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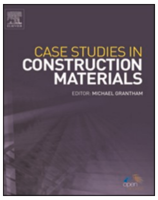

Life Cycle Assessment of construction materials: Methodologies, applications and future directions for sustainable decision-making

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ABSTRACT

This review paper presents a comprehensive analysis of Life Cycle Assessment (LCA) methodologies applied to construction materials. It begins with an introduction highlighting the significance of LCA in the construction industry, followed by an overview of LCA principles, phases and key parameters specific to construction materials. The methodological approaches utilised in LCA, including inventory analysis, impact assessment, normalisation, allocation methods and uncertainty analysis, are discussed in detail. The paper then provides a thorough review of LCA studies on various construction materials, such as cement, concrete, steel and wood, examining their life cycle stages and environmental considerations. The review also explores recent advances in LCA for construction materials, including circular economy principles, renewable alternatives, technological innovations and policy implications. The challenges and future directions in LCA implementation for construction materials are discussed, emphasising the need for data quality, standardisation, social aspects integration and industry-research collaboration. The provides valuable insights for researchers, policymakers and industry professionals to enhance sustainability in the construction sector through informed decision-making based on LCA.

1. Introduction

The construction industry has a significant impact on the environment, accounting for a substantial portion of resource consumption, energy use and greenhouse gas emissions. Construction materials play a crucial role in determining the sustainability of buildings and infrastructure. Life Cycle Assessment (LCA) is a valuable tool that allows for a comprehensive evaluation of the environmental impacts associated with construction materials throughout their entire life cycle. LCA considers the environmental burdens associated with various stages, including raw material extraction, manufacturing, transportation, construction, use and disposal. It provides a holistic and systematic approach to assess the environmental performance of materials and identify opportunities for improvement. LCA studies quantify impacts such as carbon emissions, energy consumption, water usage, air pollution, waste generation and ecosystem depletion [115,117,148].

Firstly, LCA allows for a thorough evaluation of the environmental impacts associated with construction materials. By considering the entire life cycle of these materials, from extraction to disposal, LCA provides a comprehensive understanding of their environmental footprint [107,109,185]. This insight enables decision-makers to identify the most significant areas of impact and implement targeted strategies for improvement. Secondly, LCA facilitates the comparison and selection of construction materials based on their

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environmental performance (Bribian et al., 2011; Martinez-Rocamora et al., 2016). Through quantifying and assessing impacts such as resource depletion, energy consumption, emissions and waste generation, LCA supports informed decision-making. It empowers individuals to choose more sustainable materials, encouraging the adoption of environmentally friendly practices in the construction industry.

Furthermore, LCA plays a vital role in design optimisation. It offers valuable insights into the environmental implications of design choices, empowering architects, engineers and designers to make informed decisions. By considering the life cycle impacts, LCA helps optimise the environmental performance of construction projects [164,214,59]. It guides material selection, design modifications, energy efficiency improvements and waste reduction strategies, ultimately leading to more sustainable and eco-conscious designs. In addition, LCA studies contribute to the development of environmental policies and regulations within the construction sector [159,9]. The scientific foundation provided by LCA findings assists governments and regulatory bodies in establishing standards, guidelines and certifications [182,73]. By encouraging the use of sustainable construction materials, LCA supports the implementation of regulations aimed at reducing the industry's environmental impact and driving progress toward sustainability goals.

Lastly, effective communication of LCA findings to stakeholders is essential. By providing transparent and scientifically grounded information, LCA fosters awareness and understanding among clients, investors, suppliers and the public. It promotes environmentally responsible decision-making and encourages the adoption of sustainable practices in the construction industry [150,151,196]. By integrating LCA into the construction sector, we can assess and enhance the environmental sustainability of construction materials, foster the adoption of sustainable practices and contribute to the creation of a greener built environment for future generations.

The motivation behind the review paper on LCA of Construction Materials stems from the increasing need to address the environmental impact of the construction industry. With growing concerns about climate change and resource depletion, there is a demand for sustainable and eco-friendly practices. The review paper aims to provide a comprehensive overview of LCA as a tool for evaluating the environmental performance of construction materials. By synthesising existing research and highlighting key findings, the paper seeks to promote a deeper understanding of LCA's significance, its application in material selection and design optimisation and its role in supporting policy development. Ultimately, the review paper aims to contribute to a more sustainable and environmentally conscious construction industry.

One limitation of the paper is that the scope may limit the depth of analysis on specific aspects of LCA, such as methodological intricacies or regional variations. The general nature of the review may not address specific challenges or constraints faced in different contexts. Lastly, the paper's length constraint may restrict the level of detail and comprehensive coverage of all relevant aspects of LCA.

This review paper offers readers a comprehensive analysis of LCA methodologies applied to construction materials. It covers the principles, phases, and key parameters specific to LCA in the construction industry. The paper provides a detailed discussion of methodological approaches such as inventory analysis, impact assessment, normalization, allocation methods, and uncertainty analysis. It also presents a thorough review of LCA studies on various construction materials, examining their life cycle stages and environmental considerations. Additionally, the paper explores recent advances in LCA for construction materials, including circular economy principles, renewable alternatives, technological innovations, and policy implications. The insights provided in this paper equip researchers, policymakers, and industry professionals with valuable information to enhance sustainability in the construction sector through informed decision-making based on LCA.

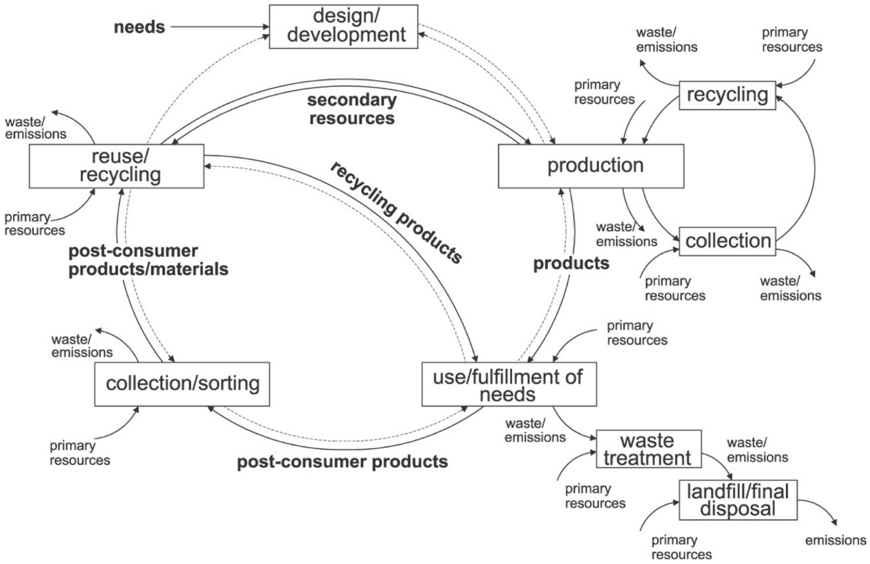

Fig. 1. Schematic representation of a generic life cycle of a product (the full arrows represent material and energy flows, while the dashed arrows represent information flows) [182].

2. Life Cycle Assessment (LCA): an overview

2.1. Definition, principles and phases of LCA

Life Cycle Assessment (LCA) is a systematic methodology used to evaluate the environmental impacts associated with a product, process, or activity throughout its entire life cycle, from raw material extraction to end-of-life disposal. LCA takes into account all stages, including manufacturing, transportation, use and disposal. It considers various environmental impact categories such as energy consumption, resource depletion, emissions and waste generation. LCA involves collecting and analysing data on inputs and outputs at each stage of the life cycle to assess the environmental performance of the assessed system. The goal is to provide a holistic and quantitative analysis that enables informed decision-making and the identification of opportunities for improving the environmental sustainability of products and activities. Fig. 1 [182] illustrates a simplified representation of the product life concept, commonly known as a "life cycle," which encompasses interconnected phases. These phases include loops that depict actions like the reuse and recycling of post-consumer products (occurring during the end-of-life phase) or the recycling of production scrap. The diagram highlights the cyclical nature of these processes, emphasising the potential for resource conservation and waste reduction through sustainable practices.

The study by Snigdha et al. [210] explored the interdependence between the design and development phase and the other stages of the product life cycle, specifically focusing on the environmental footprints of disposable and reusable personal protective equipment (PPE) in the form of body coveralls. By employing a product life cycle approach, the researchers analysed the environmental impacts associated with both disposable and reusable PPE, considering factors such as raw material extraction, manufacturing, use, and end-of-life disposal. The findings highlight the importance of considering design choices and material selection in minimising the environmental footprints of PPE throughout its entire life cycle, emphasizing the need for sustainable design practices and informed decision-making in the development phase.

LCA is guided by a set of principles that ensure a systematic and reliable approach to evaluating the environmental impacts of a product or system. These principles include considering the entire life cycle, defining clear boundaries, maintaining transparency in data and methods, accounting for all relevant impacts, applying consistent approaches, focusing on relevant impact categories and promoting continuous improvement. By adhering to these principles, LCA enables comprehensive and objective assessments, facilitates meaningful comparisons and supports informed decision-making for sustainable development. It provides valuable insights into the environmental performance of construction materials, helping stakeholders identify areas for improvement, make informed choices and contribute to more sustainable practices in the construction industry.

The standards and reports in the International Organization for Standardization (ISO) 14000 series provide, in general, an accepted framework and terminology for LCA (although not practical insights) as depicted in Table 1. Various phases of an LCA according EN ISO 14040 are summarised in Fig. 3. The phases of LCA typically encompass the following:

1. Goal and Scope Definition: This phase is crucial for establishing the purpose and boundaries of the LCA study. It involves clearly defining the goals, objectives and intended applications of the assessment [43]. The functional unit, which represents the quantifiable measure of the product's performance, is determined. The system boundaries are defined to identify which processes and activities should be included in the assessment. Additionally, the selection of impact categories is made to guide the evaluation of environmental, social and economic impacts.
2. Life Cycle Inventory (LCI): In this phase, data is collected on the energy and material inputs, emissions and waste outputs associated with each stage of the product's life cycle [181]. This involves gathering information on raw material extraction, manufacturing

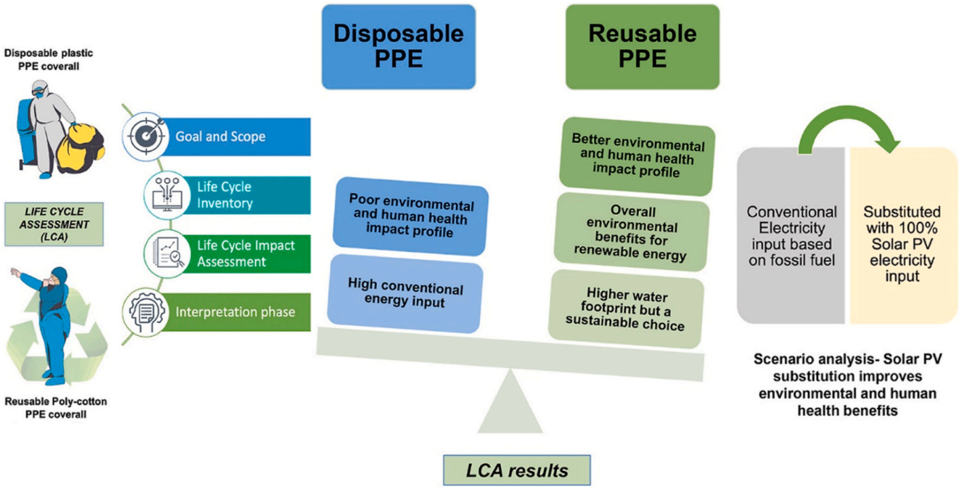

Fig. 2. Environmental footprints of disposable and reusable personal protective equipment — a product life cycle approach [210].

Table 1
Framework and terminology for LCA.

