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Life cycle assessment (LCA) in construction materials – Review

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Abstract. The construction industry is one of the most impactful sectors in terms of natural resource consumption and greenhouse gas emissions, demanding more sustainable and efficient solutions. This study systematically reviews the applicatication of Life Cycle Assessment (LCA) to evaluate sustainable materials and practices within the construction sector, emphasizing the replacement of tradicional materials with recycled, bioeconomic, and low-carbon alternatives. A systematic review was conducted using the Scopus database, covering studies published between 2020 and September 2024. The methodology included the use of VOS viewer software to generate keyword co-occurrence maps, aiding in the identification of emerging trends and patterns.

Key findings indicate substantial environmental benefits from incorporating industrial wastes, agricultural by-products, and bioeconomic materials, demonstrating substantial reductions in CO_2 emissions, energy consumption, and natural resource usage. The analysis also highlights emerging technologies, such as 3D printing and nanotechnology, as innovative tools that further enhance sustainability in construction. However, challenges persist, including limited availability of reliable regional data, methodological complexities, and gaps in integrating socio-economic variables into LCA analyses. This paper contributes to advancing sustainable construction by identifying critical gaps and challenges, proposing strategies for improved data collection, recommending enhanced interdisciplinary collaboration, and suggesting increased governmental support and regulatory frameworks to promote broader adoption of LCA in industry practices.

Key words: circular economy, construction materials, life cycle assessment, sustainability, waste.

INTRODUCTION

The construction industry is one of the most impactful sectors in terms of natural resource consumption, greenhouse gas emissions, and waste generation. In response to these environmental challenges, the search for more sustainable and efficient alternatives has become a global priority. In this context, Life Cycle Assessment (LCA) has emerged as an essential tool for holistically evaluating the environmental impacts of materials and processes used in construction, being conducted in accordance with the guidelines established by international standards ISO 14040 and ISO 14044. For the assessment of building sustainability, the EN 15643:2021 standard is also applied, ensuring a standardized and comparable approach. LCA provides a comprehensive approach, considering all phases of the life cycle of construction materials, such as production, use, maintenance, and disposal, contributing to the identification of opportunities for mitigating environmental impacts (ISO, 2006a, 2006b; CEN, 2021; Monteiro et al., 2022; Mishra et al., 2023).

In recent years, the application of Life Cycle Assessment (LCA) has expanded to encompass a variety of materials and technological innovations, with a focus on the use of industrial waste, agricultural by-products, and bioeconomic materials. For instance, studies have demonstrated that incorporating waste such as fly ash and slag into cementitious composites can significantly reduce CO_2 emissions and energy consumption compared to traditional materials (Li et al., 2022; Navaratnam et al., 2023). Additionally, bioeconomic materials such as timber and soil-cement have been analyzed using LCA, highlighting their potential to lower environmental impacts and promote circular economy practices (Leão et al., 2022; Mitterpach et al., 2022).

In this context, the use of natural fibers in construction materials has also been identified as a sustainable alternative. Studies such as Ferreira et al. (2021) conducted a bibliometric analysis on the use of plant-based fibers and their application in construction materials. Rocha et al. (2021) evaluated the use of açaí fiber in mortars, while Azevedo et al. (2021) tested pineapple fiber in the same construction material, both demonstrating the potential of these fibers to promote greater sustainability in the sector.

The relevance of this topic is underscored by the urgent need to foster sustainable practices in construction, given the growing demand for resources and the challenges posed by climate change. Developing more sustainable cementitious composites, utilizing recycled materials, and incorporating emerging technologies such as 3D printing and nanotechnology require a thorough assessment of their environmental impacts and life cycle benefits (Monteiro et al., 2022; Kalthoff et al., 2023). In this context, reviewing recent studies that employ LCA is essential to consolidate knowledge and guide future research and public policies aimed at promoting sustainability in the construction sector.This article aims to review the use of LCA in evaluating materials and sustainable practices in construction, with an emphasis on replacing natural resources with recycled, bioeconomic, and low-carbon alternatives. The goal is to provide a comprehensive overview of recent advances and highlight key trends and opportunities for mitigating environmental impacts in the construction industry.

MATERIALS AND METHODS

The research was conducted using the Scopus database, selected for its comprehensiveness and relevance in publishing scientific articles in the fields of Civil Engineering, Sustainability, and LCA. The search was performed using the following keywords: 'life cycle assessment' and 'construction materials', covering a five-year period from 2020 to 2024 to ensure that the results reflect the most recent research in the field.

After the initial collection of results, the following inclusion criteria were applied: studies published between 2020 and 2024 (up to September 2024); publications in the form of original research articles and review articles; studies focusing on the life cycle assessment (LCA) of construction materials such as bricks, concrete, mortar, and other conventional or alternative materials.

The exclusion criteria included: studies that did not apply the full LCA methodology or focused solely on building energy performance without considering construction materials; studies addressing construction methods without detailed material analyses; works not available in full-text format; and duplicate entries.

The initial search yielded 422 articles, which underwent a screening process. To ensure the review maintained its focus, 286 articles were retained after applying the aforementioned inclusion and exclusion criteria.

The analysis of the articles was conducted to identify trends in the application of LCA across different types of materials, as well as the effectiveness of sustainable alternatives. Quantitative data were extracted and organized into comparative tables, highlighting environmental impact indicators and the methods of data collection and analysis used in the selected studies.

A keyword co-occurrence analysis was performed using the VOSviewer® software to identify patterns of relationships between terms, map the core themes of the study, and explore conceptual connections within the research field.

RESULTS AND DISCUSSION

Methodologies and impact assessment methods in LCA

LCA is a structured methodology used to evaluate the potential environmental impacts of a product or service throughout its entire life cycle, from cradle to grave. During the development of LCA, various LCIA (Life Cycle Impact Assessment) methodologies have become prominent, each emerging from a specific institutional or geographical context and incorporating different impact categories. Table 1 below summarizes the characteristics of some of the most commonly used LCIA methods internationally – including their scope (midpoint, endpoint, or hybrid), considered categories, and main references:

The ISO 14040:2006 and ISO 14044:2006 standards establish the framework and requirements for conducting Life Cycle Assessment (LCA) studies in a consistent and comparable manner. In particular, ISO 14040 defines the principles and framework of LCA, while ISO 14044 details the requirements and guidelines for its implementation. These standards divide an LCA into four distinct phases - goal and scope definition, inventory analysis, impact assessment, and interpretation - ensuring a systematic and comprehensive approach (ISO, 2006a, ISO, 2006b), as illustrated in Table 2.

Table 1. Methodologies in Life Cycle Assessment (LCA)

LCA Methodology	Description	Advantages	Disadvantages
Process-Based LCA	Uses process inventories to quantify inputs and outputs throughout the life cycle	Provides a detailed and specific assessment of products and processes. Follows a standardized approach (ISO 14040/14044)	May suffer from system boundary truncation, excluding indirect impacts. Data collection can be expensive and time-consuming.
Input-Output LCA (IO-LCA)	Based on economic input-output tables to assess environmental impacts across entire economies	Captures full supply chain effects and allows macroeconomic evaluation of environmental impacts in sectors	Lower resolution for specific products, as it relies on aggregated economic data that may obscure details
Hybrid LCA	Integrates Process-Based LCA with Input-Output LCA	More comprehensive modeling, combining high-resolution process data with economy-wide system coverage. Overcomes individual limitations of Process-Based and IO-LCA	Requires complex computation and extensive data integration, making it resource-intensive
Consequential LCA (C-LCA)	Evaluates indirect impacts and systemic changes resulting from a decision or policy	Used in environmental policy studies and demand change scenarios. Captures secondary and long-term effects.	High uncertainty due to scenario assumptions. Defining system boundaries is complex, as it must account for market-driven responses
Attributional LCA (A-LCA)	Analyzes direct environmental impacts associated with a product or process	Standardized methodology, widely used for footprint assessments of specific products	Does not consider indirect effects, market dynamics, or systemic changes

To quantify and compare environmental impacts in this analysis, different methods have been developed, each with specific approaches to assessing environmental impacts across various categories.

