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ARTICLE

Environmental Impact Assessment of Building Materials Using Life Cycle Assessment

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ABSTRACT

In pursuit of environmental sustainability in the construction sector, this study employs a comprehensive life cycle assessment (LCA) approach to evaluate the environmental impact of widely used building materials in Iran, with a particular focus on energy consumption and carbon footprint. The investigation encompasses 22 widely used building materials, utilizing the Ecoinvent v3 database and Simapro8 software to assess critical environmental variables, including carbon dioxide (CO_2) emission, required primary energy, water consumption, and thermal conductivity. The findings unveil the diverse environmental profiles of these materials, with thermal conductivity typically hovering around zero to 2 W/m.K for most, but with exceptions such as lime, aluminum, rebar, and steel exhibiting significantly higher values. Moreover, aluminum, ceramics, PVC pipe, and expanded polystyrene (EPS) foam are identified as higher energy consumers during their life cycle, in contrast to concrete and cement mortar characterized by lower primary energy demands. The materials identified as high-carbon building materials are steel, stone, plaster, rebar, bitumen, concrete, glass, cement, gravel, and EPS foam. On the other hand, the materials identified as low-carbon building materials are masonry blocks, wood, tiles, bricks, drywall, MDF, and cement mortar. This research provides valuable insights for material selection and sustainable construction practices, emphasizing low-carbon materials to reduce environmental impact and contribute to the global effort to mitigate climate change through responsible construction choices.

Keywords: Environmental assessment; Low carbon materials; Carbon footprint; Building materials; Life cycle assessment; Energy consumption

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1. Introduction

Global warming, a pressing issue, necessitates the exploration of various avenues to curb greenhouse gas emissions, including architectural practices, technology, and renewable energy adoption [1]. Iran's energy consumption exceeds the global average by a staggering four to fivefold, partly due to inexpensive fuel and subsidies, ranking it among the top contributors to carbon emissions [2-5]. The construction industry is a major source, responsible for over 35 percent of global emissions during the life cycle of structures [6], significantly impacting energy consumption and the environment [7,8]. Buildings represent nearly 40% of primary energy use and about 70% of electricity, a trend that continues with rapid population growth and construction [9]. Notably, urban carbon emissions primarily originate from buildings and transportation [7,10,11].

Understanding and mitigating the carbon footprint is vital for environmental and energy research [12,13]. Eco-conscious management can reduce this footprint, fostering environmental sustainability [14]. Essentially, green management embodies the environmental performance of organizations and companies, orienting their operations towards reduced energy consumption, efficient water use, and optimal resource utilization [15]. Low carbon architecture, with net-zero energy consumption and no annual carbon emissions, relies on on-site energy generation and energy-efficient systems [16,17]. Environmental building materials are key in enhancing construction value and minimizing energy-related impacts [18]. The entire life cycle of materials, from production to demolition, affects energy consumption, greenhouse gas emissions, and global warming potential [19]. Life cycle assessment (LCA) systematically evaluates material and energy flows within a system.

Selecting sustainable materials and designs is crucial to reducing a project's carbon footprint [20]. As the global population grows and energy demand rises, particularly in the building sector, assessing thermal and cooling loads is vital in the design process [21].

The choice to investigate building materials in the Iranian context is particularly pertinent due to the country's unique energy consumption patterns and construction practices. Iran's distinct characteristics, such as its soaring energy consumption rates, disproportionate per capita energy use, and the influence of government subsidies, make it a compelling case study. Additionally, Iran's construction practices, which may differ from more developed economies, offer insights into optimizing environmental performance in rapidly growing regions. Therefore, this research seeks to bridge the knowledge gap and offer valuable insights applicable not only to Iran but also to similar contexts worldwide, where economic, political, and industrial factors intersect in shaping energy consumption and construction practices.

The present research aims to study the environmental impacts of building materials in Iran using life cycle assessment. This study investigates and categorizes the most widely used building materials in terms of thermal conductivity, required primary energy, carbon footprint, and required water. The research outcomes have the potential to promote low-carbon materials in residential construction, contributing to environmentally sustainable green buildings.

