the combustion of fossil fuels during cement production and transportation. Additionally, respiratory effects, measured in kg PM2.5 eq, show a 20.52% higher impact in concrete structures. These findings align with similar environmental impact assessments that have identified cement production as a major contributor to air pollution and acid rain (Sandanayake, 2022).

Steel-framed buildings show a significantly higher discharge of tritium (hydrogen-3) into water systems, with 197.48 kBq released, compared to 131.64 kBq from concrete structures, marking a 33.36% increase. Tritium is a radioactive isotope that poses long-term ecological and health hazards, particularly when introduced into aquatic environments (Sanford & Holtgrieve, 2022). Additionally, noble gas emissions, another category of radioactive pollutants, are only present in steel structures, with a total impact of 4,916.41 kBq.

The findings of this study align with prior research on the environmental impacts of structural materials. Guggemos and Horvath (2005) reported that concrete structures exhibit higher CO_2 emissions, whereas steel structures contribute more significantly to radioactive gas release. Similarly, Ige et al. (2024) highlighted the high energy and water consumption in cement production, reinforcing its role in climate change. These studies confirm that both concrete and steel frame systems have distinct yet substantial environmental footprints, necessitating a holistic approach to evaluating their sustainability.

Table 7
Flows with the highest contribution in the water pollution category

Flow UUID	Flow	Source	Unit	Concrete Frame Emissions	Steel Frame Emissions	Difference (%)
2404b41a-2eed-4e9d-8ab6-783946fdf5d6	**Water Discharge**	Unspecified	m³	**11,999.56**	8,808.715	**+36.2%**
152e5a83-96e8-4f54-af42-4f0925a771ac	**Waste Heat**	Surface water	MJ	**306.1286**	197.8549	**+54.68%**
58fabee9-b4b6-48ee-857a-e16ed31bb354	**Hydrogen-3 (Tritium)**	Ocean	kBq	131.6464	**197.4842**	**+33.36%**

The data from Table 8 illustrate that water pollution impacts differ notably between concrete and steel structures. Concrete structures release 3,200.85 m³ more water emissions into the environment than steel structures, indicating a 36.34% higher water consumption. This suggests that concrete production is significantly more water-intensive than steel production. However, the steel frame exhibits a 54.68% higher waste heat discharge into water, with 197.85 MJ compared to 306.13 MJ in concrete structures. Elevated waste heat emissions can disrupt aquatic ecosystems by altering water temperatures and reducing oxygen levels.

Moreover, steel structures show a 33.36% greater tritium emission into water bodies compared to concrete structures. Given that tritium is a radioactive contaminant with long-term ecological effects, its increased presence in steel frame systems highlights a critical environmental concern. While concrete structures contribute more to overall water consumption, steel structures present higher risks related to radioactive contamination.

The findings of this study align with prior research on the environmental impacts of structural materials. Guggemos and Horvath (2005) reported that concrete structures exhibit higher water consumption, whereas steel structures contribute more significantly to radioactive contamination. Similarly, Ige et al. (2024) highlighted the high energy and water consumption in cement production, reinforcing its role in climate change. Studies by Sandanayake (2022) also confirm that concrete-based construction has a significantly higher water footprint, whereas steel structures, despite lower water usage, pose greater risks associated with radioactive emissions and thermal pollution. These studies confirm that both concrete and steel frame systems have distinct yet substantial environmental footprints, necessitating a holistic approach to evaluating their sustainability.

Table 8
Flows with the highest contribution in the soil pollution category

Flow UUID	FLOW	Source	Unit	Concrete Frame	Steel Frame	Difference (%)
dab33577-e9d4-4f6d-b141-a456521d4c1b	**Waste Heat**	Industrial	MJ	18.53688	17.84791	+3.86%
7538ab50-2ef6-4e49-880d-48d5b283a79b	**Unspecified Oils**	Forestry	kg	2.580024	2.37351	+8.7%
7f8fd1ca-0412-4b2e-90fd-a9d294d947a3	**Carbon**	Industrial	kg	0.269502	0.262312	+2.7%

The environmental impact analysis presented in Table 9 highlights the differences in soil pollution contributions between concrete and steel frame structures in low-rise residential buildings. The results indicate that concrete structures exhibit marginally higher emissions across all measured soil pollution categories, including waste heat emissions, unspecified oil discharges, and carbon accumulation.

The data reveal that waste heat emissions in concrete structures are 3.86% higher than those in steel structures (18.54 MJ vs. 17.85 MJ). This difference is primarily attributable to the cement hydration process and the increased energy requirements associated with concrete production (Guggemos & Horvath, 2005). Similarly, unspecified oil emissions, primarily originating from construction machinery and material processing, are 8.7% higher in concrete frames. This suggests that the energy-intensive processes of cement and aggregate extraction contribute significantly to soil contamination (Ige et al., 2024).