ISO 14040:1997	Life cycle assessment – Principles and framework
ISO 14041:1998	Life cycle assessment – Goal & scope definition and inventory analysis
ISO 14042:2000	Life cycle assessment – Life cycle impact assessment
ISO 14043:2000	Life cycle assessment – Life cycle interpretation
ISO/TR 14047	Life cycle assessment – Examples of application of ISO 14042
ISO/TS 14048:2002	Life cycle assessment – Data documentation format

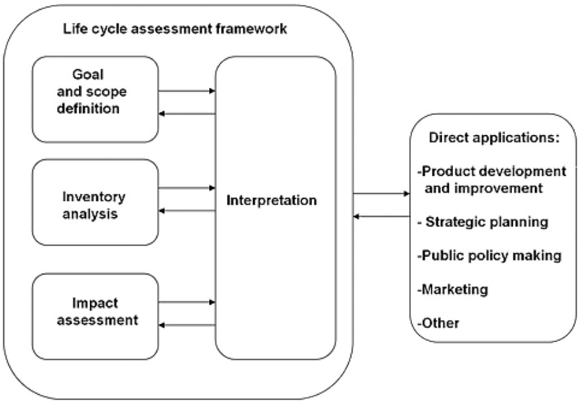

Fig. 3. Phases of an LCA according EN ISO 14040:2006 [215].

processes, transportation, product use and end-of-life scenarios. Data sources can include industry databases, literature, measurements and expert knowledge. The collected data is then organised and quantified to create a life cycle inventory database.

3. Life Cycle Impact Assessment (LCIA): The LCI data is analysed and evaluated in this phase to assess the potential environmental impacts. LCIA involves characterising and quantifying the inputs and outputs in relation to selected impact categories [12,188,82]. Various impact assessment methods, such as the ReCiPe (Resource Use, Climate Change and Ecosystem Quality) or IMPACT 2002 + , can be employed to translate the LCI results into impact scores [24,95]. This phase helps to identify the significant environmental issues associated with the product and provides a basis for comparison between different alternatives.
4. Interpretation: The interpretation phase aims to make sense of the LCA results and draw meaningful conclusions. It involves analysing and synthesising the data, identifying patterns and trends and assessing the significance of the findings [180]. Sensitivity analysis may be conducted to explore the influence of key parameters or assumptions on the results [71,72]. Comparisons between different scenarios or products are made to evaluate trade-offs and identify opportunities for improvement. The interpretation phase provides insights for decision-making and helps stakeholders understand the implications of the LCA results.
5. Reporting: The final phase involves documenting and communicating the LCA findings. A comprehensive report is prepared, which includes a detailed description of the methodology, data sources, assumptions and limitations. The report should present the results in a clear and transparent manner, using appropriate visualisations and graphics to enhance understanding. The intended audience may include policymakers, industry professionals, researchers and the public. Effective communication of the LCA results is essential for informed decision-making and facilitating sustainability discussions.

Throughout the LCA process, it is important to ensure data quality, consider uncertainty and variability and engage relevant stakeholders to provide input and validate the findings. The LCA process is iterative, allowing for refinement and improvement based on feedback and new information.

2.2. Key parameters and indicators in LCA

In LCA, various parameters and indicators are used to assess the environmental impacts of products, processes, or activities throughout their life cycle. Here are some key parameters and indicators commonly considered in LCA:

1. Energy Consumption: Energy consumption is a crucial parameter in assessing the environmental impact of a product's life cycle [106]. It quantifies the amount of energy utilised at different stages, including raw material extraction, manufacturing, transportation, product use, and end-of-life processes. By measuring energy consumption, valuable insights are gained into the energy efficiency of the system and its corresponding environmental consequences. The measurement can be expressed in units such as joules or kilowatt-hours, allowing for comparisons and evaluations across different products or processes. Understanding energy

consumption patterns throughout the life cycle enables informed decision-making and the implementation of strategies to enhance energy efficiency and reduce environmental impacts [158,64].

2. Greenhouse Gas (GHG) Emissions: GHG emissions, encompassing carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), play a critical role in assessing the impact of climate change [51,60,127]. LCA allows for the assessment and quantification of these emissions across different stages of the product's life cycle. By expressing these emissions in carbon dioxide equivalents (CO_2e), which accounts for their varying global warming potentials, LCA provides a comprehensive evaluation of the carbon footprint and global warming potential of the system under study. This enables decision-makers to understand and mitigate the climate change impact associated with the assessed system, facilitating the development of strategies to reduce GHG emissions and promote sustainability [17,219].
3. Water Usage: Water consumption and water pollution are crucial considerations in LCA. The assessment of water usage involves quantifying the amount of water utilised at each stage of the product's life cycle, encompassing extraction, manufacturing, product use, and end-of-life processes [136,171]. Furthermore, LCA evaluates the potential impacts on water resources, including issues like water scarcity or pollution. Understanding water usage provides valuable insights into the water footprint and potential ecological consequences associated with the assessed system. This information aids decision-making by highlighting areas where water efficiency can be improved, promoting responsible water management practices, and minimising the ecological impacts on water resources.
4. Material Consumption: Material inputs play a critical role in LCA as they are quantified and evaluated throughout the product's life cycle [11,56]. This includes the assessment of raw materials and intermediate products, considering their extraction, production processes, and associated environmental impacts. By analysing the amount and types of materials used at each stage, LCA provides valuable insights into resource depletion, potential impacts on biodiversity and ecosystems, and the necessity for sustainable material management strategies [167,22,25]. Understanding material consumption enables the identification of opportunities for resource efficiency, the promotion of circular economy principles, and the development of more sustainable practices in material sourcing, production, and disposal.
5. Waste Generation: In LCA, the quantity and composition of waste generated at various stages of the assessed system's life cycle are taken into account. This parameter encompasses solid waste, hazardous waste, and wastewater. By evaluating waste generation, LCA facilitates the identification of opportunities for waste reduction, recycling, and appropriate disposal methods to minimise environmental impacts [98,160,44]. It also addresses concerns related to landfill usage, the release of hazardous substances, and pollution prevention. By considering waste management strategies, LCA promotes the adoption of sustainable practices that mitigate the environmental consequences associated with waste generation and disposal [161,235].
6. Ecotoxicity: Ecotoxicity indicators play a crucial role in LCA by evaluating the potential toxic effects of substances on ecosystems and organisms [173,2,28]. These indicators assess the impacts of emissions and waste discharges on aquatic and terrestrial ecosystems. By considering factors such as persistence, bioaccumulation, and toxicity of substances, ecotoxicity indicators provide valuable insights into the potential ecological disruption caused by the assessed system. They help identify areas for improvement and guide decision-making to reduce environmental harm and promote sustainable practices. Through the assessment of ecotoxicity, LCA contributes to the protection and preservation of ecosystems and the organisms that rely on them [4,5].
7. Human Health Impacts: LCA incorporates indicators to assess the potential impacts on human health throughout the various stages of a product's life cycle [209,84]. Parameters such as human toxicity and carcinogenicity are evaluated, considering exposure to hazardous substances. By assessing human health impacts, LCA helps identify potential risks and prioritize interventions to minimise health hazards. This information guides decision-making to promote the development of safer products and processes. By considering the health implications associated with a product's life cycle, LCA contributes to the protection and enhancement of human health, facilitating the adoption of sustainable and healthier alternatives in various industries [8,86,156].
8. Resource Depletion: LCA takes into account the depletion of finite resources, including fossil fuels, minerals, and water resources [112,131,183]. Indicators such as fossil fuel depletion potential and mineral extraction potential are used to quantify the impacts on non-renewable resources. By assessing resource depletion, LCA provides insights into the long-term sustainability of the system being evaluated. These indicators help identify the environmental consequences of resource extraction and consumption, enabling the development of resource-efficient alternatives. By considering resource depletion in LCA, decision-makers can make informed choices that minimise the reliance on finite resources and promote the use of more sustainable and renewable alternatives.

These parameters and indicators play a crucial role in providing a comprehensive assessment of the environmental impacts associated with the system being evaluated in LCA. By quantifying and evaluating various impact categories, such as energy consumption, GHG emissions, water usage, material inputs, waste generation, ecotoxicity, human health impacts, and resource depletion, stakeholders can gain valuable insights into the environmental performance of the assessed system. This information enables them to make informed decisions, prioritise environmental improvements, and identify opportunities for implementing more sustainable practices. By considering these parameters and indicators, LCA facilitates the development of strategies and actions that promote environmental sustainability and support the transition towards a more sustainable future.

2.3. *Benefits and limitations of LCA in assessing construction materials*

LCA offers several benefits in assessing construction materials, including a holistic perspective on environmental impacts, comparative analysis for informed decision-making, promotion of sustainable design, identification of improvement opportunities, stakeholder engagement and compliance with regulations. However, LCA also has limitations, such as challenges related to data availability and quality, simplified modelling and assumptions, subjective boundary setting, scope limitations, limited time perspective, complexity and interactions, interpretation subjectivity, resource intensity, dynamic nature of assessments and communication challenges. Recognising these benefits and limitations helps stakeholders leverage the strengths of LCA while considering its constraints in accurately assessing construction materials' environmental performance.

Benefits of LCA in assessing construction materials:

1. Holistic Perspective: LCA provides a holistic view of the environmental impacts associated with construction materials [23,34,77,126]. It considers the entire life cycle, including raw material extraction, manufacturing, transportation, use and disposal. This comprehensive approach allows for a more accurate understanding of the materials' environmental performance and potential improvements.
2. Comparative Analysis: LCA enables the comparison of different construction materials based on their environmental impacts [11,70,138]. It helps identify which materials have lower energy consumption, greenhouse gas emissions, water usage and waste generation. This information allows stakeholders to make informed decisions and select materials with better environmental profiles.
3. Sustainable Design and Decision-Making: LCA supports sustainable design and decision-making processes [50,228]. By considering environmental impacts from the early stages of a project, LCA helps designers and decision-makers optimise material choices and construction methods to minimise environmental burdens. It promotes the selection of materials that have a lower overall environmental impact.
4. Environmental Performance Improvement: LCA serves as a tool for continuous improvement in the construction industry. By identifying environmental hotspots and areas with high impacts, LCA drives innovation and encourages the development of more sustainable materials and processes [21,57,128,170]. It facilitates the adoption of greener technologies, waste reduction strategies and resource-efficient practices.
5. Regulatory Compliance and Certification: LCA is often required for regulatory compliance and certification purposes. Many green building rating systems and certification programs, such as LEED and BREEAM, require LCA to assess the environmental performance of construction materials. Conducting LCA studies can help meet these requirements and demonstrate a commitment to sustainability.
6. Stakeholder Engagement and Communication: LCA results can be effectively communicated to stakeholders, including project teams, manufacturers, policymakers and consumers. It facilitates transparent communication about the environmental impacts of construction materials, promoting awareness and understanding [47]. LCA fosters engagement and collaboration among stakeholders towards more sustainable practices.
7. Life Cycle Thinking: LCA encourages a shift towards life cycle thinking in the construction industry [124,211,58,94]. It highlights the importance of considering environmental impacts beyond individual stages of a material's life cycle. By assessing upstream and downstream processes, LCA encourages the integration of sustainability considerations throughout the entire supply chain, leading to more sustainable construction practices.
8. Cost Reduction and Resource Efficiency: LCA can help identify opportunities for cost reduction and resource efficiency. By analysing material flows, energy consumption and waste generation, LCA uncovers potential areas for optimisation and waste minimisation [99,119,39]. This can lead to reduced operational costs, improved resource management and enhanced overall project economics.
9. Regulatory Compliance and Public Image: LCA assists in meeting regulatory requirements related to environmental impact assessments [20,234]. By conducting LCA studies, companies can ensure compliance with environmental regulations and demonstrate a commitment to sustainable practices. This can enhance their public image, strengthen stakeholder relationships and attract environmentally conscious clients.
10. Decision-Making Transparency: LCA provides a transparent and science-based approach to decision-making [168]. The use of standardised methodologies and data transparency increases the credibility of the assessment. This transparency helps stakeholders evaluate the environmental performance of construction materials objectively and make well-informed decisions based on reliable information.