Table 2. Life Cycle Assessment (LCA) Stages According to ISO 14040 e ISO14044

Stage	Description	Main objective	Example of application
1. Goal and scope definition	Establishes the study's purpose, system boundaries, functional unit, and assumptions	Ensure that the study has a clear and well-defined approach	Comparing the environmental impact of two types of concrete based on carbon footprint per cubic meter

Table 2 (continued)

2. Life cycle inventory (LCI) analysis	Collection of data on all input flows (raw materials, energy) and output flows (emissions, waste) throughout the product or process life cycle	Quantify environmental flows associated with each stage of the studied system	Survey of energy consumption, CO_2 emissions, and waste generated in cement production
3. Life cycle impact assessment (LCIA)	Conversion of inventory data into environmental impacts using recognized methods (e.g., ReCiPe, CML-IA, Eco-indicator 99)	Evaluate environmental impacts in categories such as climate change, acidification, and resource depletion	Identification of a material's contribution to global warming and human toxicity
4. Interpretation of results	Critical analysis of results, including uncertainties, limitations, and recommendations	Provide reliable conclusions and recommendations to reduce environmental impacts	Indicating process improvements to reduce CO_2 emissions and improve energy efficiency

Source: Adaptado de ISO (2006a), ISO (2006b).

Table 3 presents the main Environmental Impact Assessment methods used in LCA, highlighting their characteristics, evaluated impact categories, and key advantages and disadvantages. The methods are divided into midpoints, which represent specific impact categories such as greenhouse gas emissions and natural resource consumption, and endpoints, which consider the final damages to human health, ecosystems, and resource availability (Hauschild et al., 2011).

Among the most widely used methods, CML-IA, developed by the Center for Environmental Sciences at Leiden University, stands out for focusing on traditional impact categories, such as global warming potential and acidification, in accordance with EN 15804 (European Committee for Standardization, 2012).

ReCiPe integrates both midpoint and endpoint approaches, providing a more comprehensive view of environmental impacts (Huijbregts et al., 2017). IMPACT 2002+ is a hybrid model that integrates different impact categories and considers multiple environmental damages (Jolliet et al., 2003). Eco-indicator 99 prioritizes a simplified interpretation of environmental damages, making it widely used for comparing sustainable alternatives (Goedkoop & Spriensma, 2001). Meanwhile, the ILCD method, developed by the European Union, aims to standardize LCA for regulatory and decision-making purposes (European Commission, 2010).

Each of these methods has its advantages and limitations, and the choice of the most appropriate one depends on the objective of the analysis and the desired level of detail. Methods like ReCiPe and IMPACT 2002+ provide greater depth by integrating different impact categories, while Eco-indicator 99 and CML-IA are simpler and widely used for comparative analyses. The ILCD method, on the other hand, is recommended for regulatory applications and environmental policy studies.

Table 3. Environmental Impact Assessment Methods in LCA

Method	Impact categories assessed (unit of measurement)	Types of results provided
CML-IA (Center for Environmental Sciences - Leiden University)	Climate change (kg CO_2-eq), Acidification (kg SO_2-eq), Eutrophication (kg PO_4^{3-}-eq), Abiotic resource depletion (kg Sb-eq), Aquatic ecotoxicity (m^3), Terrestrial ecotoxicity (m^3), Photochemical oxidation (kg C_2H_4-eq), Human toxicity (kg 1,4-DCB-eq), Ozone depletion (kg CFC-11-eq)	Quantitative indicators for specific impact categories.
ReCiPe	Climate change (kg CO_2-eq), Terrestrial acidification (kg SO_2-eq), Particulate matter formation (kg PM_{10}-eq), Ozone depletion (kg CFC-11-eq), Terrestrial ecotoxicity (kg 1,4-DCB-eq), Aquatic ecotoxicity (kg 1,4-DCB-eq), Terrestrial eutrophication (kg N-eq), Marine eutrophication (kg N-eq), Freshwater eutrophication (kg P-eq), Fossil resource depletion (kg oil-eq), Metal resource depletion (kg Fe-eq), Land use (m^2a), Ionizing radiation (kBq Co-60-eq), Photochemical oxidant formation (kg NMVOC), Human toxicity (kg 1,4-DCB-eq), Water use (m^3)	Provides both midpoint-level indicators and final damage assessments (human health, ecosystem integrity, resource depletion)
IMPACT 2002+	Climate change (kg CO_2-eq), Acidification (kg SO_2-eq), Eutrophication (kg PO_4^{3-}-eq), Carcinogenicity (kg C_2H_3Cl-eq), Non-carcinogenicity (kg C_2H_3Cl-eq), Inorganic respiratory toxicity (kg $PM_{2.5}$-eq), Photochemical oxidation (kg C_2H_4-eq), Non-renewable resource depletion (MJ), Aquatic ecotoxicity (PAF m^3 at day), Terrestrial ecotoxicity (PAF m^2 at day)	Links individual impact categories with final damages (human health, ecosystem quality, resource depletion).
Eco-indicator 99	Human health (DALY), Ecosystem quality (PDF m^2 at year), Resource depletion (MJ)	Simplified scoring system for direct decision-making, providing damage-oriented results for human health, biodiversity, and resource use
ILCD (International reference life cycle data system)	Climate change (kg CO_2-eq), Acidification (mol H^+-eq), Terrestrial eutrophication (mol N-eq), Freshwater eutrophication (kg P-eq), Marine eutrophication (kg N-eq), Particulate matter formation (kg $PM_{2.5}$-eq), Photochemical oxidation (kg NMVOC), Ozone depletion (kg CFC-11-eq), Aquatic ecotoxicity (CTUe), Terrestrial ecotoxicity (CTUe), Human toxicity, cancer (CTUh), Human toxicity, non-cancer (CTUh), Fossil resource use (MJ), Mineral and metal resource use (kg Sb-eq), Water use (m^3)	Regulatory-compliant indicators, linked to policy applications and decision-making

Software and Databases for LCA

The selection of appropriate software and databases for LCA is a key factor in determining the quality of the results obtained. These tools vary in terms of complexity, level of detail in the information provided, and available functionalities, and they should be selected based on the user's needs and the study’s objectives.

According to De Saxcé et al. (2012), commercially available LCA tools consist of several components, among which Life Cycle Inventory (LCI) databases play a crucial role. These databases contain datasets that represent different production processes, including both input flows (such as the use of natural resources) and output flows (such as emissions generated throughout the life cycle). Furthermore, to ensure transparency and traceability, each dataset must be accompanied by detailed documentation.

Several LCA software packages include GREET, GaBi, Umberto, SimaPro, and OpenLCA. The selection of LCA software is critical, as each has unique features that may vary in terms of database availability, functionality, data quality management, user interface, and modeling principles (Silva et al., 2017). The results of an LCA are directly influenced by the databases, methods, and impact assessment models embedded in the software, which play a fundamental role in supporting the LCA process (Silva et al., 2019).