2. Literature review

In 2014, Solís-Guzmán conducted a study examining the carbon footprint associated with residential building construction in Spain [22]. In this research, a novel approach was introduced for evaluating the product life cycle to quantify the carbon footprint, allowing for the measurement of greenhouse gas emissions stemming from construction projects. This methodology involves the computation of carbon footprint about resource utilization and waste generation. Following the adoption of this approach, individual elements, such as water, energy, food, transportation, construction materials, and waste, were scrutinized separately. The findings underscored the substantial impact of construction materials on carbon emissions, while other contributors to the carbon footprint included machinery, electricity, and food.

Similarly, Zhao et al. investigated the carbon footprint of industrial sites across various regions of China, leveraging energy consumption data [23]. Initially, they devised a model to estimate carbon emissions resulting from fossil fuel usage in different Chinese regions, subsequently assessing greenhouse gas emissions through ecological footprint indicators. Their research revealed that the cumulative carbon emissions attributable to fossil fuels and energy consumption within residential and commercial zones accounted for a striking 89.12% of the total carbon emissions.

Sinha et al. conducted an assessment of the environmental impact of building structures [24]. Their research approach involved a comparative analysis between the environmental footprint estimations derived from the simplified Environmental Load Profile of Building Structures (ELP-s) and those generated using commercially available Life Cycle Assessment (LCA) software, GaBi and SimaPro. The study focused on two reference buildings constructed from concrete and wood, with a particular emphasis on material selection and the simplification of the analytical tool. The study findings revealed that wood products consumed more energy when compared to other materials employed in the construction of wooden buildings. Notably, materials such as Gulam, plasterboard, stone wool, and transportation exhibited considerably larger carbon footprints than other elements utilized in constructing wooden buildings.

Pawar et al. conducted a study on the utilization of Phase Change Materials (PCMs) to enhance the energy efficiency of buildings, particularly by integrating PCMs into building materials such as bricks [25]. PCMs, characterized by their high density and isothermal properties during phase change, offer promising potential for energy conservation. The research involved experiments with three-chamber types using normal, grooved, and PCM-treated grooved bricks. Results indicated that PCM-treated grooved bricks significantly improved heat retention within buildings during hot summer conditions, highlighting the efficacy of PCM-infused building materials in boosting energy efficiency.

Ghanbari et al. delved into the environmental ramifications, specifically energy consumption and CO_2 emissions, associated with the production of natural and recycled aggregates through the application of Life Cycle Assessment (LCA) [26]. The research outcomes highlighted a noteworthy reduction of 30% and 36% in annual energy consumption and carbon dioxide emissions in Iran when recycled and natural aggregates were employed in construction, as opposed to solely relying on natural aggregates.

Sizirici et al. conducted a comprehensive review of strategies aimed at reducing the carbon footprint within the construction industry, encompassing phases from design to operation [27]. They identified a range of techniques and systems for carbon reduction and found that the mining and manufacturing of materials and chemicals were responsible for substantial energy consumption, contributing to a staggering 90% of the total CO_2 emissions. Importantly, the study underscored the potential for significant environmental benefits through fundamental alterations in the production of construction materials, the recycling of construction waste, and the incorporation of alternative additives in building materials.

Sudarsan et al. conducted an investigation centered on sustainable building materials to promote carbon neutrality in India [6]. They argue that eco-friendly materials serve as effective alternatives to facilitate carbon neutrality. In an effort to mitigate embodied carbon emissions, they proposed an alternative approach involving the utilization of sustainable materials such as Ferrock and recycled steel.

Ranjetha et al. explored the utilization of low-carbon products to enhance construction sustainability [28]. They advocate for achieving sustainability through the incorporation of locally available waste or industrial by-products as either partial or complete replacements for conventional materials. Their assessment encompassed the construction system and the application of sustainable building materials within the context of the Low-Cost Model House & Geopolymer Concrete House, highlighting the advantages in terms of environmental impact, economic considerations, and social aspects. Overall, their findings indicate that the adoption of green technology and the integration of waste by-products into concrete confers numerous benefits.