Additionally, the carbon emissions to soil, likely due to construction material residues and site preparation activities, show a minor 2.7% increase in concrete structures compared to steel frames. This aligns with findings by Sandanayake (2022), which highlight that concrete-based construction has a higher ecological footprint due to extensive raw material consumption and processing. The relatively lower impact of steel frames in this category can be attributed to the higher recyclability and reuse potential of steel components (Oladazimi et al., 2020).

Comparing these findings with prior studies, the overall trend aligns with existing literature on soil contamination in construction. Research by Mehra et al. (2021) emphasizes that cement-based structures contribute more significantly to soil pollution due to their extensive reliance on raw material extraction and land disruption. Conversely, studies by Ding et al. (2016) suggest that steel structures, while lower in direct soil emissions, pose environmental risks through heavy metal leaching from corroded steel components, an aspect not covered in the current dataset but worth investigating further.

The findings underscore the necessity of sustainable construction strategies to mitigate soil contamination. Implementing measures such as improved waste management, on-site material recycling, and the adoption of alternative low-impact construction materials, such as geopolymer concrete, could significantly reduce the environmental burden associated with conventional concrete structures (Najjar et al., 2022). Furthermore, enhancing soil remediation techniques and optimizing construction processes could contribute to more sustainable building practices.

In conclusion, while the differences in soil pollution levels between concrete and steel frame structures are relatively small, they highlight the broader environmental trade-offs associated with conventional construction materials. Future studies should explore the long-term impact of these pollutants on soil quality and investigate innovative materials that minimize environmental degradation while maintaining structural performance.

Table 6
Contribution of process impacts in concrete frame sample

Impact Category	Clay Brick	Sand	Cement	Gravel	Polystyrene	Water	Land Transport	Rebar
Acidification	2.181	0.281	7.980	1.264	5.952	0.0089	9.815	1.963
Human Health - Carcinogenics	2.14E-04	1.810E-06	7E-05	7.3E-06	4.57E-05	1.5E-07	7.0709E-05	-4.E-06
Ecotoxicity	5661.86	789.305	12368.8	3362.22	4085.907	27.607	33953.419	1.050
Eutrophication	0.886	0.0819	8.007	0.413	0.566174	0.0144	4.495	0.123
Fossil Fuel Depletion	1265.16	77.602	1203.24	507.186	6223.805	2.553	4243.896	
Global Warming	894.529	42.824	2898.45	255.340	1839.936	2.495	2233.277	
Human Health - Non-Carcinogenics	7.6E-05	1.121E-05	0.00040	6.3E-05	5.06E-05	6.7E-07	0.000712	-4.8E-06
Ozone Depletion	8.73E-05	7.383E-06	0.00011	5.2E-05	9.53E-06	1.0E-07	0.000437	
Respiratory Effects	0.296	0.049	2.418	0.232	0.453	0.00604	2.202	
Smog	42.692	7.651	151.444	32.507	74.159	0.117	220.90	45.459

The environmental impact analysis presented in Table 10 highlights that land transport exhibits the highest contribution to categories such as acidification, ecotoxicity, ozone depletion, and smog formation. This is primarily due to the extensive reliance on fossil fuel-based transportation for raw materials, which aligns with findings by Sandanayake (2022), emphasizing transportation as a critical contributor to construction-related emissions .

Additionally, cement production emerges as the dominant factor in global warming potential, eutrophication, respiratory effects, and non-carcinogenic human health impacts. This aligns with Ige et al. (2024), who highlight cement's high CO_2 emissions and water-intensive processing as key environmental concerns.

Moreover, polystyrene demonstrates significant impacts in fossil fuel depletion, smog formation, and acidification. These effects are linked to its petrochemical origins and energy-intensive manufacturing processes, as noted in previous studies (Guggemos & Horvath, 2005). Given the substantial environmental burdens associated with these three processes—land transport, cement, and polystyrene—targeted mitigation strategies such as optimizing transportation logistics, adopting alternative low-carbon cement solutions, and promoting recyclable insulation materials are essential for reducing the construction sector's ecological footprint .

Table 7
Contribution of process impacts in steel frame sample

Impact Category	Clay Brick	Sand	Cement	Polystyrene Joist	IPE Section	Water	Land Transport	Rebar
Acidification	2.18133	0.59641	4.96508	5.952373	-0.00609	0.00595	10.38675	0.896817
Human Health - Carcinogenics	2.1E-05	3.8E-06	4.3E-05	4.58E-05	2.50E-08	9.9E-08	7.48E-05	-2.00E-06
Ecotoxicity	5661.86	1673.87	7695.75	4085.907	0.047284	18.2986	35929.09	-0.00346
Eutrophication	0.88635	0.17374	4.98191	0.566175	-0.00037	0.00959	4.757439	0.056383
Fossil Fuel Depletion	1265.16	164.572	748.645	6223.805		1.69252	4490.839	
Global Warming	894.529	90.8181	1803.38	1839.936		1.65436	2363.227	
Human Health - Non-Carcinogenics	7.6E-05	2.3E-05	0.00025	5.06E-05	-9.60E-09	4.4E-07	0.000754	-2.00E-06
Ozone Depletion	8.7E-05	1.5E-05	7.3E-05	9.54E-06		6.9E-08	0.000463	
Respiratory Effects	0.29629	0.10564	1.50487	0.453538		0.00400	2.330869	
Smog	42.6927	16.2257	94.2267	74.15975	-0.14095	0.07795	233.7566	20.76869