Databases such as Ecoinvent, GaBi Database, and Agribalyse provide robust and updated life cycle inventories for different sectors. The choice between different LCA software and databases should take into account factors such as cost, level of detail, availability of regional data, and compatibility with the impact assessment methods used in the study (Table 4).

Seto et al. (2017) emphasize in their comparative study the importance of selecting software that is suitable for the specific requirements of each LCA research. Among the key criteria for this selection, the tool's ability to accurately model the defined functional unit and system boundaries stands out. Additionally, the authors present a method that enables a rigorous comparison between different approaches, ensuring methodological precision while minimizing redundancy and duplication of efforts during the evaluation process.

The reliability of LCA results is influenced by multiple factors. In addition to the accuracy of primary data and the proper definition of system boundaries, methodological aspects play a crucial role in the robustness of assessments. According to Nicholson et al. (2019), the choice of allocation method can significantly impact the results, as different methodological approaches may lead to substantial variations in the estimation of environmental impacts.

The availability of regional and specific databases presents a significant challenge for conducting LCA studies. The lack of adequate national databases often leads researchers to rely on international datasets, which may not accurately reflect local conditions. According to Zocche (2014), this practice can result in distorted outcomes, as relevant regional aspects are not always considered, creating uncertainties that complicate decision-making. To mitigate this limitation, some studies choose to adapt international data or develop proprietary inventories, which, while improving study accuracy, require additional time and resources.

Moreover, the selection of LCA software must be aligned with the study's objectives, ensuring that the modeling of production processes is conducted accurately and efficiently. Given the continuous evolution of LCA tools and the need to keep databases updated, a careful selection of resources is essential to ensure that the results obtained are representative and appropriate for the specific demands of each project.

Table 4. Overview of LCA software: origin, usage, and database integration

Software	Country of origin	Main region of use	Access	Relevant notes	Databases
SimaPro	Netherlands (Holland)	Global	Paid	Widely used for LCA, detailed modeling	Ecoinvent, Agri-footprint, ELCD, USLCI, Industry Data 2.0, Swiss IO, WFLDB, Exiobase
GaBi Software	Germany	Global	Paid	Vast database, modeling in different sectors	GaBi Database, Ecoinvent, E, LCD, USLCI, Agri-footprint, Industry Data 2.0, Thinkstep, Exiobase
openLCA	Germany	Global	Free	The only professional-grade open-source	ELCD, USLCI, Agribalyse, WFLDB, Ecoinvent, Agri-footprint, Exiobase, NMD, USLCI, Thinkstep
Umberto	Germany	Europe	Paid	Versatile, material/energy flow analysis	Ecoinvent, ELCD, USLCI, Agri-footprint, WFLDB, Thinkstep Databases, Industry Data 2.0, Exiobase
One Click LCA	Finland	Europe	Paid	Automated, specific to civil construction	EPD, Ecoinvent, ELCD, USLCI, Agri-footprint
Athena impact estimator	Canada	North America	Free	Simplified analysis for construction	Athena LCI Database
BEES	USA	North America	Free	Environmental/ economic assessment of construction products	BEES Database
TEAM	France	Europe	Paid	Pioneer, industrial focus and buildings	DEAM, Ecoinvent, ELCD, USLCI
Ecochain (Mobius/ Helix)	Netherlands	Europe	Paid	User-friendly online platform for environmental footprints	Ecoinvent, EF, NMD, Agri-footprint, USLCI, WFLDB
eToolLCD	Australia	Oceania / Asia-Pacific	Freemium	Specialized in sustainable buildings	eToolLCD's database, Ecoinvent, ELCD, USLCI, EPD

ELCD = European Reference Life Cycle Database; USLCI = U.S. Life Cycle Inventory Database; EF = Environmental Footprint Database; NMD = Nationale Milieudatabase; WFLDB = World Food LCA Database; Souche: ACV Brasil (s.d.); IBICT (2016); Enciclo (2022); Ecochain (2023).

Keyword Co-occurrence

A keyword co-occurrence map was generated, forming five main clusters, as illustrated in Fig. 1. These clusters represent distinct thematic areas within LCA and sustainability of construction materials, allowing for the identification of key interrelationships and research trends in the field.

The blue cluster is centered around the core concept of life cycle assessment, including terms such as 'life cycle' and 'life cycle analysis', 'carbon dioxide', and 'energy utilization'. This cluster emphasizes the crucial role of LCA as a tool for evaluating the environmental impact of construction materials. The presence of terms related to carbon dioxide emissions and energy consumption highlights the research focus on reducing the carbon footprint and improving energy efficiency throughout the materials life cycle. This reforces LCA as a well-established methodology for guiding sustainability decision-making in the construction sector.

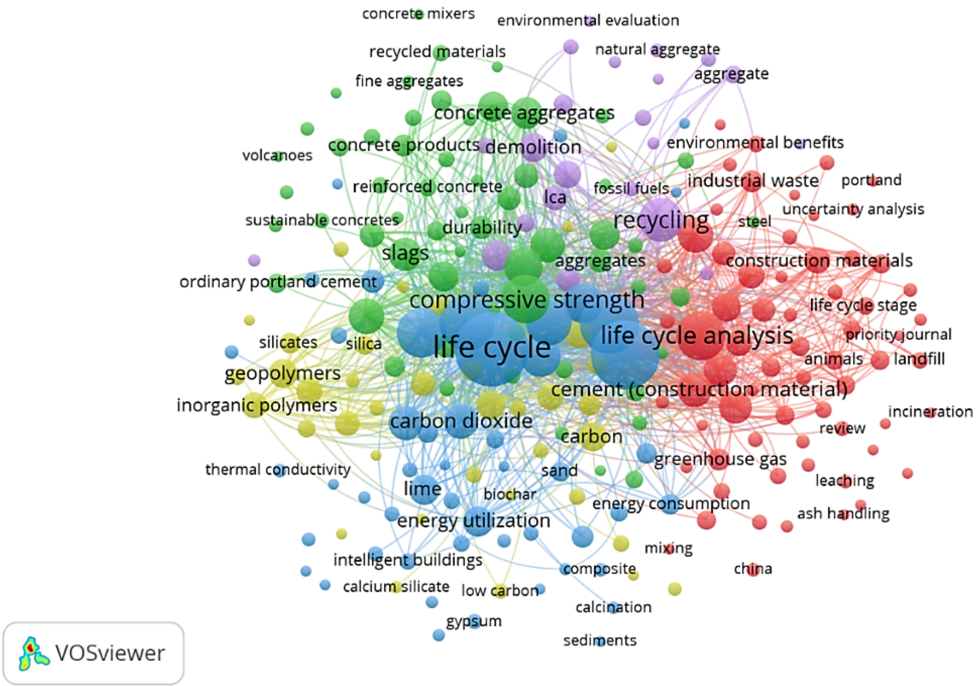

Figure 1. Keyword Co-occurrence Map.

The green cluster focuses on construction materials and durability, with key terms such as 'concrete aggregates', 'recycled materials', and 'durability'. This cluster reflects a strong research emphasis on developing more durable and sustainable construction materials by incorporating recycled waste, such as slag and alternative aggregates. These materials aim not only to reduce environmental impact but also to extend the service life of buildings, aligning with the principles of the circular economy. The co-occurrence of these terms suggests an increasing commitment to enhancing material longevity while promoting resource efficiency in construction.