Overall, LCA offers numerous benefits in assessing construction materials. It supports sustainable design, promotes innovation and facilitates informed decision-making for greener construction practices. By considering the full life cycle of materials, LCA enables the construction industry to minimise environmental impacts and move towards more sustainable and resource-efficient solutions.

Limitations of LCA in assessing construction materials:

1. Data Availability and Quality: LCA heavily relies on accurate and reliable data to assess the environmental impacts of construction materials [7,33,75]. However, obtaining comprehensive and high-quality data throughout the entire life cycle can be challenging. Data gaps, inconsistencies and uncertainties can impact the accuracy and reliability of LCA results, limiting the robustness of the assessment.
2. Simplified Models and Assumptions: LCA involves the use of simplified models and assumptions to represent complex systems. These simplifications may not fully capture the variability and intricacies of real-world conditions. Assumptions made during the modelling process can introduce uncertainties and affect the accuracy and representativeness of the assessment [97,197].
3. Boundary Setting: Defining the system boundaries and functional unit in LCA is a subjective process and can influence the outcomes. Different boundary settings can lead to different conclusions regarding the environmental impacts of construction

materials [61,77]. The choice of boundaries may exclude certain impacts or overlook significant stages in the life cycle, limiting the comprehensiveness of the assessment.

4. Scope Limitations: LCA primarily focuses on environmental impacts and may not fully address other important aspects of sustainability, such as social and economic considerations [83,89]. While LCA provides valuable insights into the environmental performance of construction materials, it should be complemented with other assessment methods to achieve a more comprehensive sustainability analysis.
5. Limited Time Perspective: LCA results are based on the current understanding of environmental impacts and technological capabilities. However, the construction industry is dynamic and new technologies, materials and practices emerge over time. LCA may not fully capture future advancements, limiting its ability to guide long-term decision-making [62].
6. Complexity and Interactions: The construction sector involves complex systems with numerous interactions between materials, processes and stakeholders. LCA simplifies these complexities, which may overlook certain interactions or interdependencies that can influence environmental impacts [42]. It is challenging to capture the full complexity of the construction industry within an LCA framework.
7. Interpretation and Subjectivity: The interpretation of LCA results requires subjective judgment and depends on the priorities and values of stakeholders. Different interpretations and weighting of environmental impacts can lead to varying conclusions and recommendations. This subjectivity introduces a level of uncertainty and can hinder the comparability of LCA studies [232].
8. Resource Intensive: Conducting a comprehensive LCA study requires substantial resources, including time, expertise and data [181]. It can be cost-prohibitive for small-scale projects or organisations with limited resources. This limitation may restrict the widespread application of LCA in the assessment of construction materials.
9. Dynamic Nature of Assessments: LCA assessments are based on specific assumptions, technology choices and inventory data at a particular point in time. As knowledge and understanding of environmental impacts evolve, LCA assessments need to be updated regularly to reflect the latest information and ensure their accuracy and relevance [190].
10. Communication Challenges: Communicating LCA results to various stakeholders can be challenging due to the complexity of the assessment and the need for effective knowledge transfer. Presenting LCA findings in a clear and understandable manner to decision-makers, policymakers and the public requires effective communication strategies.

Understanding these limitations is crucial when using LCA to assess construction materials. It is important to consider them alongside the benefits and to exercise caution in interpreting and applying the results to ensure a balanced and informed decision-making process. Integrating complementary assessment methods and continuous improvement of data quality and modelling techniques can help address some of these limitations over time.

3. Methodological approaches in LCA for construction materials

Methodological approaches in LCA for construction materials involve several key aspects. Inventory analysis focuses on quantifying inputs, outputs and emissions throughout the life cycle. Impact assessment evaluates the environmental effects of these inputs and emissions, considering categories such as greenhouse gas emissions, energy consumption and water usage. Interpretation and normalization help in comprehending and comparing the results, often by expressing them in standardized units. Allocation methods and system boundaries define how to allocate impacts among co-products and set the scope of the assessment. Uncertainty and sensitivity analysis assess the reliability and robustness of the results. These methodological considerations enable more accurate and comprehensive environmental assessments of construction materials, aiding in sustainable decision-making.

3.1. Inventory analysis

Inventory analysis plays a vital role in conducting a comprehensive LCA for construction materials [179,224,48]. It involves a systematic and detailed examination of the material's entire life cycle, from the extraction of raw materials to the disposal stage. During inventory analysis, data is collected on various aspects, including the consumption of resources, energy use, water consumption, emissions to air, water, soil and waste generation [10,110,75]. These data points are carefully quantified and organised in an inventory table, which provides a structured overview of the material's environmental inputs and outputs at each life cycle stage.

The inventory analysis serves multiple purposes. Firstly, it allows for a comprehensive assessment of the material's environmental impacts, enabling researchers and practitioners to identify and understand the environmental hotspots and areas of concern. This identification of hotspots can guide the prioritisation of efforts for environmental improvement and inform decision-making processes. Furthermore, inventory analysis provides a foundation for subsequent phases of LCA, such as impact assessment and interpretation [181,203,81]. By accurately quantifying the environmental inputs and outputs, it enables the estimation of potential environmental impacts associated with the construction material. This impact assessment phase evaluates the consequences of these inputs and outputs on various impact categories such as global warming potential, resource depletion, human health impacts and ecosystem damage.

The complete life cycle stages of building materials encompass the value chain or supply chain processes [141,30]. This involves the extraction of raw materials, processing and manufacturing of these materials, transportation, construction and retrofitting, utilisation and maintenance, demolition and waste management, as well as disposal and circular processing through methods such as reuse, recycling and recovery (refer to Fig. 4). LCA serves as a valuable technique for evaluating the potential environmental impacts linked to a product, enabling the assessment of environmental consequences across all stages of the building materials' lifespan (refer to Fig. 5).

The interpretation of the inventory analysis results is an important step in LCA. It involves analysing and understanding the implications of the collected data, considering factors such as spatial and temporal boundaries, data quality and uncertainties. The interpretation phase enables stakeholders to make informed decisions, identify improvement opportunities and compare different construction materials or strategies [217]. Moreover, inventory analysis supports the evaluation of different allocation methods and system boundaries [101,87]. It allows researchers to define the functional unit and allocation rules for distributing the environmental burdens among co-products or by-products associated with the construction material. Determining appropriate system boundaries is crucial for accurately assessing the material's life cycle impacts and avoiding potential shifts of burdens between life cycle stages or processes. Additionally, inventory analysis facilitates the consideration of uncertainty and sensitivity analysis [13,14,223]. LCA practitioners can identify and quantify uncertainties associated with data inputs, models and assumptions. Sensitivity analysis helps understand the influence of different parameters and assumptions on the overall results, providing insights into the robustness and reliability of the assessment.

3.2. *Impact assessment*

The application of LCA in Environmental Impact Assessment (EIA) for construction materials is a valuable tool for evaluating the environmental consequences of these materials throughout their entire life cycle. LCA offers a systematic and comprehensive approach to quantify and assess the potential environmental impacts associated with construction materials, considering their extraction, production, transportation, use, and disposal stages. By considering the entire life cycle, LCA provides a holistic understanding of the environmental footprint of construction materials, enabling stakeholders to identify and prioritize areas for environmental improvement [137,194,217]. This integration of LCA into EIA ensures that environmental considerations are adequately addressed in decision-making processes related to construction materials, promoting more sustainable practices and outcomes.

LCA enables a comprehensive analysis of various environmental impact categories associated with construction materials, including greenhouse gas emissions, energy consumption, air and water pollution, land use, and waste generation. By considering the entire life cycle of these materials, LCA provides a holistic perspective on their environmental performance, allowing for the identification of potential environmental hotspots and improvement opportunities. During the EIA phase, LCA integrates detailed data on material inputs, energy consumption, emissions, and waste generation with impact characterisation models [126,212,213]. These models convert the inventory data into environmental impact indicators, facilitating the comparison and aggregation of results across different impact categories. This step helps stakeholders identify significant environmental impacts and understand the relative contributions of different life cycle stages and processes.

Through the use of LCA in EIA, decision-makers can assess the environmental consequences associated with different construction materials and make informed choices. LCA allows for the comparison of various materials, design alternatives, and construction practices, taking into account their potential environmental impacts [70,116,202]. This information aids in the identification of environmentally preferable options and the formulation of sustainable strategies to mitigate environmental impacts. Moreover, LCA can uncover opportunities for improvement and innovation within the construction industry. It provides insights into the environmental performance of specific materials, highlighting areas where resource efficiency, energy conservation, emission reduction, and waste management practices can be enhanced. LCA empowers stakeholders to evaluate the potential benefits of adopting alternative materials, implementing recycling or reuse strategies, and optimizing design and construction processes.

LCA is guided by the principle of assessing and mitigating the impacts associated with different materials and stages throughout the life cycle of building materials. Each process activity within the life cycle involves the consumption of energy and resources, as well as the release of pollutants. Fig. 6 illustrates the variation in inputs and outputs across these activities [94]. Extraction and manufacturing activities are responsible for approximately 90% of the environmental pollutants generated in the life cycle, excluding treatment processes. During transportation and construction, emissions of nitrogen oxides (NOx) and carbon dioxide (CO_2) from fossil fuel

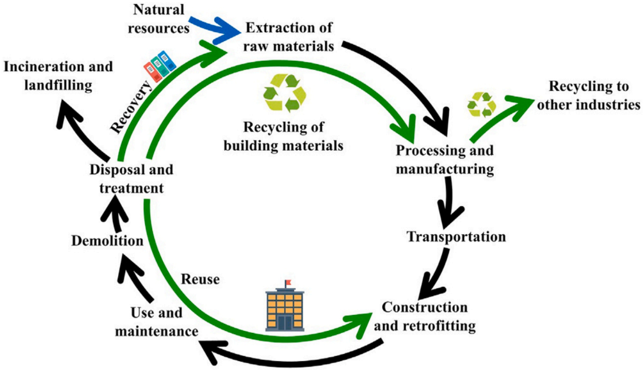

Fig. 4. Conceptual diagram of construction materials life cycle [94].

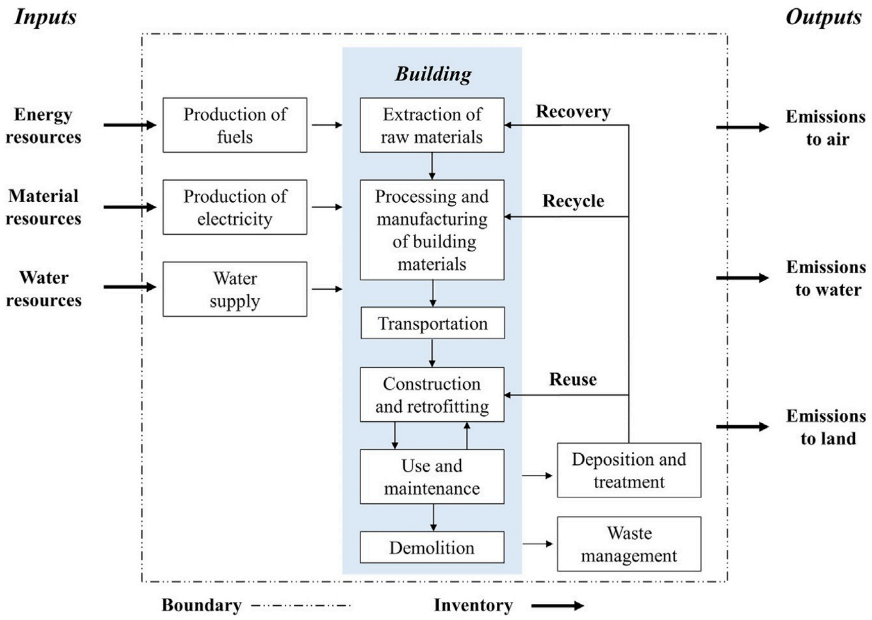

Fig. 5. Life Cycle Assessment application framework for building materials [94].