In contemporary construction projects, the adoption of Building Information Modeling (BIM) has gained significant popularity. BIM is employed for designing and executing optimal and sustainable construction projects, thereby increasing production efficiency, infrastructure stability, and quality, and reducing recycling costs and repetitive tasks within the construction sector [28]. In Iran, numerous stakeholders in the construction industry are actively investigating the impact of BIM on cost control and reduction, ultimately aiming to enhance the cost-benefit ratio in their construction endeavors [30,31]. BIM represents a comprehensive collaborative approach within the construction sector, and despite its relatively short history, it has experienced substantial growth over the past decade, primarily attributable to its capabilities in construction projects. BIM functions as a common language that unifies all project stakeholders and system divisions, fostering a harmonized project team [32,33].

However, it is worth noting that, despite the global importance of Building Information Modeling and its associated training, this emerging trend, particularly the aspect of training, has been somewhat overlooked in Iran [34].

Table 1 provides a subjective comparison between the present study and superior published papers to highlight the distinct features, methodologies, and contributions of the present research about existing literature.

Table 1. Comparative analysis of current study and superior published papers.

Criteria	The present study	[6]	[18]	[21]
Drivers	Environmental sustainability in construction sector	Emphasizes the importance of sustainable building materials for carbon neutrality in the Indian scenario.	Identifies the exponential increase in technological development and human population as drivers for environmental concerns.	Addresses global issues of energy availability and environmental threats, emphasizing the need for companies to reduce waste, energy consumption, and emissions.
Limitations	Iran’s unique energy consumption patterns, construction practices	Discusses limitations of the study, such as the challenge of obtaining accurate data and the complexity of the construction industry.	Identifies limitations, including the complexity of LCA and the challenges in its implementation, especially in the early stages of product development.	Acknowledges the quantitative differences in values obtained from different databases and emphasizes the focus on decision-making path rather than absolute numerical differences.
Problem statement	Mitigating carbon emissions in urban areas, sustainable construction materials	Focuses on promoting carbon neutrality in the Indian construction scenario through sustainable building materials.	Discusses the importance of sustainable production and materials selection in eco-friendly product development.	Highlights the challenges in early environmental impact assessment during material selection and proposes the EcoAudit tool as a solution.
Methodology tools	Life Cycle Assessment (LCA) using Simapro8 software, Ecoinvent v3 database	Not explicitly discussed in the provided context.	Utilizes Life Cycle Assessment (LCA) methodology and the EcoAudit tool for environmental impact assessment.	Uses a comparative validation method based on eight published LCA evaluations, employing the EcoAudit tool for early environmental impact assessment.
Technical evaluation parameters	Thermal conductivity, required primary energy, carbon dioxide emissions, water consumption	Not explicitly discussed in the provided context.	Discusses embodied energy and carbon footprint as key indicators for environmental impact assessment.	Introduces embodied energy and carbon footprint as metrics for pre-assessing environmental impact in the conceptual stage of product development.
New contribution	Comprehensive assessment of 22 building materials in the Iranian context	Emphasizes the importance of sustainable materials for carbon neutrality in the Indian construction context.	Highlights the significance of using dedicated software for pre-assessing environmental impact in the conceptual stage of product development.	Introduces the EcoAudit tool as a simplified approach for early environmental impact assessment, contributing to faster and reliable information during material selection.

3. Materials and method

3.1 Life cycle assessment approach

Life Cycle Assessment (LCA) stands as a standardized and widely accepted method for the environmental evaluation of processes, products, and services. It constitutes the third element of a comprehensive sustainability assessment, following technical and economic evaluations [35,36].

By ISO 14040 and ISO 14044 standards, Life Cycle Assessment unfolds through four distinct stages [35]: 1) defining the goal and scope, 2) inventory analysis, 3) impact assessment, and 4) interpretation.