The red cluster is primarily associated with waste management and recycling strategies, containing terms like 'industrial waste', 'greenhouse gas', and 'environmental benefits'. This cluster highlights the growing concern about industrial waste disposal, as well as efforts to mitigate greenhouse gas emissions through improved recycling techniques and sustainable waste management practices. The strong link between industrial waste and environmental benefits suggests that research is increasingly focusing on transforming waste into valuable resources, further contributing to sustainability goals in the construction industry.

The yellow cluster emphasizes alternative cementitious materials, with keywords such as ‘geopolymers’, ‘inorganic polymers’, ‘silicates’, and ‘low-carbon’. This cluster demonstrates the growing interest in alternatives to traditional Portland cement, driven by the need to reduce dependence on high-carbon materials. The presence of terms related to thermal conductivity and advanced material properties indicates that researchers are not only developing greener materials but also ensuring that they meet technical performance requirements for practical application in construction.

The relationships between these clusters reveal an increasing convergence in sustainability research, where studies are moving beyond impact assessment and incorporating practical solutions for emission reduction, material efficiency, and waste reutilization. The strong interconnections between the blue, green, and red clusters suggest a holistic approach, where LCA methodologies, recycled materials, and waste management strategies are being integrated into sustainable construction practices. Meanwhile, the yellow cluster's focus on low-carbon alternatives demonstrates a parallel effort to further decarbonize the industry through material innovation.

Thus, the keyword co-occurrence analysis, as illustrated in Fig. 1, provides a structural representation of ongoing research efforts and emerging trends in sustainable construction. The clustering of keywords reveals how different research areas are interlinked, reinforcing the multifaceted nature of sustainability in construction materials. These findings indicate that the field is not only focused on evaluating environmental impacts but also on actively seeking and implementing innovative solutions that contribute to a more sustainable built environment.

Application of LCA in Traditional and Sustainable Materials

LCA has established itself as an essential tool for assessing the environmental impact of construction materials throughout all stages of their lifecycle, from raw material extraction to disposal or recycling. This tool enables a detailed analysis of the production, transportation, use, and end-of-life phases, providing valuable insights for decision-making with a focus on sustainability. The selection of midpoints and endpoints in Life Cycle Assessment (LCA) depends directly on the chosen impact method and the objectives of the study. In the context of civil construction, intermediate indicators such as global warming potential (GWP), acidification, eutrophication, and human toxicity are generally considered (Asadollahfardi et al., 2019). Endpoints encompass final impacts related to human health, ecosystem quality, and natural resources, allowing a comprehensive understanding of the environmental consequences of construction activities and facilitating the prioritization of sustainable decisions (Partonia et al., 2024). The application of LCA in the construction sector is crucial, as it accounts for a significant share of greenhouse gas emissions, energy consumption, and natural resource use.

The prediction of the service life of concrete structures within LCA must also consider the entire life cycle of the material, from raw material acquisition to final disposal, as described by Hájek et al. (2011). Concrete's life cycle includes various stages such as production, construction, operation, maintenance, and recycling, each directly influencing structural durability. The Integrated Life Cycle Assessment (ILCA) methodology developed by the International Federation for Structural Concrete (FIB) emphasizes a holistic approach, integrating environmental, economic, and social aspects into durability analysis (FIB, 2013). Predictive models, particularly those based on chloride diffusion, are widely employed to estimate concrete deterioration and forecast reinforcement corrosion, a major cause of structural failure (Bento, 2018). Lopes et al. (2022) note that most predictive models apply Fick's Second Law, often incorporating adjustments for non-saturated concrete conditions, chloride binding, and cracking. These models are categorized into empirical, analytical, and numerical types, with distinctions between deterministic and probabilistic approaches. Approximately 72% of these models are analytical, with Monte Carlo simulation emerging as the predominant numerical method for probabilistic predictions (Lopes et al., 2022). Furthermore, adapting ILCA methodologies to various concrete structures, such as bridges, buildings, and dams, allows optimization of maintenance strategies and extension of service life, significantly reducing environmental impacts and operational costs (FIB, 2013). Thus, integrating durability prediction models into LCA and ILCA ensures more accurate assessments of the longevity and sustainability of concrete structures over their lifecycle.

Defining System Boundaries in LCA

The boundaries of LCA study are fundamental for defining the scope of the evaluation, specifying the stages, material flows, and processes included in the analysis. This definition is essential to ensure comparability between studies and to guarantee that all significant stages, in terms of environmental impact, are adequately considered. System boundaries, geographical boundaries, and temporal boundaries all play critical roles in shaping the accuracy and reliability of LCA outcomes. Among the gaps identified is the lack of detailed and reliable regional information, especially regarding emissions from specific production processes, limiting the representativeness of studies, especially in developing countries (Asadollahfardi et al., 2019; Katebi et al., 2023). Another gap highlighted is the need for integrated studies that simultaneously assess the environmental impacts of materials and energy consumption associated with air conditioning and maintenance of buildings, such as clean rooms (Partonia et al., 2024).

- System Boundaries: System boundaries define unit processes and life cycle phases included in the analysis, from raw material extraction to final disposal. This scope, known as 'cradle-to-grave' provides a comprehensive view of impacts throughout the entire production and use chain, ensuring a complete analysis of emissions and resource consumption (Mishra et al., 2023). Conversely, a 'cradle-to-gate' scope focuses only on the stages up to production, excluding use and disposal, which may be suitable for comparing production processes without considering post-use impacts (Monteiro et al., 2022). Studies such as those by Li et al. (2022) show that properly defining these boundaries is crucial for accurately capturing environmental effects at each specific stage.
- Geographical Boundaries: Geographical boundaries determine where the analyzed processes occur, accounting for regional variations in resource availability, waste disposal methods, and production practices. Defining these boundaries is essential, as environmental impacts can vary significantly between regions due to factors such as energy matrix, local environmental policies, and waste management practices. Monteiro et al. (2022) demonstrate that an LCA considering geographical specificities provides more representative results, particularly in comparative studies of conventional and sustainable materials. Zhao & Yang (2023), in their study on the use of recycled materials in semi-flexible pavements, highlight the importance of evaluating performance under different environmental conditions to promote solutions that are aligned with regional needs.

• Temporal Boundaries: Temporal boundaries define the time period considered in the LCA, including factors such as material durability, service life, and replacement cycles. Properly defining temporal boundaries is crucial for capturing all relevant environmental impacts over the complete life cycle of materials, ensuring the inclusion of initial phases as well as impacts associated with maintenance and replacement (Navaratnam et al., 2023). Moreover, when evaluating long-lasting materials used in construction, temporal boundaries should reflect not only the life cycle of the materials but also the potential implications of prolonged use (Bošković & Radivojević, 2024). This approach enables a more precise analysis of accumulated impacts and a better understanding of the environmental benefits of durable materials.

The definition of boundaries in LCA is essential to ensure an accurate and meaningful evaluation of the environmental impacts associated with construction materials. According to ISO 14040 and ISO 14044, system boundaries delineate which life cycle stages, processes, and flows are included or excluded from the assessment, directly influencing the results and comparability of studies (ISO, 2006a; ISO, 2006b). One of its main advantages is precision in analysis: well-defined boundaries allow for a detailed and systematic assessment of each life cycle stage, from raw material extraction to final disposal. This precision facilitates the identification of critical phases where impact mitigation strategies, such as the use of industrial waste and agricultural by-products, can be implemented, leading to significant reductions in CO_2 emissions and resource consumption (Rocha et al., 2022; Navaratnam et al., 2023). With clearly defined boundaries, the collected data becomes more representative and reliable, fostering informed decision-making aligned with sustainability principles (Monteiro et al., 2022).