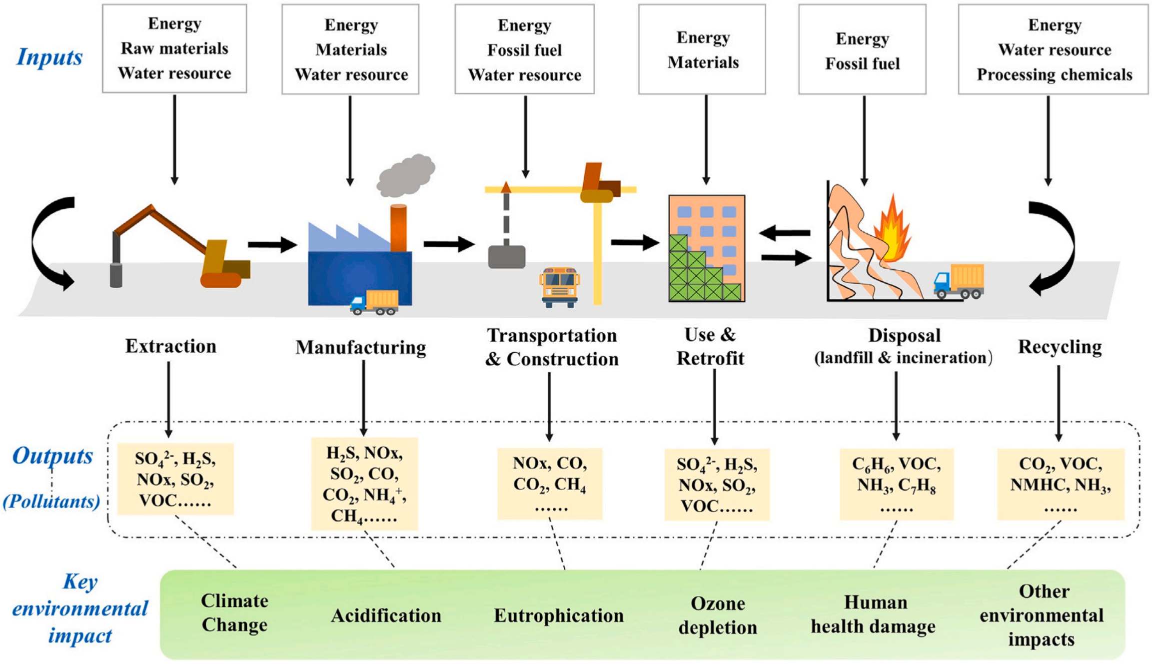

Fig. 6. Key Environmental impacts during the life cycle of construction materials [94].

consumption contribute to environmental impacts. Waste treatment in buildings, particularly the handling of waste plaster and wood, leads to the accumulation of organic acids in landfills. Furthermore, the incineration of wood, plastic, and paper releases pollutants such as ammonia (NH_3), heavy metal ions, and volatile organic compounds (VOCs), which pose risks to human health and ecological systems.

In summary, the application of LCA in EIA for construction materials provides a comprehensive understanding of the environmental implications of these materials and facilitates informed decision-making for sustainable practices. Through the evaluation of various environmental impact categories and the consideration of the entire life cycle, LCA enables the identification of environmentally preferable solutions, encourages resource efficiency, and promotes the adoption of sustainable construction practices. By integrating LCA into the assessment process, stakeholders can make well-informed choices that minimise environmental impacts, optimize resource utilization, and contribute to the transition towards more sustainable construction practices.

3.3. Interpretation and normalisation

The interpretation and normalisation approach in LCA for construction materials is a vital component in extracting valuable insights from the LCA results and providing meaningful information to stakeholders. Once the inventory analysis and impact assessment phases are completed, the interpretation stage focuses on analysing and comprehending the environmental implications revealed by the LCA findings [152,159,63]. LCA practitioners carefully examine the results to identify significant environmental impacts throughout the life cycle of construction materials. They analyse the data, consider the established system boundaries and assumptions made during the assessment, and interpret the findings within the specific context of the project or application. This process enables stakeholders to obtain a comprehensive understanding of the environmental performance of various materials and processes and assists in making informed decisions regarding sustainable practices.

The interpretation step in LCA for construction materials also encompasses the evaluation of the potential implications of the identified impacts [140,19,92]. Stakeholders assess the significance of these impacts in relation to environmental priorities, regulatory requirements, and sustainability goals. They carefully consider the trade-offs between different environmental indicators, such as greenhouse gas emissions, energy consumption, water use, and waste generation, to ensure informed decision-making. This evaluation process allows stakeholders to weigh the environmental consequences of different materials and processes, enabling them to make choices that align with their environmental objectives. By considering the broader context and relevant sustainability criteria, stakeholders can prioritise actions and strategies that effectively address the identified impacts.

In addition to interpretation, the normalisation approach plays a crucial role in LCA for construction materials by providing a relative perspective on the environmental impacts. Normalisation involves comparing the impact indicators obtained from the assessment to reference values or benchmarks [32,46]. The main objective of normalisation is to contextualise the results and facilitate their understanding. By normalising the impact indicators, stakeholders can assess the magnitude and significance of the environmental impacts in relation to established reference values. This allows for meaningful comparisons between different construction materials or processes and provides a basis for benchmarking and target setting. Normalisation can be achieved through various methods, such as using environmental or sustainability indicators, regional or national averages, or specific industry standards [18,174,187]. These reference values help stakeholders evaluate the performance of construction materials against established benchmarks, identify areas for improvement, and guide decision-making towards more sustainable practices.

Overall, the interpretation and normalisation approach in LCA for construction materials plays a vital role in effectively communicating LCA results to stakeholders. It enhances the relevance and understanding of the findings, enabling informed decision-making in the construction industry. Through interpretation, stakeholders can identify significant environmental hotspots and prioritize areas for improvement. Normalisation further supports this process by providing a comparative perspective, allowing for benchmarking and target setting. By fostering a comprehensive understanding of the environmental impacts, the interpretation and normalisation approach promote the adoption of sustainable practices and materials, driving continuous improvement in the sustainability performance of construction materials.

3.4. Allocation methods and system boundaries

Allocation methods and system boundaries are critical aspects of LCA in the assessment of construction materials. They establish the scope and limits of the analysis, as well as the allocation of environmental burdens across various processes or products within a life cycle. Allocation methods are particularly relevant when multiple products or co-products are generated from a shared process or input. In the context of construction materials, this commonly occurs with the production of by-products or waste materials during manufacturing or extraction. Allocation methods ensure that the environmental impacts associated with these co-products or by-products are appropriately and fairly attributed, enabling a more accurate assessment of their sustainability performance [227,232].

Allocation methods in LCA for construction materials encompass a range of approaches, including mass-based allocation, economic allocation, energy allocation, and system expansion. Mass-based allocation distributes environmental burdens based on the mass of products or co-products, while economic allocation considers their economic value [238,27,49,85]. Energy allocation assigns burdens according to the energy content, while system expansion accounts for the potential impacts of alternative scenarios or technologies [133,31]. The selection of an allocation method depends on the specific objectives and context of the LCA study and should be transparently justified. It is crucial to ensure the chosen method is suitable and aligns with the assessment's goals, promoting consistency and reliability in the evaluation of environmental impacts.

System boundaries play a crucial role in LCA studies on construction materials as they define the scope and extent of the assessment. These boundaries typically encompass the entire life cycle of the materials, from raw material extraction to end-of-life stages, including manufacturing, transportation, use, and disposal. Defining the system boundaries is essential for capturing the full range of environmental impacts associated with the construction materials and preventing burden shifting between life cycle stages [67,146]. It allows for a comprehensive assessment that considers both direct and indirect processes, as well as upstream and downstream impacts. However, establishing system boundaries can be complex due to the interconnectedness of supply chains and the consideration of various factors. Transparency and consistency in defining the boundaries are crucial for ensuring the credibility and comparability of LCA results. Detailed documentation of the chosen system boundaries, including data sources and assumptions, facilitates the understanding and evaluation of the assessment's scope by stakeholders.

3.5. Uncertainty and sensitivity analysis

Uncertainty and sensitivity analysis are crucial components of LCA studies for construction materials. They assist in addressing the inherent variability, limitations, and uncertainties associated with data, models, and assumptions, thereby providing a deeper understanding of the robustness and reliability of LCA results. Uncertainty analysis focuses on quantifying and characterising the uncertainty within LCA inputs and outputs [130,36,88]. This involves identifying and assessing sources of uncertainty, such as data quality variations, measurement errors, parameter uncertainties, and assumptions made within the model. Monte Carlo simulations are commonly employed to propagate uncertainties throughout the LCA model, allowing for the generation of probability distributions for the results [35,37,129]. Sensitivity analysis, on the other hand, explores the impact of varying input parameters on the LCA outcomes, enabling the identification of influential factors and potential areas for improvement. Through these analyses, LCA studies for construction materials gain insights into the reliability of their findings, enhancing the decision-making process and supporting more informed and sustainable choices.

Sensitivity analysis is a valuable tool in LCA studies for construction materials as it examines the influence of input parameters on the outcomes. Its primary objective is to identify which parameters have the most significant impact on the results and to what extent changes in those parameters affect the outcomes. Sensitivity analysis can be conducted through various techniques, such as one-at-a-time analysis or more advanced approaches like global sensitivity analysis [195,222,226]. On the other hand, uncertainty analysis aims to quantify and characterise the uncertainties associated with LCA inputs and outputs. It helps in understanding the reliability and robustness of the LCA results. Uncertainty analysis identifies and assesses sources of uncertainty, such as data quality, measurement errors, and model assumptions. Monte Carlo simulations are commonly used to propagate uncertainties and generate probability distributions for the results.

Both sensitivity and uncertainty analyses provide valuable insights into the reliability, limitations, and confidence intervals associated with the LCA results for construction materials. They help decision-makers understand the range of possible outcomes and assess the influence of different input parameters on the conclusions drawn from the study. By accounting for uncertainties and conducting sensitivity analysis, LCA practitioners can enhance the transparency and credibility of the assessment [40,97,103]. Moreover, these analyses can guide data collection efforts and research priorities. They highlight areas where additional data or improved models are needed to reduce uncertainty and enhance the accuracy of LCA studies. This iterative process of refining data and models improves the overall quality and usefulness of LCA in evaluating the environmental performance of construction materials.

Transparency and documentation are essential in uncertainty and sensitivity analysis for LCA of construction materials. Clearly stating assumptions, data sources, and methodologies ensures reproducibility and enables stakeholders to evaluate the findings. Engaging experts and stakeholders provides valuable insights, enhances the robustness of the analysis, and encourages diverse perspectives. By following best practices, such as transparent reporting and incorporating expert judgment, uncertainties can be addressed effectively, and sensitivity analysis can identify influential parameters. This approach improves the reliability and relevance of LCA results, supports informed decision-making, and enhances the understanding of the potential impacts and limitations associated with the environmental assessment of construction materials.