The categorization of life cycle assessment into four distinct types, namely: 1) cradle to grave, 2) cradle to gate, 3) gate to gate, and 4) cradle to cradle, hinges upon the specific purpose and scope of the study. These classifications differ primarily in their selection of the system boundaries applied [35].

During the initial stage of defining goals and scope, the products and processes subject to evaluation are initially identified. Subsequently, the functional unit is chosen, and the requisite level of assessment is established.

In a comprehensive and idealized life cycle assessment, often referred to as "cradle to grave", the life stages of building systems typically encompass the following sequence: raw material extraction, material production, construction activities, operational use, and end-of-life considerations. However, it's essential to note that this study primarily focuses on comparing energy consumption and carbon dioxide production associated with various building materials, with specific attention to materials used in construction. As a result, the research scope is specifically limited to the stages of raw material extraction, material production, and construction operations.

3.2 Widely used building materials

The initial pivotal step in the execution of this research involves the selection and ranking of the most commonly employed construction materials in Iran for environmental assessment. To achieve a comprehensive compilation and identification of these crucial construction materials, two distinct approaches may be considered. The first approach hinges on the guidance outlined in section 5 of Iran's Office of National Building Regulations, which pertains to construction materials and products [37]. The second approach relies on the classification of prevalent and extensively utilized materials within the domains of architecture, structural engineering, and building infrastructure in Iran.

Based on the combined insights derived from the two aforementioned sources as acknowledged by the author of the present study, a comprehensive list comprising the 22 most used building materials in Iran is presented in **Table 2**.

Table 2. The 22 most widely used building materials in Iran.

No.	Material	No.	Material
1	Steel	12	Cement mortar
2	Concrete	13	Rebar
3	Glass	14	Plaster
4	Wood	15	Stone
5	Brick	16	Masonry block
6	Cement	17	Gravel
7	Ceramics	18	Sand
8	Tile	19	Drywall (Gypsum board)
9	Aluminum	20	Expanded Polystyrene (EPS) foam
10	PVC pipe	21	Bitumen
11	Lime	22	Medium-density fibreboard (MDF)

3.3 Data analysis method

In the Simapro software, the calculation of primary energy is based on the Cumulative Energy Demand (CED) method, wherein the total demand is assessed as primary energy. This software also computes the greenhouse effect attributed to CO_2 emissions resulting from human activities, quantifying them in terms of their Global Warming Potential (GWP). For this specific study, the GWP index has been evaluated in alignment with the characteristic factors outlined by the IPCC (International Panel on Climate Change) for the year 2023, considering a time horizon of 100 years. Within the context of

Iran's construction sector, water consumption emerges as a crucial concern. The chosen indicator for this study encompasses all fresh water sourced from various origins (rivers, lakes, oceans, and wells), encompassing water employed for cooling processes.

In the present research, the selected functional unit corresponds to one kilogram of construction materials, with a comprehensive analysis of various stages, including material production at the factory, transportation from the factory to the construction site, the construction process, demolition of the building, and final product disposal. During the construction phase, detailed examination encompasses aspects such as raw material procurement, transportation, and construction processes. To calculate the energy consumption of materials, the data related to the latent energy of the material unit, transportation energy, which includes the fuel consumption of machines; and also the energy of building construction is given to the software to evaluate the total energy consumption. In terms of material transportation from the factory to the construction site, the study accounts for the use of 20-28 ton trucks, considering an average travel distance of 100 kilometers.

Table 3 displays the values employed to assess the impact of transporting one ton of material via different modes of transportation, represented through a linear correlation (Equation 1). Here, "d_i" signifies the distance covered by each mode of transport (in kilometers), while "m_i" denotes the coefficients assigned to each mode of transportation.

Table 3. Impact coefficients for the transportation stage of one ton of materials from the factory to the building construction site.