Moreover, well-defined boundaries are fundamental for ensuring comparability between LCA studies. key aspect in comparative analyses is the standardization of the Functional Unit (FU), which defines the reference basis for measuring environmental impacts. Since LCA results are highly dependent on the FU, comparisons between studies are only valid if they adopt the same unit ensuring equivalent system boundaries and life cycle stages (ISO, 2006a; ISO, 2006b). Additionally, different environmental assessment methodologies apply distinct characterization factors to substances identified in the Life Cycle Inventory (LCI), potentially leading to variations in impact results even when the FU remains the same. These methodological differences highlight the need for careful selection of impact assessment methods to ensure consistency in comparisons (Li et al., 2022; Krajnović et al., 2024). When properly standardized, LCA enables a critical analysis of the environmental performance of conventional and alternative materials under similar conditions. For instance, when comparing slag-based concrete with traditional Portland cement, a well-defined FU and a consistent impact assessment approach allow for a more accurate quantification of environmental benefits, supporting the transition to more sustainable construction materials (Moro et al., 2023).

Finally, defining boundaries helps focus the analysis on areas with the greatest environmental impact, optimizing the time and resources dedicated to research. Concentrating on the most impactful stages, such as production and transportation, can result in substantial gains in the sustainability of materials, highlighting points where energy use and greenhouse gas emissions are most significant (Bošković & Radivojević, 2024; Zhou et al., 2024a). This targeted approach allows efforts to be directed toward areas where improvements are most needed, resulting in a more efficient construction industry that is resilient to environmental challenges.

The definition of boundaries LCA faces significant challenges, particularly in complex systems like construction, which involve a diversity of materials and processes. For such systems, establishing appropriate boundaries is crucial to ensure that all relevant impacts are accounted for. Monteiro et al. (2022) highlight that when applying LCA to materials such as cement with nanotechnology, considering all life cycle phases can be challenging due to variability in manufacturing methods and usage. This complexity can hinder comparisons between studies, especially those involving sustainable and traditional alternatives, which have distinct value chains and impacts (Cavagnoli et al., 2024). Thus, clarity and precision in defining boundaries are essential to ensure data consistency and representativeness, enabling reliable conclusions.

Another major challenge lies in the availability and quality of data, which are critical for accurately delineating study boundaries. Specific data for certain processes or materials are often scarce or inconsistent, limiting the representativeness of the analysis (Navaratnam et al., 2023). Additionally, Zhao & Yang (2023) in their study on semi-flexible pavements incorporating recycled materials, emphasize the importance of considering environmental factors and long-term performance indicators to account for regional variations and ensure material durability. In circular economy practices, such as the use of industrial by-products and waste, LCA boundaries require constant reassessment to account for the extended use cycle, adding complexity and increasing data demands in the analysis (Arce et al., 2023; Zhou et al., 2024a). These aspects emphasize the need for integrated methodologies and specific databases to capture cumulative impacts and facilitate the application of LCA in sustainability contexts.

Conventional materials

Recent studies have demonstrated the potential LCA to evaluate and drive improvements in conventional construction materials. For instance, Anurag & Goyal (2023) applied LCA to assess the environmental impact of using low-grade limestone sludge as a partial substitute for clinker in the production of low-carbon cementitious binders. The LCA revealed 41.39% reductions in CO_2 emissions (kg CO_2 eq/T) and a 28.80% decrease in costs. while maintaining comparable mechanical properties with a 28-day compressive strength of 49.25 MPa. Similarly, Sadok et al. (2022) used LCA to evaluate cementitious materials based on calcined sediments from the Chorfa II reservoir, demonstrating that replacing 5%, 15%, and 25% of cement with calcined sediment led to reductions in CO_2 emissions per ton of material of 3.57% (901.73 kg CO_2 eq/T), 10.70% (835 kg CO_2 eq/T), and 17.84% (768.29 kg CO_2 eq/T), respectively. For pastes and mortars, similar reductions were observed, reaching up to 18% (391.12 kg CO_2 eq/T) for pastes and 16.59% (364.40 kg CO_2 eq/T) for mortars.

The application of LCA to traditional construction materials, such as Portland cement, has revealed opportunities for the adoption of more sustainable alternatives. For example, Guo et al. (2022) applied LCA to evaluate the performance of concretes incorporating limestone calcined clay cement (LC3) and found that this cement significantly reduces CO_2 emissions by up to 42%, without compromising concrete strength. Additionally, incorporating 50% LC3 in recycled aggregate concrete resulted in a 94% reduction in the chloride rapid migration coefficient, while the strength loss was only 12% at 300 days, compared to the reference group. The study also indicated a significant improvement in the electrical resistance of concrete due to the formation of a denser matrix and the reduction of available OH^- in the pore solution.

Similarly, Habibi et al. (2021) used Response Surface Methodology (RSM) to optimize concrete mixtures containing recycled aggregates, silica fume, and ground granulated blast furnace slag. LCA, was combined with optimization techniques demonstrating that it is possible enhance the sustainability of conventional construction materials. The results indicated that the reduction in Global Warming Potential (GWP, in kg CO_2 eq) for the optimized mix designs was 41% without considering the service life and 80% when considering an equivalent service life. Additionally, compared to conventional concrete, waste generation was reduced from 6,412 kg to 2,605 kg over a 110-year period, and 425 kg of waste per cubic meter was recycled in the optimized mix designs.

Sustainable materials and innovations

The application LCA has been essential in evaluating and promoting the use of industrial waste and by-products in construction material production, highlighting their potential to reduce environmental impacts. For instance, Arce et al. (2023) investigated the use of ferronickel slag as a binder in alkali-activated mortars, observing a 70% reduction in CO_2 emissions compared to Portland cement mortars. The study demonstrated that the optimized mix exhibited a flexural strength of 8.5 MPa before heat exposure and 10.5 MPa after exposure, along with a compressive strength of 69.5 MPa before heating and 33.9 MPa after heating, with a mass loss of 7.7% and thermal shrinkage of 3.4%. Similarly, Bumanis et al. (2022) demonstrated that using phosphogypsum as a partial cement substitute can reduce CO_2 emissions by 57 wt.% and energy consumption by 30%. The LCA was conducted using SimaPro software, based on the Ecoinvent database, to calculate the environmental impact of a ternary gypsum-phosphogypsum-Portland cement-pozzolan binder.

Research by Danish et al. (2024) demonstrated that incorporating reclaimed fly ash in geopolymers can reduce the Global Warming Potential (GWP) by 29.6% to 35.4% compared to cement mortars (CM). Additionally, geopolymers containing 20% to 80% RFA exhibited reductions in GWP, acidification potential, and energy consumption ranging from 1.6% to 8.2%, 3.8% to 28.9%, and 3.1% to 17.7%, respectively, compared to geopolymers composed entirely of ground granulated blast furnace slag. Raza et al. (2024) analyzed the sustainability of geopolymer and hydrid cement mixes, incorporating alkaline activators (NaOH, ranging from 5% to 25% by weight) and ordinary Portland cement (OPC, ranging from 15% to 35% by weight). The microstructural analysis revealed that the hybrid mix containing 35% OPC exhibited the highest mechanical strength due to the increased formation of calcium aluminum silicate hydrate and calcium silicate hydrate gels, compared to geopolymers containing 25% NaOH. The economic assessment and LCA using the ReCiPe Midpoint method indicated that the geopolymer mix with 5% NaOH had the lowest cost and environmental impact. However, considering a multi-criteria decision-making approach, the authors concluded that hybrid cement mixes with 35% OPC represent the most sustainable solution for construction applications.