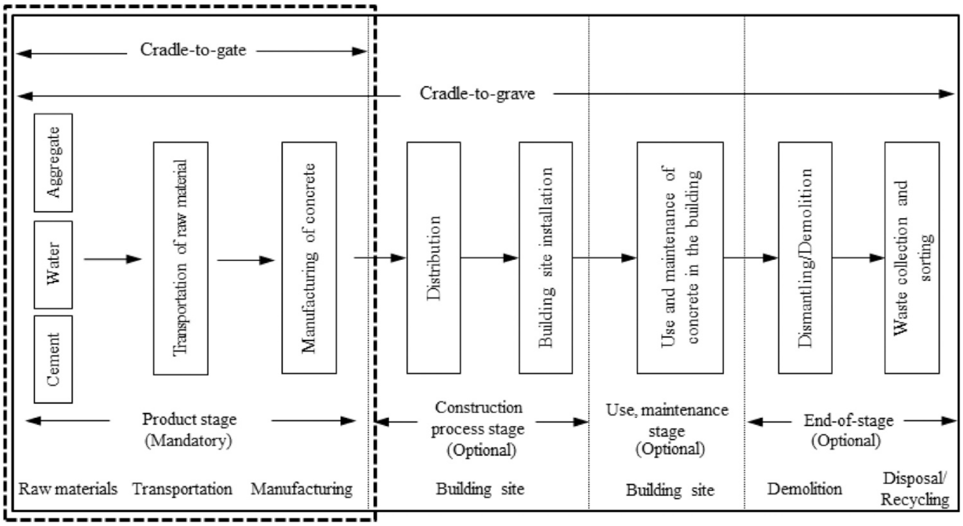

Fig. 7. System boundary of concrete LCA [111].

4. Review of LCA studies on construction materials

4.1. Cement and concrete

LCA studies on cement and concrete have been widely conducted to assess their environmental impacts throughout their life cycle. These studies analyse various stages, including raw material extraction, manufacturing, transportation, construction, use and end-of-life. Cement production, in particular, is known to have significant greenhouse gas emissions due to the energy-intensive process of clinker production. Fig. 7 shows the system boundary of concrete LCA. LCA studies aim to quantify the carbon footprint, energy consumption, water usage and other environmental indicators associated with cement and concrete production. They provide valuable insights into potential areas for improvement, such as the use of alternative materials, energy-efficient technologies and recycling practices, to reduce the environmental impact of these essential construction materials.

4.1.1. Raw materials extraction

LCA studies have played a vital role in evaluating the environmental impact of cement and concrete production. One important phase of this production process is the extraction of raw materials, which includes activities such as quarrying limestone, clay mining and obtaining aggregates. LCA studies focusing on raw materials extraction provide valuable insights into the environmental implications of this stage and offer opportunities for improving sustainability in the cement and concrete industry. These studies examine various environmental factors associated with raw materials extraction, including energy consumption, carbon emissions, water usage, land disturbance and resource depletion. By quantifying the environmental impacts at this stage, LCA helps identify potential hotspots and areas for improvement in terms of environmental performance.

The findings of LCA studies on raw materials extraction in cement and concrete production have highlighted several key areas of concern. Energy consumption during extraction, particularly the use of fossil fuels, has been identified as a significant contributor to carbon emissions. This includes the energy required for operating machinery and equipment, as well as electricity consumption. Water usage is another important aspect examined in LCA studies. The extraction of raw materials often involves substantial water requirements, leading to potential impacts on local water resources. Efficient water management strategies and technologies are needed to reduce the water footprint of raw materials extraction.

Land disturbance and biodiversity loss are also significant concerns associated with raw materials extraction. Quarrying activities can lead to habitat destruction and loss of biodiversity, necessitating the adoption of sustainable land management practices. Resource depletion, particularly the depletion of non-renewable resources such as limestone and clay, has been identified as a critical issue. LCA studies help assess the extent of resource depletion and encourage the exploration of alternative materials or recycling options to minimise reliance on virgin resources.

The insights gained from LCA studies on raw materials extraction in cement and concrete production have influenced industry practices and policies [135]. They have provided a foundation for the development of sustainable mining practices, resource-efficient technologies and the implementation of environmental management systems. However, it is important to note that LCA studies may vary in terms of their methodologies, system boundaries and regional contexts. Different studies may focus on specific geographical areas or use different data sources, which can lead to variations in the results and conclusions.

Vieira et al. [224] conducted an LCA review on the manufacturing of common and ecological concrete. Although the study focused on the overall concrete manufacturing process, including raw materials extraction, it lacked a detailed analysis of the environmental impacts specific to this phase. A more comprehensive assessment of the extraction processes for key raw materials like limestone, clay and aggregates would have provided a deeper understanding of their environmental implications. Manjunatha et al. [135] performed an LCA of concrete prepared with sustainable cement-based materials. While the study considered the sustainability aspects of cement and concrete, it did not specifically analyse the raw materials extraction phase. A comprehensive assessment of the environmental impacts associated with the extraction of raw materials from sustainable sources, such as recycled aggregates or alternative cementitious materials, would have enhanced the study's findings.

Ankur and Singh [6] conducted a review on the LCA phases of cement and concrete manufacturing. While the review covered various aspects of the life cycle, including raw materials extraction, it provided a general overview without delving into specific environmental impacts. A more detailed analysis of the extraction phase, considering factors such as energy consumption, land use and water usage, would have provided a more comprehensive understanding of the environmental performance of cement and concrete production. Gursel and Ostertag [74] investigated the impact of Singapore's importers on the LCA of concrete. Although the study touched on raw materials extraction, it primarily focused on the environmental implications of importing concrete. Further analysis of the extraction phase, particularly regarding the sourcing of raw materials from different regions, would have enhanced the study's insights into the global environmental impacts associated with concrete production.

Koroneos and Dompros [114] conducted an environmental assessment of the cement and concrete life cycle in Greece. The study encompassed various life cycle stages, including raw materials extraction. However, the study's findings were limited to the Greek context and did not consider potential variations in extraction practices and environmental impacts in other regions. A broader analysis of raw materials extraction, considering regional differences and specific environmental challenges, would have increased the study's applicability. Cordoba et al. [38] explored advances and opportunities for eco-efficient ready-mix concrete production in the Metropolitan Region of Buenos Aires. While the study addressed the environmental performance of the concrete industry, it did not specifically focus on the raw materials extraction phase. A more comprehensive assessment of the extraction processes, including the identification of potential environmental hotspots and the exploration of sustainable sourcing options, would have provided valuable insights into the eco-efficiency of the concrete industry.

In summary, the selected LCA studies on raw materials extraction for cement and concrete production offer valuable contributions to understanding the environmental impacts of these processes. However, there is a need for more comprehensive and regionally specific assessments that consider the environmental implications of raw materials extraction in greater detail. Future research should aim to address this gap and provide more robust insights into the sustainability of cement and concrete production by focusing on the specific environmental challenges associated with raw materials extraction.

4.1.2. Production process

LCA provides a comprehensive framework to evaluate the entire life cycle of cement, from raw material extraction to the production of the final product. Clinker production is a critical stage in cement manufacturing and is known to have significant environmental impacts. LCA studies focus on assessing the energy consumption, carbon dioxide emissions and air pollutants generated during clinker production. They investigate strategies for optimizing process parameters, utilizing alternative raw materials and implementing emission reduction technologies to mitigate these impacts. The cement production processes and associated life-cycle impacts are depicted in Fig. 8. Cement grinding, the process of pulverising clinker and additives, is also examined in LCA studies. The energy consumption, emissions and environmental implications of grinding processes, as well as the use of grinding aids and additives, are evaluated. These studies provide insights into optimising grinding operations and identifying more sustainable grinding techniques. Packaging and transportation of cement are integral components of LCA studies. They consider the energy consumption, emissions and waste generation associated with packaging materials, logistics and transport methods. LCA studies explore strategies such as eco-friendly packaging materials, optimised packaging designs and efficient transportation routes to minimise environmental burdens.

The findings from LCA studies on cement production processes help in identifying environmental hotspots and guiding sustainable practices. They contribute to the development of eco-friendly cement production techniques, including the use of alternative fuels, renewable energy sources and waste heat recovery systems. LCA studies also inform the industry's efforts to reduce carbon emissions, improve resource efficiency and enhance overall sustainability performance. By assessing the environmental impacts across the entire life cycle of cement, LCA studies support decision-making processes, facilitate benchmarking and drive continuous improvement in the cement industry. They play a crucial role in promoting sustainable practices, fostering innovation and addressing environmental challenges associated with cement production.

The concrete production processes and associated life-cycle impacts are shown in Fig. 9. The production processes of concrete, including mixing, transportation and placement, are analysed in LCA studies. These studies assess the energy consumption, greenhouse gas emission and air pollutants associated with concrete production. They investigate strategies to improve energy efficiency, reduce emissions and optimise the use of materials during the manufacturing process. The construction stage of concrete, which involves activities like formwork, reinforcement and curing, is another area of focus in LCA studies. The environmental impacts related to construction practices, such as energy consumption, waste generation and emissions from equipment and machinery, are evaluated. These studies aim to identify opportunities for more sustainable construction practices, including the use of innovative techniques, efficient resource management and waste reduction.

Martínez-Rocamora et al. [139] reviewed LCA databases focused on construction materials. This study provided a comprehensive

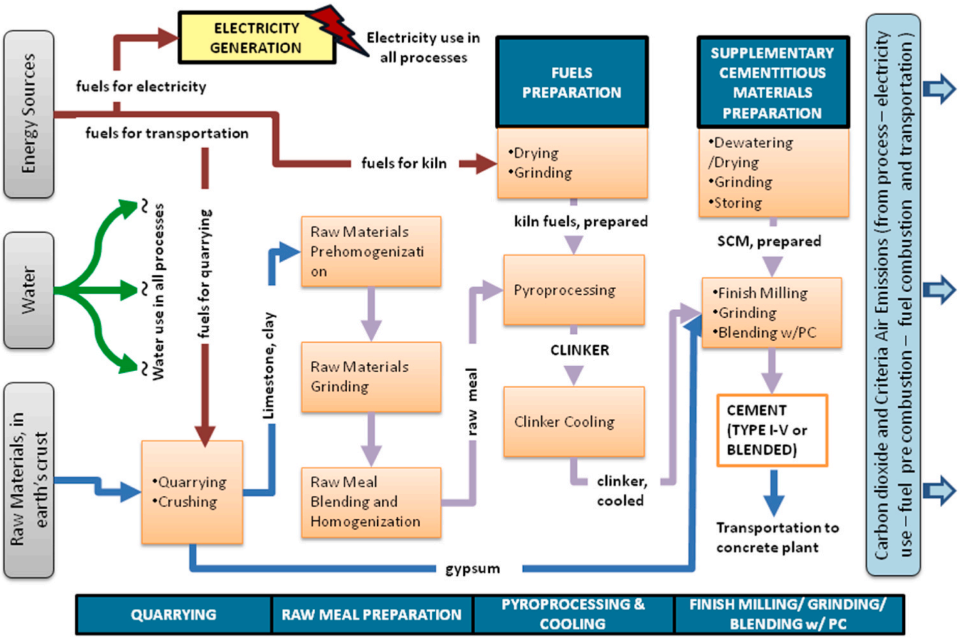

Fig. 8. Cement production processes and associated life-cycle impacts (https://greenconcrete.berkeley.edu).