Variable	By truck (m_1)	By rail (m_2)	By ship (m_3)
Required primary energy (Mj-Eq/km)	3.266	0.751	0.17
Global warming potential (kg CO_2-Eq/km)	0.193	0.039	0.011
Required water (l/km)	1.466	1.115	0.097

$$(m_1 \times d_1) + (m_2 \times d_2) + (m_3 \times d_3) = Transport\ Impact \quad (1)$$

As illustrated in Equation (1), the software undertakes an analysis of transportation impact by considering a combination of three transportation modes: truck, rail, and ship, with a standardized distance of 100 kilometers. The calculated density for each material is expressed in kilograms per cubic meter.

The calculation of thermal conductivity for materials, denoted in W/m.K, is determined using Equation (2). In this equation, "K" represents the thermal conductivity constant, "t_2" and "t_1" denote the temperature disparities on either side of the material, and "L" signifies the thickness or distance.

$$q = -K \frac{t_1 - t_2}{L} \quad (2)$$

The unit for required primary energy is Mj-Eq/kg, carbon dioxide emissions are measured in kg CO_2-Eq/kg, and water consumption is quantified in liters per kilogram.

4. Results and discussion

Table 4 presents the computed values for thermal conductivity, required primary energy, global warming potential (expressed as carbon dioxide emission rate), and water consumption associated with each building material. These values have been derived from an analysis conducted using the Simapro software and are based on data sourced from Ecoinvent.

Figures 1 to 4 illustrate the comparative analysis of thermal conductivity, necessary primary energy, CO_2 emissions, and water consumption for the 22 building materials. As depicted in **Figure 1**, the thermal conductivity of the majority of construction materials either approaches zero or falls within the zero to 2 W/m.K range. However, four materials, namely lime, aluminum, rebar, and steel, notably deviate from this trend, with lime exhibiting the highest thermal conductivity. According to the output presented in **Table 4**, and possesses the lowest thermal conductivity.

The differences in thermal conductivity among the materials are primarily influenced by their inherent physical properties. Materials with high thermal conductivity, like steel and aluminum, possess densely packed structures that facilitate efficient heat transfer, making them suitable for specific applications. Conversely, materials with low thermal

Table 4. Life cycle environmental assessment for widely used building materials.

No.	Material	Density (kg/m^3)	Thermal conductivity (W/m.K)	Required primary energy (Mj-Eq/kg)	Carbon dioxide (kg CO_2-Eq/kg)	Required water (l/kg)
1	Brick	1800	0.95	3.56	0.27	1.89
2	Sand	1020	0.29	6.27	0.09	1.42
3	Masonry block	1530	0.70	2.18	0.12	2.05
4	Gravel	30	0.04	15.65	0.82	14.45
5	Tile	2100	1.50	2.20	0.29	3.01
6	Drywall (Gypsum board)	2380	1.65	2.66	0.27	4.10
7	Bitumen	1800	0.50	11.54	1.39	20.37
8	Cement	3150	1.40	4.24	0.86	3.94
9	Cement mortar	1525	0.70	2.17	0.24	3.94
10	Concrete	2380	1.65	1.11	1.14	3.01
11	Stone	60	0.04	26.39	1.51	32.38
12	Wood	600	0.13	21.00	0.20	5.12
13	Ceramics	2000	1.00	105.49	7.34	39.73
14	Plaster	60	0.04	26.39	1.51	32.38
15	Expanded Polystyrene (EPS) foam	150	0.05	51.52	0.81	30.34
16	Medium-density fibreboard (MDF)	600	0.13	18.40	0.27	5.12
17	Rebar	6500	60.00	22.34	1.43	24.19
18	Steel	7900	50.00	24.34	1.53	26.15
19	Aluminum	2700	239.00	136.80	8.57	214.34
20	PVC pipe	1400	0.17	73.21	4.27	512.00
21	Glass	2500	0.95	15.51	1.14	16.54
22	Lime	8920	380.00	35.59	2.00	77.79

conductivity, such as sand and gravel, have loosely packed, insulating compositions that impede heat flow. These inherent characteristics dictate a material's performance in terms of energy efficiency, making it crucial to consider thermal conductivity when selecting materials for construction to achieve desired environmental and energy-related outcomes.