Furthermore, the reuse of waste materials has also shown great potential for reducing environmental impacts. Shao et al. (2024) evaluated the environmental impact of replacing fine aggregates with waste oyster shells (WOS) in mortar production across 13 environmental categories. The results demonstrated that WOS incorporation led to reductions in 9 out of 13 categories, including Global Warming Potential (GWP), Ozone

Depletion Potential (ODP), Acidification Potential (AP), Particulate Matter Formation Potential (PMFP), Ozone Formation: Human Health (OFHH), Ozone Formation: Terrestrial Ecosystems (OFTE), Land Use Potential (LUP), Mineral Resource Scarcity (MRS), and Terrestrial Ecotoxicity (TE). The GWP was reduced from 596 kg CO_2 eq/m³ (WOS-0) to 586 kg CO_2 eq m^{-3} (WOS-60), representing a 1.7% decrease, while AP decreased from 1.03 kg CO_2 eq/m³ to 0.976 kg CO_2 eq/m³, reflecting a 5.2% reduction. Despite these environmental benefits, the study also found increases in four impact categories: Freshwater Eutrophication Potential (FEP), Marine Eutrophication Potential (MEP), Marine Ecotoxicity (ME), and Fossil Resource Scarcity (FRS). Specifically, MEP increased by 12%, 24%, and 36% for WOS-20, WOS-40, and WOS-60, respectively, compared to WOS-0. The main contributor to these increased impacts was the electricity consumption required for WOS pretreatment, including washing, calcination, and grinding processes. Additionally, the transportation distance of WOS was identified as a secondary factor, with FRS and ODP increasing by up to 30% and 33% at 400 km transport distances Bioeconomic construction materials, as evaluated by Bueno et al. (2023), demonstrated the potential of circular economy-based end-of-life scenarios by reusing Sargassum species in construction materials, reducing environmental impacts, and promoting sustainable marine waste management. Similarly, Bošković & Radivojević (2024) investigated hemp-lime constructions, highlighting their carbon sequestration potential and reduced emissions throughout the material life cycle.

The introduction of geopolymer mortars made with masonry units and recycled concrete aggregates, as described by Kul et al. (2023), revealed significant reductions in environmental impacts, particularly regarding CO_2 emissions and resource consumption. Likewise, Rocha et al. (2022) highlighted the use of açaí seed ash as a partial cement substitute, providing a regional solution aligned with circular bioeconomy principles in the Amazon. These studies illustrate how the application of LCA is fundamental for identifying and quantifying the benefits of replacing conventional materials with more sustainable alternatives.

Additionally, Fernando et al. (2021) quantified the greenhouse gas (GHG) emissions, environmental impacts, and cost benefits of using fly ash (FA) and rice husk ash (RHA) in alkali-activated concrete (AAC) compared to Portland Cement (PC) concrete. The study found that alkali activators contributed to 74% of total GHG emissions, while heat curing accounted for only 9%. Despite this, the incorporation of 10% RHA into AAC resulted in a slight reduction in overall emissions and improved sustainability metrics. Additionally, the study highlighted that utilizing FA and RHA significantly reduced freshwater and marine water ecotoxicity, as it prevented waste disposal into landfills, rivers, and storage lagoons. Similarly, Guignone et al. (2022), conducted an LCA to evaluate the environmental performance of concrete incorporating recycled glass powder (RGP) for bridge retrofitting. Their findings showed that partially substituting cement with RGP led to reductions in CO_2 emissions and energy consumption, particularly during the manufacturing phase, which was identified as the most environmentally impactful stage. Furthermore, the study revealed that RGP incorporation enhanced durability properties and reduced maintenance-related impacts, making it a viable alternative for sustainable infrastructure rehabilitation.

Advances in the use of cementitious composites

Innovations involving geopolymeric materials based on soil waste were highlighted by Sandanayake et al. (2022), who proposed a new framework to assess their environmental impacts, emphasizing that using waste as raw material can significantly reduce both CO_2 emissions and energy consumption. Similarly, López-García et al. (2022) explored the transformation of mineral wool waste into lightweight aggregates, a strategy that demonstrated emission reductions while promoting waste recycling in construction.

LCA was also applied by Czernik et al. (2022) to evaluate the environmental performance of cementitious adhesives in thermal insulation systems, showing that alternatives to cement significantly improve the sustainability of these materials. Alvi et al. (2023), on the other hand, investigated cementitious composites containing graphene oxide and recycled aggregates, demonstrating that the use of nanomaterials not only increases durability but also enhances sustainability.

Furthermore, LCA has been critical in evaluating bio-based materials and by-products. Essaghouri et al. (2023), for instance, compared hempcrete walls to traditional constructions, revealing that hempcrete offers significant environmental benefits, including reduced CO_2 emissions and carbon sequestration potential. Similarly, Zhou et al. (2024b) applied LCA to the recycling of copper slag as a cement substitute in mine fill, emphasizing its effectiveness in reducing emissions and promoting the sustainable use of industrial waste.

Innovation in producing construction materials using industrial waste was also evidenced by Kvočka et al. (2020), who analyzed prefabricated facade panels made from geopolymer-based materials with high fractions of recycled construction and demolition waste. LCA highlighted the reduction in CO_2 emissions and the improved environmental performance of these materials. Cascione et al. (2022) integrated bio-based materials into wall panels, promoting circularity in construction design, while Chen et al. (2022) investigated cement particle and biochar panels, showcasing their carbon sequestration capabilities.

In the context of pavement, Zhao & Yang (2023) emphasized the use of recycled materials such as fly ash, rubber particles, and reclaimed aspfalt pavement as effective strategies to reduce carbon emissions and promote sustainability in construction. The valorization of waste was also explored by Umer et al. (2024), who developed geopolymer concrete using biomass-derived sodium silicate, fostering circular economy principles.

The application of sustainable cementitious composites has proven to be an effective strategy to reduce the environmental impacts associated with the construction sector. LCA plays a crucial role in evaluating these new technologies, enabling the identification and quantification of improvements in carbon emissions and resource consumption.

Yang et al. (2024) discussed advancements in environmental sustainability through innovative low-carbon cementitious composites, demonstrating how these new materials can contribute to reducing carbon emissions throughout their lifecycle. The approach of low-carbon composites presents a promising alternative to Portland cement, which is well-known for its high carbon footprint.

Similarly, Liu et al. (2023) evaluated cementitious composites containing iron ore tailings, demonstrating a significant reduction in the carbon footprint of these materials, reinforcing the role of industrial waste in building a more sustainable sector. Amari et al. (2024) highlighted the use of blast furnace slag in zeolite-based geopolymers, presenting a viable and eco-efficient alternative to traditional Portland cement. This substitution reduces CO_2 emissions and improves the environmental performance of composites.

The use of cementitious composites also extends to innovations in specific materials. Ardra et al. (2024) demonstrated that the infusion of mycelium into geopolymer bricks can reduce environmental impact, promoting more sustainable alternatives for non-structural walls. This innovative approach explores the combination of bioeconomic materials with geopolymer technology, aligning with the concept of sustainable construction.