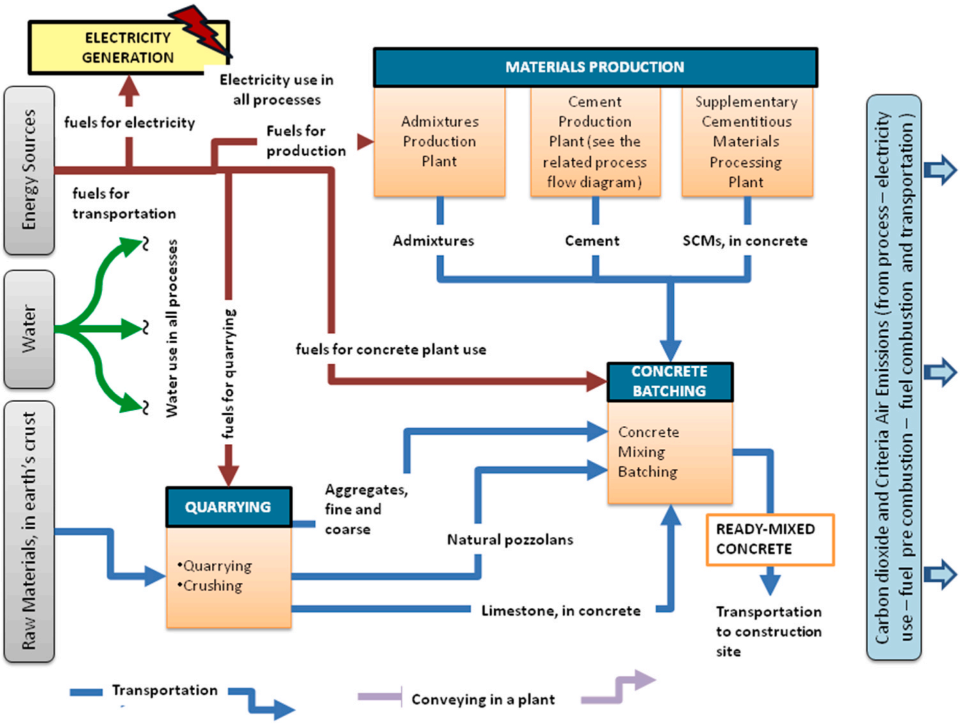

Fig. 9. Concrete production processes and associated life-cycle impacts (https://greenconcrete.berkeley.edu).

overview of available databases, which is valuable for researchers and practitioners. However, the analysis could have delved deeper into the quality and reliability of the data sources. Lasvaux et al. [121] compared generic and product-specific LCA databases for construction materials. Their findings emphasised the importance of using product-specific data for accurate assessments. However, the study lacked a detailed examination of the methodologies used to generate the databases, which could have influenced the results. Hoxha et al. [93] investigated the influence of construction material uncertainties on residential building LCA reliability. This study highlighted the need to address uncertainties and variability in LCA studies. However, the analysis focused on residential buildings only, limiting its broader applicability.

Hammond and Jones [79] conducted a study on embodied energy and carbon in construction materials. Their research contributed valuable insights into the energy and carbon footprint of various materials. However, the study's scope could have been expanded to include a more comprehensive assessment of environmental impacts beyond energy and carbon. Vieira et al. [224] reviewed LCA studies on common and ecological concrete manufacturing. Their analysis shed light on the environmental benefits of using ecological concrete. However, the review could have incorporated a more critical evaluation of the methodologies used in the reviewed studies. Tinoco et al. [218] conducted a systematic literature review on the LCA and environmental sustainability of cementitious materials for 3D concrete printing. This study provided valuable insights into a specific application of concrete. However, the review could have included a more rigorous assessment of the quality and reliability of the reviewed studies. Zhang et al. [237] conducted a review of LCA studies on recycled aggregate concrete. Their analysis highlighted the potential environmental benefits of using recycled aggregates. However, the review could have addressed the limitations and challenges associated with the use of recycled materials in concrete production.

Xing et al. [232] critically reviewed the LCA of recycled aggregate concrete. Their study provided a comprehensive analysis of the environmental impacts associated with this type of concrete. However, the review could have included a more detailed discussion of the methodological approaches used in the reviewed studies. Mohammadi and South [147] conducted an LCA of benchmark concrete products in Australia. This study provided valuable insights into the environmental impacts of concrete products specific to the Australian context. However, the study could have explored the potential variations in impacts across different regions.

Nevertheless, the LCA studies on concrete production have significantly advanced our understanding of the environmental implications of this material. In light of the progress made, there is still a need for further research that addresses limitations in data quality, methodological approaches and the inclusion of broader environmental impact categories. Moreover, future studies should strive for more standardized methodologies and transparency in reporting to enhance the comparability and reliability of results. By addressing these challenges, the LCA studies can continue to provide valuable insights and guide sustainable practices in the concrete industry.

4.1.3. Use and maintenance phase

The use and maintenance phase of LCA for cement and concrete is a critical aspect in assessing their environmental impact and sustainability throughout their operational lifespan. This phase involves evaluating the activities and processes related to the utilization, operation, and maintenance of cement and concrete structures, including buildings, bridges, roads, and infrastructure projects. Numerous studies have focused on analysing the use and maintenance phase in LCA for cement and concrete, yielding valuable insights into their environmental performance and identifying potential areas for enhancement [104,208,76]. By examining the impacts and resource consumption during this phase, stakeholders can identify strategies to improve the efficiency, durability, and overall sustainability of cement and concrete materials.

During the use phase, the energy consumption and associated greenhouse gas emissions from the operation of cement and concrete structures are crucial considerations in LCA. This includes energy for heating, cooling, lighting, and maintaining indoor conditions, as well as machinery and equipment used in concrete-related activities. Optimal energy efficiency in buildings and infrastructure can significantly reduce their environmental impact. Strategies such as incorporating insulation materials, improving HVAC systems, utilising renewable energy sources, and implementing energy management strategies have proven effective [149,165,191,236]. Additionally, the maintenance phase is vital as it impacts the durability, performance, and service life of cement and concrete structures. Regular maintenance, repair, and rehabilitation activities are necessary for longevity, but their environmental implications, including materials used, energy consumed, and waste generated, must be carefully managed.

Research on the maintenance phase of LCA for cement and concrete has focused on strategies to extend the service life of structures, minimise the need for major repairs or replacements, and reduce the environmental impact associated with maintenance activities [125,239,76]. This includes investigating innovative materials, coatings, and protective systems that enhance durability and resistance, as well as promoting sustainable maintenance practices and efficient resource utilization. LCA studies assess the environmental impact of the use and maintenance phase by considering parameters such as energy consumption, greenhouse gas emissions, water usage, waste generation, and pollutant release. These studies provide valuable insights for decision-makers, engineers, and stakeholders, enabling them to identify opportunities to enhance the sustainability performance of cement and concrete structures throughout their operational life.

4.1.4. *End-of-life considerations*

End-of-life considerations are a crucial aspect of LCA for cement and concrete, encompassing the evaluation of their environmental impact and sustainability once they reach the end of their useful life. This phase involves assessing disposal, recycling, and reuse options for cement and concrete structures. LCA studies provide valuable insights into the potential environmental benefits and challenges associated with the management of cement and concrete waste. Disposal methods for these materials have traditionally involved landfilling, which can have adverse environmental effects such as the consumption of landfill space and potential leaching of harmful substances into the soil and groundwater. LCA studies aim to assess the environmental consequences of landfill disposal and explore alternative waste management options that minimise these impacts [100,132,233].

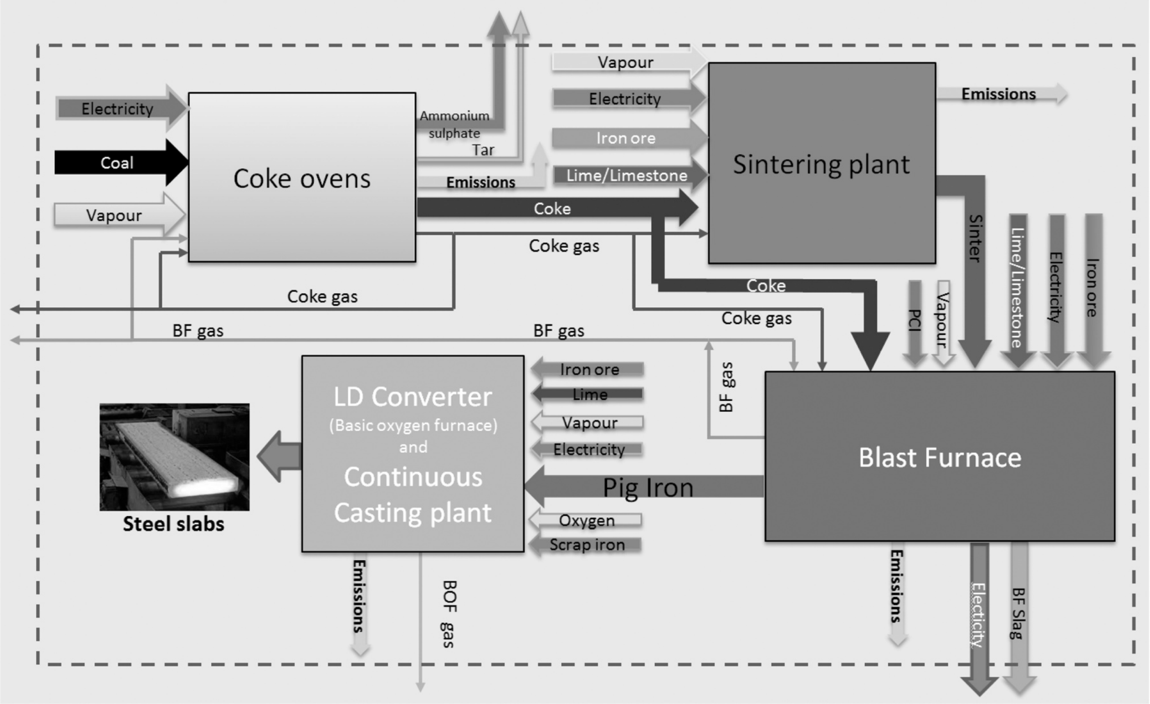

Fig. 10. The system boundaries. The by-products cross the boundaries (dashed line) and have part of the environmental impacts allocated to them. (BOF: Basic Oxygen Furnace (also known as LD converter), BF: Blast Furnace, PCI: Pulverised Coal Injection.) [184].

Recycling plays a pivotal role in end-of-life considerations for cement and concrete, with LCA studies assessing the potential for recycling these materials and evaluating the environmental benefits of diverting waste from landfills. Concrete recycling involves the crushing and reuse of concrete waste as aggregates in new construction projects, reducing the demand for virgin materials and conserving natural resources. This practice contributes to several environmental benefits, including reduced energy consumption, decreased greenhouse gas emissions, and minimised landfill waste. Additionally, LCA studies emphasise the importance of exploring the feasibility and environmental advantages of reusing existing cement and concrete structures [144,232,80]. Rather than demolishing and constructing new ones, repurposing these structures, such as buildings, bridges, or roads, significantly reduces the environmental impact associated with the production of new cement and concrete materials.

In addition to disposal, recycling, and reuse options, LCA studies encompass various end-of-life strategies for cement and concrete, evaluating their environmental impact. These strategies may include technologies for treating and stabilising cement and concrete waste, as well as exploring the potential for energy recovery through processes like waste-to-energy or thermal treatment [52,96]. LCA assessments also consider the transportation and logistics involved in the end-of-life phase. The distance and energy required to transport waste materials for disposal or recycling are evaluated to determine their environmental impact. Minimizing transportation distances and optimizing logistics can contribute to reducing the carbon footprint associated with the end-of-life management of cement and concrete waste.

In conclusion, end-of-life considerations play a crucial role in LCA for cement and concrete, providing insights into the environmental consequences of waste management strategies. By promoting recycling, reuse, and responsible disposal practices, LCA studies contribute to the development of sustainable approaches to the end-of-life phase of cement and concrete structures. Ongoing research and innovation in this field are vital to improving waste management practices, reducing environmental impacts, and advancing the overall sustainability of the cement and concrete industry. By considering the full life cycle of these materials, stakeholders can make informed decisions that prioritize environmental conservation and resource efficiency.

4.2. Steel and metal alloys

Life Cycle Assessment (LCA) studies on steel and metal alloys provide valuable insights into the environmental impacts associated with their production, use and disposal. These studies analyse various stages, including raw material extraction, processing, manufacturing, transportation and end-of-life considerations. Fig. 10 shows the system boundaries for LCA of steel produced in an Italian Integrated steel mill [184]. LCA helps identify opportunities for improving the environmental performance of steel and metal alloys by assessing factors such as energy consumption, greenhouse gas emissions, water usage and waste generation. The findings of LCA studies can inform decision-making processes, guide sustainable practices and drive innovations in the steel and metal industries to reduce their ecological footprint and enhance their overall sustainability.