The environmental impact analysis presented in Table 11 highlights that, with the exception of fossil fuel depletion—where polystyrene joists exhibit the highest impact—land transport emerges as the dominant contributor to most impact categories, including acidification, ecotoxicity, eutrophication, human health (carcinogenics and non-carcinogenics), and ozone depletion. This aligns with prior research (Sandanayake, 2022), which underscores the substantial role of material transportation in construction-related emissions.

Additionally, cement remains the leading contributor to global warming and respiratory effects due to its energy-intensive production and high CO_2 emissions, which corroborates findings by Ige et al. (2024). Meanwhile, clay bricks show notable contributions to acidification (2.18133 kg SO_2 eq) and ecotoxicity (5661.86 CTUe), indicating the environmental burden associated with their extraction and firing processes.

A comparative analysis of material contributions in concrete and steel frames reveals distinct patterns. In steel frame systems, the IPE section has negligible or even slightly negative impacts in categories such as acidification and eutrophication, likely due to the high recyclability and lower embodied energy of steel (Guggemos & Horvath, 2005). Conversely, in concrete frame structures, cement plays a significantly greater role in categories such as global warming and eutrophication, reinforcing its status as one of the most environmentally intensive materials in the construction sector.

Overall, the findings indicate that land transport remains a critical factor in the environmental footprint of both structural systems, while specific materials—such as cement in concrete frames and IPE sections in steel frames—contribute to variations in impact intensity across different categories. These results highlight the need for sustainable transport strategies, alternative low-carbon cement formulations, and increased use of recycled materials to mitigate environmental impacts.

4. Conclusion

This study conducted a Life Cycle Assessment (LCA) to evaluate the environmental impacts of conventional concrete and steel frame structures in low-rise residential buildings within Guilan Province, Iran. The findings highlight significant trade-offs between these two structural systems, with concrete frames contributing more substantially to carbon dioxide emissions, acidification, eutrophication, and respiratory effects due to the cement production process. In contrast, steel frames are associated with higher emissions of radioactive pollutants, such as radon-222 and tritium, posing potential health and environmental risks.

A key observation is that land transport has the highest environmental impact across multiple categories, including acidification, ecotoxicity, eutrophication, and smog formation. This result is consistent with prior research (Sandanayake, 2022), which emphasizes the significant contribution of transportation to construction-related emissions. Additionally, cement production remains the leading contributor to global warming and eutrophication, corroborating findings from Ige et al. (2024), who highlight the energy-intensive nature of cement manufacturing. Studies by Najjar et al. (2022) also confirm that the cement industry is a major driver of CO_2 emissions and advocate for alternative materials to reduce its environmental burden.

When comparing the two structural systems, concrete frames exhibit higher impacts on greenhouse gas emissions and resource depletion, while steel structures contribute more significantly to radioactive contamination. This distinction aligns with the findings of Guggemos & Horvath (2005), who demonstrated similar environmental trade-offs between these materials in construction. Furthermore, regional studies on Middle Eastern construction practices (AbdolkhaniNezhad et al., 2022) indicate that local climate and material availability play crucial roles in determining sustainability outcomes, reinforcing the need for region-specific solutions.

To mitigate these environmental burdens, several strategies should be considered. Optimizing transportation logistics and prioritizing locally sourced materials can substantially reduce emissions from material transport. Moreover, alternative construction materials—such as geopolymer concrete, recycled steel, and other innovative options that may be explored in future studies—offer promising pathways for lowering the carbon footprint of buildings. In addition, ventilation improvements in steel-framed buildings may help alleviate health risks associated with radon emissions. Collectively, these strategies highlight the potential of adopting sustainable practices to advance healthier and more environmentally responsible built environments.

Although this study focused on environmental impacts, it is worth noting that Guilan's high humidity may negatively affect the durability and performance of concrete and steel structures. Considering this factor is beyond the scope of the current research and is recommended for future studies.

Overall, this study contributes to the ongoing discourse on sustainable construction by providing empirical data on the environmental trade-offs between concrete and steel frames in Iran. Future research should focus on expanding regional LCA databases, exploring hybrid structural systems that balance sustainability and performance, and investigating emerging technologies in material science to develop low-impact alternatives. Achieving long-term sustainability in the construction sector requires an integrated approach, combining material innovations, efficient building design, and sustainable supply chain management to minimize environmental impacts while ensuring durability and cost-effectiveness.

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