Furthermore, the replacement of conventional materials with recycled ones is also a growing trend in cementitious composites. Choi et al. (2023) showed that substituting natural sand with recycled sand in UHPC (ultra-high-performance concrete) and UHPFRC (ultra-high-performance fiber-reinforced concrete) composites can significantly reduce environmental impact while maintaining good mechanical properties.

Filippis et al. (2021) contributed to advancements by demonstrating that replacing sodium hydroxide in slag-activated mixtures can reduce the environmental impacts of binders, improving the eco-efficiency of the mixtures. The application of LCA in these cases allows for the identification of the impact of changes in binder formulations, quantifying improvements in terms of emissions and resource efficiency.

Nair & Sairam (2021) reviewed the use of wollastonite in cement-based construction materials, concluding that the addition of this material improves mechanical properties while reducing environmental impact. This substitution of conventional raw materials with sustainable alternatives underscores the importance of seeking new additives and substitutes.

Zhao et al. (2020) revealed that using recycled concrete aggregates from precast blocks results in a significant reduction in environmental impacts without compromising structural performance. This demonstrates how circular economy principles and material recycling can be effectively integrated into the production of cementitious composites.

Other approaches include the treatment of waste and by-products to improve the environmental performance of cementitious composites. Grabias-Blicharz & Franus (2023) critically reviewed the mechanochemical processing of fly ash, concluding that the proper use of treated fly ash can significantly reduce the environmental impact of cementitious materials. Nasir et al. (2024) reviewed the historical progress and future challenges of alkali-activated binders, highlighting the importance of LCA as a tool to assess the sustainability of these binders and identify opportunities for improvement.

Finally, Labianca et al. (2024) evaluated cementitious products with the addition of biochar, emphasizing that this additive enhances the mechanical properties of composites while reducing carbon emissions. The use of biochar as an additive represents an innovative and sustainable alternative, promoting the integration of organic by-products into construction.

The application of LCA has played a crucial role in the evaluation and development of innovative and sustainable cementitious materials. Recent studies have demonstrated the effectiveness of LCA in quantifying the environmental impacts of advanced technologies and in replacing conventional materials with more eco-friendly alternatives. For example, Monteiro et al. (2022) analyzed the inclusion of nanotechnology in cements and concretes, emphasizing the need to consider environmental impacts throughout the entire life cycle of nanomaterial manufacturing processes. LCA enabled the identification of not only mechanical performance gains but also potential environmental challenges associated with nanomaterial production.

Similarly, Li et al. (2023) used LCA to demonstrate that the incorporation of carbonated steel slag powders into cementitious mixtures can significantly improve mechanical performance while reducing CO_2 emissions throughout the material's life cycle. This approach is crucial for the transition toward more sustainable and low-carbon cementitious materials.

These advancements highlight how the application of sustainable and innovative cementitious composites can reduce the environmental impacts of the construction sector. The use of industrial waste, recycled materials, and organic additives, combined with the application of LCA, provides a promising pathway for the development of more responsible and efficient construction practices.

Comparisons and Sustainable Alternatives

Integration can be achieved using combined methodologies, such as Life Cycle Cost Assessment (LCC) associated with environmental LCA. Software such as BEES offers a platform to simultaneously assess economic and environmental aspects, enabling more balanced and informed decision-making (Asadollahfardi et al., 2019; Katebi et al., 2023).

Recent studies have explored various types of waste and by-products. Caneda-Martínez et al. (2021) revealed that using recycled concrete powder in eco-cements can significantly reduce carbon emissions associated with the material's life cycle. Similarly, Cappucci et al. (2022) evaluated agro-concrete blocks made from wheat husks, demonstrating a lower carbon footprint compared to traditional concrete. Cavagnoli et al. (2024) also used LCA to analyze prefabricated panels made of recycled PET, highlighting a reduction in environmental impact and improvements in the thermal and acoustic properties of these panels.

The introduction of industrial waste and by-products into construction materials has been a common approach in LCA studies, as highlighted by Naran et al. (2022). These authors investigated the incorporation of waste into environmentally friendly concretes, demonstrating that adding ashes and recycled materials not only reduced environmental impacts but also improved the mechanical properties of the concrete. Üçer Erduran et al. (2020) reinforced this concept by showing that the reuse of recovered masonry materials significantly reduces environmental impacts and construction costs, thereby promoting circular economy principles.

Furthermore, the incorporation of multiple industrial wastes into construction materials has been successful in terms of environmental efficiency. Sun et al. (2021) demonstrated that the inclusion of binary and ternary industrial wastes in injection materials resulted in satisfactory technical performance and reduced environmental impacts. On the other hand, Tang et al. (2021) concluded that fly ash-based geopolymeric materials have a lower environmental impact compared to traditional Portland cement-based materials, particularly in terms of CO_2 emissions and energy consumption.

The application of LCA has been essential for comparing the environmental performance of conventional materials with more sustainable alternatives. Recent studies indicate that replacing traditional materials with industrial or recycled waste can significantly reduce environmental impacts, particularly in terms of CO_2 emissions and energy consumption.

Navaratnam et al. (2023), for instance, reviewed industrial waste-based cementitious materials, concluding that the use of fly ash and slag promotes a circular economy by reducing carbon emissions. Similarly, Krajnović et al. (2024) investigated alkali-activated repair mortars incorporating blast furnace slag and glass waste, observing superior environmental performance compared to conventional materials.

The use of recycled aggregates has also proven effective in reducing the carbon footprint of construction. Cerchione et al. (2023) demonstrated that reusing waste and recycled materials in the concrete production cycle can contribute to sustainable practices, emphasizing the importance of the circular economy. In European contexts, Colangelo et al. (2020) and Colangelo et al. (2021) highlighted the environmental feasibility of replacing natural aggregates with recycled ones, observing reductions in carbon emissions.

LCA enables a detailed analysis of these substitutions, as demonstrated by Sirico et al. (2024), who evaluated low-carbon concretes with vitrified ashes from urban solid waste incineration, showing that this substitution does not compromise structural performance but significantly reduces environmental impacts. Shao et al. (2022) also applied LCA to compare different carbonation routes for slag waste, concluding that pre-treatment with CO_2 is an effective strategy for reducing emissions.

Additional studies, such as Fořt et al. (2020), reinforce the importance of material recycling, highlighting that reusing residual bricks can promote a circular economy and significantly reduce the construction sector's carbon footprint. These LCA-based comparisons provide a solid foundation for adopting sustainable practices, enabling informed decisions and promoting the development of alternatives with lower environmental impacts.

The analysis of different end-of-life scenarios is crucial for identifying more sustainable solutions, as evidenced by Costa et al. (2022) in their evaluation of wood fly ash, which concluded that recycling it into construction materials is the most sustainable option. Dal Pozzo et al. (2024), in assessing stone consolidants used in cultural heritage conservation, demonstrated the importance of selecting products that enhance durability and reduce environmental impacts. These choices are guided by the use of LCA to achieve a holistic understanding of impacts throughout the materials' life cycle.

These examples highlight how LCA is essential for developing sustainable practices in construction, promoting the substitution of virgin resources with recycled waste, optimizing the life cycle of materials, and minimizing the carbon footprint. By integrating LCA with the concepts of circular economy and bioeconomy, it is possible to move toward a more sustainable, efficient, and environmentally responsible construction industry, fostering a more resilient future for the sector.

Emerging technologies and recent advances

LCA has proven to be an indispensable tool in the innovation of construction materials, enabling a comprehensive evaluation of environmental impact throughout the entire product life cycle. This approach has been essential in guiding the replacement of conventional materials with sustainable alternatives, particularly those utilizing industrial waste and by-products.