4.2.1. Extraction and processing

The extraction and processing of steel and metal alloys involve multiple processes and activities that can have significant environmental implications. LCA studies in this field aim to quantify and assess various environmental factors such as energy consumption, water usage, greenhouse gas emissions, air and water pollution and waste generation. One of the primary areas of investigation in LCA studies is the mining and extraction of raw materials. This includes the exploration and extraction of iron ore, bauxite, copper and other minerals used in steel and alloy production. LCA evaluates the environmental impacts of mining operations, considering factors such as land disturbance, energy consumption, water usage and the release of pollutants into the air and water.

Refining processes are also examined in LCA studies, which involve the purification and treatment of raw materials to obtain the desired metal or alloy. These processes can be energy-intensive and may generate waste products or by-products that require proper management and disposal. Alloying and casting, forming and shaping, heat treatment and surface finishing are additional stages evaluated in LCA studies. These processes involve the transformation of the raw materials into specific steel or metal alloy products, such as sheets, bars, tubes, or structural components. LCA assesses the energy requirements, emissions and waste generation associated with these processes, considering factors like material losses, energy efficiency and the use of additives or chemicals.

Transportation is another important aspect considered in LCA studies. The movement of raw materials, intermediate products and finished goods throughout the supply chain can contribute to energy consumption and emissions. LCA analyses the environmental impacts associated with transportation, considering factors such as distance travelled, mode of transportation and fuel consumption. Moreover, LCA studies in the extraction and processing of steel and metal alloys contribute to the development of cleaner production methods and the implementation of circular economy principles. They promote the adoption of energy-efficient technologies, such as recycling and reusing materials, reducing waste generation and optimising resource utilisation. LCA findings help identify opportunities for improvement and guide the industry towards more sustainable practices. By providing a scientific basis for decision-making, LCA studies enable stakeholders to make informed choices for environmentally friendly and efficient solutions. They support the identification of areas for improvement, resource optimisation and the reduction of environmental burdens throughout the life cycle of steel and metal alloys.

The extraction and processing of steel and metal alloys have significant environmental impacts due to their energy-intensive nature and the use of finite resources. LCA studies have been conducted to analyse and quantify these impacts throughout the entire life cycle of steel and metal production, from raw material extraction to end-of-life considerations. One notable LCA study by Dolganova et al. [54] focused on ferro niobium, a key alloying element in steel production. The study assessed the environmental impact of ferro niobium production, including the extraction of raw materials, energy consumption, emissions and waste generation. By conducting a comprehensive LCA analysis, the study provided insights into the hotspots of environmental impact and identified opportunities for improving the sustainability of ferro niobium production.

Another area of interest is the eco-friendliness of additive manufacturing of metals, also known as 3D printing. Gao et al. [66] conducted an LCA study to evaluate the energy efficiency and life cycle impacts of eco-friendly additive manufacturing processes. The study compared the environmental performance of additive manufacturing with conventional manufacturing methods, highlighting the potential benefits of reducing material waste and energy consumption in metal production. The environmental impact assessment of metal production processes as a whole has been addressed in studies such as Norgate et al. [155]. These studies analyse the extraction and processing stages, including mining, ore beneficiation, smelting and refining, to assess their energy consumption, greenhouse gas emissions and other environmental burdens. Such assessments help in identifying the key areas where improvements can be made to reduce the overall environmental impact of metal production.

In addition to primary metal production, LCA studies have also explored the environmental implications of steel and metal products throughout their life cycle. For instance, Shah et al. [205] conducted an LCA study comparing different types of household water tanks, including those made of low-density polyethylene (LLDPE), mild steel and reinforced cement concrete (RCC). The study evaluated the environmental impacts associated with the production, use and disposal of these tanks, providing insights into the most environmentally friendly option.

Furthermore, the end-of-life considerations for steel and metal alloys have been investigated in LCA studies. Viklund-White [225] focused on the environmental evaluation of recycling galvanized steel, analysing the energy savings and reduction in environmental burdens achieved through the recycling process. The study demonstrated the environmental benefits of recycling as a strategy for sustainable resource management.

4.2.2. Manufacturing and fabrication

Life Cycle Assessment (LCA) studies provide a comprehensive analysis of the environmental impacts associated with the manufacturing and fabrication of steel and metal alloys. These studies examine the entire life cycle of these materials, considering all stages from raw material extraction to final product disposal. By assessing the environmental indicators and impacts throughout the life cycle, LCA helps identify areas of improvement and potential environmental hotspots. One of the key focuses of LCA studies in this field is the quantification of energy consumption. These studies analyse the energy inputs required at various stages of the manufacturing and fabrication process, including the extraction of raw materials, refining, alloying, casting, shaping and finishing. By evaluating energy consumption, LCA helps identify opportunities for energy optimisation and efficiency improvements.

Greenhouse gas emissions are another important aspect addressed in LCA studies. These studies assess the carbon footprint associated with steel and metal alloy production, considering emissions from energy use, combustion processes and transportation. By identifying the sources of emissions, LCA enables the development of strategies to reduce greenhouse gas emissions, such as the adoption of cleaner energy sources and improved process efficiency. Water usage is also evaluated in LCA studies. The manufacturing and fabrication of steel and metal alloys often involve water-intensive processes such as cooling, quenching and cleaning. LCA helps quantify water consumption and assess the potential environmental impacts, such as water scarcity and water pollution. By identifying water-efficient practices and technologies, LCA supports the conservation and responsible management of water resources.

Air pollution and waste generation are additional areas of focus in LCA studies. These studies analyse the emissions of air pollutants, such as particulate matter, nitrogen oxides and sulphur dioxide, from manufacturing and fabrication processes. They also assess the generation and disposal of waste materials, such as slag, dust and scrap metal. LCA helps identify strategies to minimise air pollution and waste generation, such as the implementation of emission control technologies and recycling initiatives. Moreover, LCA studies explore the environmental implications of different manufacturing techniques and technologies. They compare traditional methods with emerging practices, such as additive manufacturing (3D printing), to evaluate their energy efficiency, material usage and overall environmental performance. By assessing the environmental benefits and drawbacks of different approaches, LCA supports the adoption of more sustainable and eco-friendly manufacturing processes. Additionally, LCA studies consider the potential environmental benefits of recycling and the use of secondary raw materials in steel and metal alloy manufacturing. They assess the impact of recycling processes on energy consumption, emissions and resource conservation. LCA findings highlight the importance of a circular economy approach, where materials are recycled and reused, reducing the demand for virgin resources and minimising environmental impacts.

Several LCA studies have been conducted to evaluate the environmental impacts of manufacturing and fabrication processes in the steel and metal alloy industry. In the study by Westfall et al. [229], a cradle-to-gate LCA was performed to assess the global manganese alloy production. The researchers evaluated various impact categories and found that energy consumption and greenhouse gas emissions were significant contributors to the environmental burden. This study highlights the importance of optimising energy efficiency and reducing emissions in the production of manganese alloys. Shah et al. [204] conducted an environmental LCA of wire arc additively manufactured steel structural components. The study focused on evaluating the environmental impacts associated with the entire life cycle of the components. The findings emphasised the potential benefits of additive manufacturing technologies in terms of material efficiency and waste reduction. However, the study also acknowledged the need for further research to address energy consumption and emissions during the manufacturing process.

Peng et al. [169] conducted an LCA of selective-laser-melting-produced hydraulic valve bodies. The study integrated design and manufacturing optimisation to assess the environmental impacts from cradle to gate. The results highlighted the potential for reducing energy consumption and environmental burdens through optimisation strategies such as lightweight design and process parameter optimisation. This study suggests that incorporating design considerations can contribute to more sustainable manufacturing processes. Kokare et al. [113] performed an environmental and economic assessment of a steel wall fabricated by wire-based directed energy deposition. The study evaluated the impacts of different manufacturing scenarios and compared them with conventional manufacturing methods. The findings revealed potential reductions in material waste and energy consumption with the adoption of wire-based directed energy deposition, highlighting its environmental advantages.

Gao et al. [66] conducted a study on eco-friendly additive manufacturing of metals, focusing on energy efficiency and life cycle analysis. The research examined various energy sources and their environmental implications in additive manufacturing processes. The findings emphasised the importance of utilizing renewable energy sources and optimizing process parameters to reduce energy consumption and environmental impacts. Niero & Olsen [154] conducted a LCA of aluminum cans within the context of a circular economy. The study examined the environmental impacts associated with different recycling scenarios, including the effects of alloying elements. The results emphasised the potential environmental benefits of closed-loop recycling systems and the importance of proper management of alloying elements to minimise environmental burdens.

Overall, these LCA studies provide valuable insights into the environmental impacts of manufacturing and fabrication processes in the steel and metal alloy industry. They highlight the importance of optimising energy efficiency, reducing emissions, incorporating design considerations, exploring additive manufacturing technologies and promoting circular economy principles to enhance the sustainability of these processes. The findings can guide industry stakeholders, policymakers and researchers in making informed decisions towards more sustainable and environmentally friendly practices in the steel and metal alloy sector.

4.2.3. Use and recycling

LCA studies on the use and recycling of steel and metal alloys have addressed various aspects of their life cycle, including production, transportation, fabrication and end-of-life scenarios. These studies have highlighted the environmental burdens associated with each stage and have aimed to identify strategies for reducing impacts and promoting recycling. One area of focus in LCA studies is the cradle-to-gate assessment of steel and metal alloy production. These studies analyse the extraction of raw materials, energy consumption, emissions and waste generation during the manufacturing process. By quantifying the environmental impacts of production, researchers can identify opportunities for optimising resource efficiency, reducing greenhouse gas emissions and minimising waste generation.

Furthermore, LCA studies have explored the environmental implications of using steel and metal alloys in various applications. This includes assessing their performance in different sectors such as construction, automotive, aerospace and consumer goods. By evaluating the energy consumption, emissions and potential environmental releases during the use phase, these studies provide insights into the environmental benefits and trade-offs associated with steel and metal alloy applications. The recycling of steel and metal alloys has also been a key focus of LCA studies. Evaluating the environmental benefits of recycling compared to primary production is important for understanding the potential for resource conservation and reduced environmental impacts. LCA studies have examined the recycling processes, energy requirements, emissions and the potential for material recovery and reuse. They have also explored the impact of recycling rates, collection systems and technological advancements on the overall sustainability of steel and metal alloy recycling.

Dubreuil et al. [55] explored metals recycling maps and allocation procedures in LCA. The study emphasised the importance of accurate allocation methods for metals recycling, considering regional variations in recycling rates and environmental impacts. However, it suggested that further improvements in data collection and allocation approaches were needed for a more precise representation of recycling processes. Santero and Hendry [198] focused on harmonising LCA methodologies for the metal and mining

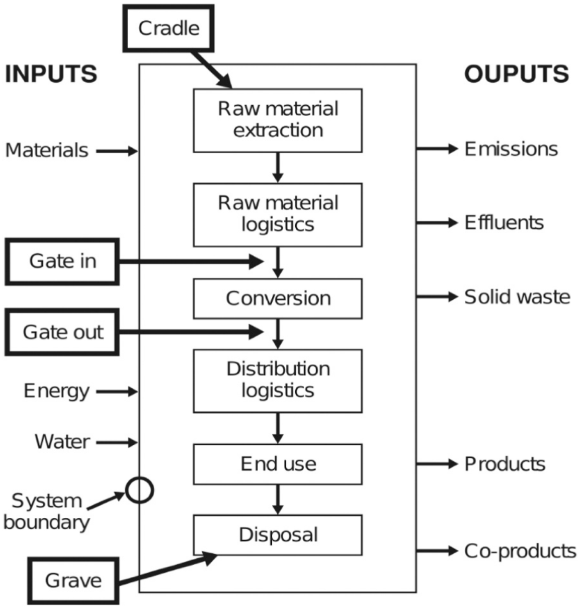

Fig. 11. Whole life cycle from the regeneration of trees to the disposal of wood [193].

industry. The authors acknowledged the need for standardised approaches to ensure consistency and comparability of LCA results. They highlighted challenges related to data availability and methodological differences, stressing the importance of developing industry-specific guidelines. However, additional research was required to establish a comprehensive framework for harmonization.