Figure 2 reveals that aluminum boasts the highest demand for primary energy throughout its life cycle, followed by ceramics and PVC pipe. Conversely, concrete and cement mortar exhibit the lowest required primary energy. Materials like concrete and cement mortar require lower primary energy due to their abundant availability and energy-efficient production processes. Conversely, aluminum, ceramics, and PVC pipe demand higher primary energy, largely because of the energy-intensive extraction, processing, and manufacturing involved in their production.

Figure 3 provides insights into the carbon dioxide emission associated with various building materials. Notably, aluminum emerges as the most significant contributor to CO_2 emission within the realm of building materials. Following closely are ceramics, PVC pipe, and lime, all occupying subsequent ranks. Moreover, materials such as steel, stone, plaster, rebar, bitumen, concrete, glass, cement, gravel, and EPS foam fall into the category of high-carbon building materials. Conversely, after sand, which exhibits minimal CO_2 emission, masonry blocks and wood belong to the classification of low-carbon building materials. Materials like tiles, bricks, drywall, MDF, and cement mortar also qualify as low-carbon building materials.

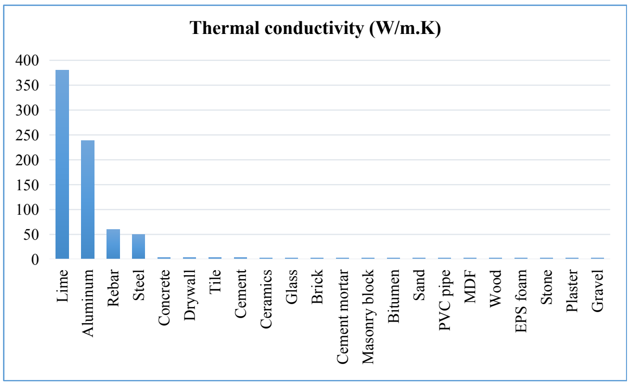

Figure 1. Comparison of thermal conductivity of widely used building materials.

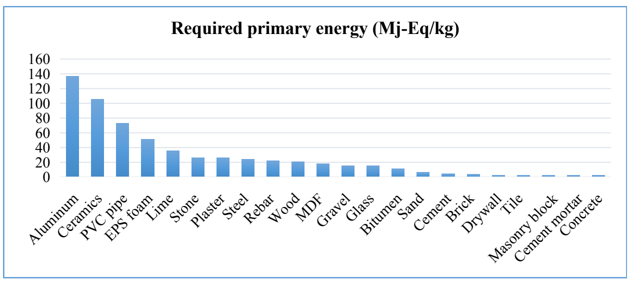

Figure 2. Comparative assessment of required primary energy across widely used building materials.

High-carbon materials like aluminum, ceramics, and PVC pipe often involve energy-intensive extraction and manufacturing processes, contributing significantly to their carbon emissions. In contrast, low-carbon materials like sand, masonry block, and wood have more environmentally favorable characteristics, such as lower energy consumption during production.

Figure 4 depicts the comparative evaluation of water consumption during the life cycle of these building materials. Notably, PVC pipe, aluminum, and lime exhibit the highest water consumption levels, while sand and brick demonstrate the lowest water usage. Materials like sand and brick have lower water consumption due to their natural composition and simpler production methods. In contrast, materials like aluminum, PVC pipe, and lime require more water as their production processes, which often involve mining, refining, or chemical treatments, are inherently water-intensive.

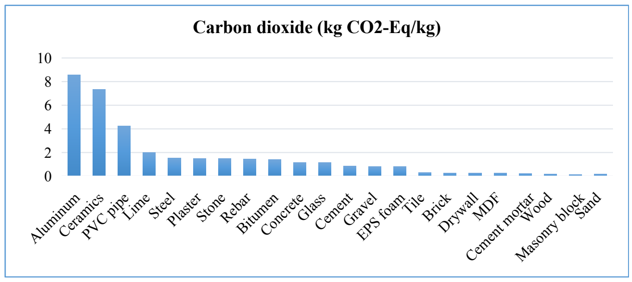

Figure 3. Ranking of widely used building materials in terms of carbon dioxide emissions.