For example, Los Santos-Ortega et al. (2023) used LCA to assess mortars doped with recycled tire rubber, demonstrating that incorporating waste contributes to reducing environmental impacts, especially CO_2 emissions. Similarly, Roux et al. (2024) applied LCA to optimize formulations of geopolymer mortars for 3D printing, showing that optimized formulations can reduce the carbon footprint and improve environmental efficiency compared to conventional materials.

These studies exemplify how the application of LCA can guide innovations in construction materials, providing a detailed analysis of the environmental impacts of alternatives using industrial waste and by-products. By adopting this approach, it is possible to promote sustainability and drive the transition toward more responsible practices in the construction sector.

Recent advances in the application of LCA have focused on utilizing sophisticated models and emerging technologies to predict and improve the environmental performance of construction materials. LCA has established itself as a fundamental tool for assessing environmental impacts across all stages of a material's life cycle, from raw material extraction to disposal or recycling.

For example, Moro et al. (2023) explored CO_2 curing techniques in mortars composed of natural and recycled concrete aggregates. This study demonstrated that CO_2 curing not only captures carbon but also contributes to improving the environmental performance of materials throughout their life cycle. This approach aims to transform the curing process into a decarbonization opportunity, aligning with the sector's sustainability goals.

Additionally, LCA has been instrumental in evaluating new technologies, such as 3D printing of materials. Yoris-Nobile et al. (2023) highlighted that 3D printing of artificial reefs, using strategically selected materials, can promote marine conservation and reduce environmental impacts. This technique allows for the creation of customized structures, optimizing material use and minimizing waste.

The application of LCA has played a crucial role in promoting innovative and bioeconomic materials while driving the transition to a circular economy in the construction sector. By providing a comprehensive evaluation of environmental impacts throughout the entire life cycle of materials, LCA offers a solid scientific foundation for developing sustainable and circular solutions, identifying opportunities for process optimization and improved resource efficiency.

The use of LCA has also expanded to assess innovative materials and optimize construction processes. For instance, Suphunsaene et al. (2023) developed a fast-drying plaster mortar that demonstrated resource efficiency and significant environmental benefits for the ASEAN region (Association of Southeast Asian Nations). This innovation addresses specific local market needs, highlighting the importance of tailoring materials and processes to regional conditions.

In the context of material recycling, Sambataro et al. (2023) explored 3D-printed concrete with recycled rubber, revealing a substantial reduction in the carbon footprint compared to traditional casting methods. This study emphasizes the potential of emerging technologies, such as 3D printing, to promote circular economy practices and reduce the environmental impact of construction materials.

The application of emerging technologies like 3D printing has also been evaluated through LCA. Kalthoff et al. (2023) and Khan et al. (2023) investigated the use of 3D printing in constructing cementitious components, highlighting advantages in material efficiency and environmental impact reduction. Supported by LCA, these studies demonstrated how 3D printing can optimize resource use and minimize emissions throughout the life cycle, contributing to the sustainability of the construction sector.

These recent advances demonstrate how LCA, combined with emerging technologies and new analytical models, can guide the development of more sustainable practices and materials in the construction sector. LCA's ability to provide a detailed view of the entire life cycle of materials allows for the identification and exploration of opportunities to reduce greenhouse gas emissions, energy consumption, and the use of natural resources. This is particularly relevant in the construction sector, given its significant environmental impact and the growing demand for sustainable alternatives.

Challenges and Limitations

Although LCA has become an essential tool in evaluating the environmental impacts of materials and practices in the construction industry, it adoption still faces particularly in developing countries. One of the primary challenges is the variability in production processes, which can result in inconsistent and hard-to-interpret data. According to Francioso et al. (2023), the lack of precise data regarding production conditions and the specific processes used to manufacture construction materials compromises the validity of LCA analyses. This absence of detailed information makes it difficult to compare different materials and technologies, thus reducing the reliability of conclusions drawn from LCA results. Additionally, the complexity of construction systems, which often involve multiple materials and their interactions, adds further challenges to the modeling process. The main challenges include the complexity of obtaining reliable and regionalized data, the lack of adequate databases, and difficulties in comparing studies due to methodological and geographic variations (Asadollahfardi et al., 2019; Katebi et al., 2023). The challenge associated with the technical complexity of the methodology and the need to train professionals responsible for implementing LCA are also mentioned (Katebi et al., 2023).

The adoption of LCA in developing countries faces even more substantial barriers. In Sri Lanka, Amarasinghe et al. (2021) highlight that awareness of LCA among construction professionals remains extremely limited. While some consultants have received training, the majority of industry professionals lack knowledge of the subject and do not actively seek continuous updates. Furthermore, there is insufficient organizational support for implementing LCA, and unlike in developed countries, there is no legislation requiring its use. The absence of local databases further complicates the data collection process, making LCA adoption more challenging.

Similarly, in South Africa, Kwofie et al. (2020) note that despite recognizing LCA as a vital tool for sustainable development in the construction industry, its usage remains low due to structural, theoretical, and practical barriers. These include a lack of effective government support, limited education on LCA, and the absence of robust databases. Overcoming these challenges requires creating government support systems, investing in education and training, and developing accurate databases to facilitate LCA's adoption as a decisive tool for sustainability in construction.

In Brazil, Zocche (2014) observes that while there is significant academic interest in LCA, there are substantial difficulties in establishing partnerships with companies to apply this methodology, which limits its potential as an innovation tool in the industry. The lack of national databases specific to LCA is also a major obstacle to its effective implementation. These barriers hinder LCA's practical application and limit its potential contribution to innovation in the construction industry.

Addressing these challenges requires a multifaceted approach. This includes developing standardized methodologies, improving data quality and availability, integrating socio-economic considerations into LCA, and fostering collaboration among stakeholders. Moreover, stronger government support, investments in education and training, and the development of robust databases are crucial to overcoming the obstacles to LCA implementation. By doing so, the full potential of LCA can be realized in promoting sustainable practices within the construction industry, both in developing and developed countries.

It is recommended to strengthen the technical training of professionals, develop regional databases specific to the construction sector, and encourage the adoption of specialized software such as SimaPro and BIM tools, enabling detailed and representative analyses (Asadollahfardi et al., 2019; Katebi et al., 2023; Partonia et al., 2024). In addition, government incentive strategies and specific regulations can expand the practical adoption of the methodology.

FINAL CONSIDERATIONS

The studies reviewed reinforce the fundamental role of LCA as a tool for promoting sustainable practices in the construction sector. LCA provides a detailed view of environmental impacts throughout the life cycle of materials, identifying opportunities to reduce CO_2 emissions, save energy, and minimize the use of natural resources through alternatives such as industrial waste and agricultural by-products. Furthermore, emerging technologies, such as 3D printing and nanotechnology, offer new pathways for sustainable innovation in the sector.

However, significant challenges persist, such as obtaining reliable data for each stage of the analysis and the complexity of production systems, which may compromise the representativeness of the results. However, significant challenges persist, such as obtaining reliable data for each stage of the analysis and the complexity of production systems, which may compromise the representativeness of the results. To address these issues, policymakers should develop regulatory frameworks that mandate or incentivize the use of LCA in project approvals and material selection processes. Industry professionals could benefit from integrating LCA findings into their sustainability strategies, facilitating informed decisions on material selection and construction practices. Additionally, aligning LCA results with existing sustainability certification systems, such as LEED or BREEAM, would further encourage the adoption of environmentally responsible construction methods.

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