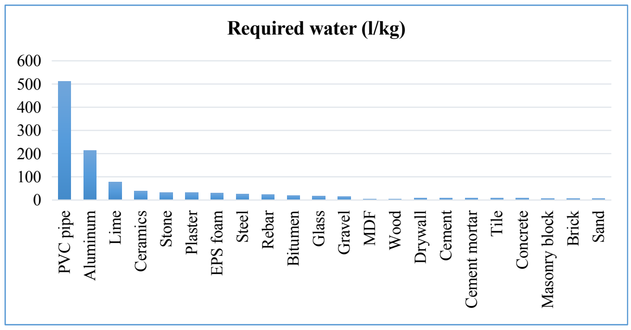

Figure 4. Comparison of widely used construction materials in terms of required water.

5. Conclusions

Recent years have witnessed a growing emphasis on mitigating carbon emissions in urban areas as part of the broader environmental sustainability agenda. Sustainable construction materials, known for their low carbon footprint, not only enhance the value of construction projects but also mitigate their environmental repercussions. Throughout the entire life cycle, from production to disposal, construction materials exert substantial environmental impacts, and the choice of construction methods significantly influences energy consumption and greenhouse gas (GHG) emissions.

The present study delved into the environmental assessment of commonly used building materials in Iran, employing the life cycle assessment methodology. The environmental evaluation relied on data from the Ecoinvent v3 database within the Simapro8 software. The key environmental variables scrutinized encompassed: 1) carbon dioxide emission, 2) required primary energy, 3) water consumption throughout the life cycle, and 4) thermal conductivity. The investigation encompassed 22 frequently employed construction materials in Iran, enabling a comparative analysis of these environmental factors.

The environmental assessment unveiled that, for most widely used building materials, thermal conductivity typically hovers around zero or falls within the range of zero to 2 W/mK. However, four materials namely lime, aluminum, rebar, and steel, have emerged as exceptions, displaying the highest thermal conductivity values. Consequently, material selection, particularly for external layers of buildings, warrants careful consideration. In terms of required primary energy during their life cycle, aluminum, ceramics, PVC pipe, and expanded polystyrene (EPS) foam proved to be more energy-intensive compared to their counterparts. Conversely, concrete and cement mortar have been associated with the least required primary energy.

Environmental analysis categorized materials into low-carbon and high-carbon categories, with low-carbon materials encompassing sand, masonry block, wood, cement mortar, medium-density fiberboard (MDF), drywall (gypsum board), brick, tile, expanded polystyrene (EPS) foam, gravel, cement, glass, concrete, bitumen, rebar, plaster, stone, steel, lime, PVC pipe, ceramics, and aluminum. The carbon neutrality of wood can be attributed to its organic matter content, while sand's low greenhouse effect is linked to its organic constituents. Notably, concrete and steel emerged as relatively high-carbon materials. Additionally, it was observed that PVC pipe, aluminum, and lime exhibit the highest water consumption throughout their life cycle, while sand and brick materials display the lowest water consumption.

The findings provide builders, policymakers, and stakeholders with valuable insights to make more sustainable choices. Builders can prioritize low-carbon materials like wood, sand, and masonry block, and implement energy-efficient construction practices. Policymakers should consider incentivizing the use of such materials through regulations and incentives, promoting sustainable building practices. Stakeholders can advocate for the adoption of environmentally friendly construction materials and practices. Additionally, it is recommended to establish policies that encourage research and development in sustainable construction materials and methodologies, fostering innovation in the industry. For future research, investigators can delve into the specific environmental and economic implications of these materials in Iranian construction projects, as well as explore advanced technologies and alternative materials that align with low-carbon objectives. Furthermore, investigating the integration of low-carbon materials in larger infrastructure projects and assessing their long-term performance could yield valuable insights for the industry.

Conflict of Interest

There is no conflict of interest.

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