Paraskevas et al. [163] proposed an environmental modelling approach for assessing the sustainability of aluminum recycling. Their study developed a LCA tool to evaluate the environmental impacts of different recycling scenarios. Although it provided valuable insights into the potential environmental benefits of aluminum recycling, the study could be enhanced by considering a broader range of impact categories and expanding the scope to cover the entire life cycle of aluminum. Rahman et al. [176] conducted a LCA of steel in the ship recycling industry in Bangladesh. They investigated the environmental impacts associated with ship dismantling and recycling processes. The study revealed significant environmental burdens, such as air and water pollution resulting from inadequate waste management practices. However, it could be strengthened by exploring potential mitigation measures and alternative recycling technologies. Viklund-White [225] examined the use of LCA for evaluating the environmental impact of recycling galvanized steel. The study highlighted the environmental benefits of recycling and provided insights into the associated impacts. However, it could have been strengthened by considering a wider range of factors and incorporating more comprehensive data in the analysis.

4.3. Wood and timber products

Life Cycle Assessment (LCA) studies on wood and timber products have provided valuable insights into their environmental impact throughout their life cycle. These studies analyse various stages, including raw material extraction, processing, manufacturing, use and disposal or recycling. LCA investigations have highlighted the renewable and low-impact characteristics of wood as a construction material compared to other alternatives. They have also identified the importance of sustainable forest management practices and responsible sourcing to minimise environmental impacts. LCA studies on wood and timber products contribute to informed decision-making, enabling stakeholders to make environmentally conscious choices in construction, furniture production and other applications involving wood. The whole life cycle from the regeneration of tress to the disposal of wood is depicted in Fig. 11.

4.3.1. Sourcing and forestry practices

LCA investigations focus on evaluating the entire life cycle of wood and timber products, including the extraction of raw materials, transportation, processing, manufacturing, use and end-of-life options such as recycling or disposal. By examining these stages, LCA studies help identify the potential environmental hotspots, resource consumption and emissions associated with different forestry practices and sourcing strategies. One key aspect of LCA studies is the assessment of forest management practices. Sustainable forestry management ensures the responsible and ethical sourcing of wood, taking into account factors such as biodiversity conservation, carbon sequestration, soil health and water quality. LCA studies shed light on the impact of forestry practices on these environmental factors, helping stakeholders make informed decisions and adopt sustainable sourcing strategies. Additionally, LCA studies evaluate the environmental performance of different wood processing techniques, such as sawing, drying and treating. These assessments help identify opportunities for improving resource efficiency, reducing energy consumption and minimising waste generation throughout the manufacturing process.

The findings from LCA studies on sourcing and forestry practices of wood and timber products provide valuable information for policymakers, industry professionals and consumers. They promote the adoption of sustainable forestry management practices, responsible sourcing and the use of certified wood products, ultimately contributing to the preservation of forests and the reduction of environmental impacts associated with the wood industry.

Sahoo et al. [192] explored an LCA of redwood lumber products in the US, providing a comprehensive assessment of the environmental performance of this specific wood species. Their study highlights the importance of considering the entire life cycle, including the extraction, processing and use of redwood, in understanding its environmental impacts. Such studies help inform decision-making processes regarding the sustainability of using specific wood species. Abbas & Handler [1] examined an LCA of forest harvesting and transportation operations in Tennessee. This study investigated the environmental implications of these activities and emphasised the need for sustainable forestry practices. The findings underscore the importance of minimising resource consumption and emissions during forest operations, thereby promoting responsible sourcing and minimising environmental impacts.

Sathre & González-García [201] assessed the environmental performance of wood-based building materials through an LCA. This study offers insights into the environmental implications of using wood as a construction material compared to other alternatives. It demonstrates the potential environmental benefits of wood products, particularly in terms of carbon sequestration and reduced energy consumption during manufacturing. Chen et al. [29] evaluated an LCA of cross-laminated timber (CLT) produced in Western Washington, considering the role of logistics and wood species mix. Their study highlights the importance of optimizing supply chain logistics and selecting appropriate wood species to minimise environmental impacts and enhance the sustainability of CLT production. Mirabella et al. [145] assessed the environmental benefits of eco-design strategies and a forest wood short supply chain in the furniture industry through an LCA. Their study highlights the potential environmental advantages of using locally sourced wood and implementing eco-design principles in reducing the life cycle impacts of furniture production.

These studies, along with others in the field, contribute to the understanding of the environmental implications associated with sourcing and forestry practices of wood and timber products. They provide crucial information for policymakers, industry professionals and consumers to make informed decisions regarding sustainable sourcing, responsible forest management and the use of wood products with lower environmental footprints. While LCA studies in this domain offer valuable insights, it is important to consider certain limitations. LCA methodologies rely on data availability and the accuracy and representativeness of the data used can influence the study outcomes. Additionally, the context-specific nature of forestry practices and wood sourcing may limit the generalisability of findings across different regions and wood types.

4.3.2. Processing and manufacturing

LCA studies in the field of wood and timber products focus on evaluating the entire life cycle, from raw material extraction and processing to manufacturing, use and end-of-life stages. They consider various factors such as energy consumption, greenhouse gas emissions, water usage, waste generation and resource depletion. One key aspect of LCA studies is the assessment of different processing and manufacturing techniques employed in the wood industry. This includes evaluating the environmental impacts of various wood processing methods, such as sawmilling, veneer production and wood preservation treatments. The use of different manufacturing processes, such as timber construction, furniture production and wood-based panel manufacturing, is also analysed.

These studies examine the environmental performance of wood and timber products compared to alternative materials, providing valuable insights into the sustainability advantages of wood as a renewable resource. They also explore the potential environmental benefits of using innovative technologies and sustainable practices in wood processing and manufacturing. Furthermore, LCA studies in this field highlight the importance of responsible sourcing and forest management practices. They assess the environmental impacts associated with wood harvesting, transportation and certification systems, emphasising the need for sustainable forestry practices to minimise negative environmental consequences.

In Fig. 12, the system boundary of transparent wood production is depicted. The processed wood forms are represented by yellow-coloured boxes, while the processes involved in transparent wood production are depicted by blue-coloured boxes. The chemicals used for delignification and infiltration are shown by green-coloured boxes with green arrows and the energy source utilised during production is represented by orange-coloured boxes with orange arrows. The steps in transparent wood production, namely wood harvesting and processing (1), delignification (2) and infiltration (3), are clearly marked in the diagram.

The field LCA has been instrumental in evaluating the environmental impacts associated with the processing and manufacturing of wood and timber products. The study by Jungmeier et al. [105] focused on the allocation methodology within LCA of wood-based products. It addresses the challenge of allocating environmental impacts across multiple products and provides insights into improving the accuracy of LCA results. However, the study's scope is limited to methodology and further research is needed to explore the practical implementation of allocation methods in real-world scenarios. Similarly, in the study conducted by Puettmann and Milota [175] on LCA for wood-fired boilers in the wood products industry, the researchers emphasised the need to consider the entire life cycle of wood energy systems. However, it is important to note that the study primarily focused on energy-related impacts and did not comprehensively evaluate other environmental indicators. This limitation suggests that a more holistic approach to assessing the environmental performance of wood-fired boilers could provide a more complete understanding of their overall sustainability. Furthermore, Johnson et al. [102] developed a model for biomass collection and wood processing life cycle analysis, highlighting the significance of accounting for energy consumption and emissions throughout the entire biomass supply chain. Nonetheless, the study could have benefited from further validation with real-world data to enhance the accuracy and applicability of the model. By incorporating actual data from biomass collection, transportation and processing activities, the researchers could have provided more robust and reliable insights into the environmental impacts associated with these processes.

Moreover, the LCA performed by Tucker et al. [220] on forest and wood products in Australia yielded valuable insights into the environmental impacts throughout the life cycles of various wood products. However, it is crucial to acknowledge that the

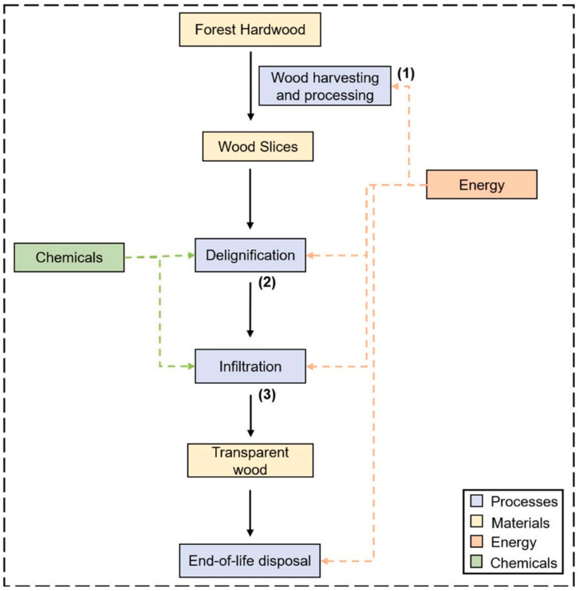

Fig. 12. The system boundary of the transparent wood production [177].

generalizability of the study's findings may be limited due to regional variations in forest management practices and wood processing techniques. These regional differences can significantly influence the environmental performance of wood products, highlighting the importance of considering local context and specificities when conducting LCA studies in the forestry and wood products sector. In their discussion on LCA opportunities in the forest products sector, Kutnar & Hill [118] emphasised the need for a comprehensive approach that encompasses environmental, social and economic aspects. While the study provided a valuable overview of the potential of LCA in this field, it could have been further enriched by incorporating more specific case studies and practical applications. By illustrating real-world examples of LCA implementation in the forest products sector, the researchers could have demonstrated the practical benefits and challenges associated with adopting LCA methodologies and informed decision-making processes for sustainable wood and timber manufacturing.

Nevertheless, these LCA studies on the processing and manufacturing of wood and timber products have made valuable contributions to our understanding of the environmental implications of various production methods. Each study has provided unique insights and highlighted important aspects of sustainability in the industry. However, it is important to recognize the limitations of these studies and the need for further research to address gaps in knowledge. By addressing these limitations and conducting more comprehensive and region-specific assessments, future LCA studies can guide the development of sustainable practices in the wood and timber industry.

4.3.3. Structural applications and durability

LCA studies on structural applications and durability of wood and timber products focus on quantifying various environmental indicators, such as greenhouse gas emissions, energy consumption, water usage and waste generation. These assessments compare the environmental performance of wood and timber products with alternative materials, such as steel or concrete, to determine their relative sustainability.

Moreover, LCA studies analyse the impacts of different wood treatment methods, coatings and protective measures used to enhance the durability and longevity of wood products. They investigate the effects of maintenance practices, exposure to weather conditions and natural decay processes on the environmental performance of wood and timber structures. Furthermore, LCA studies also consider the end-of-life options for wood and timber products, including recycling, reuse and disposal. These assessments assess the environmental implications of different end-of-life scenarios and provide insights into the potential benefits of recycling or reusing wood products compared to their disposal.

Pierobon et al. [172] conducted an LCA-based comparative case study on hybrid cross-laminated timber (CLT) structures in mid-rise non-residential construction. Their findings highlighted the environmental benefits of using hybrid CLT, including reduced embodied carbon emissions compared to traditional construction materials. The study showcased the potential of CLT as a sustainable alternative for mid-rise buildings, emphasising the importance of considering specific construction scenarios in LCA assessments. Woodard and Milner [230] addressed the sustainability of timber and wood in construction. Their study provided a comprehensive overview of the environmental aspects related to timber and wood products, including the role of sustainably managed forests, carbon sequestration potential and the importance of responsible sourcing. It emphasised the need for holistic assessments that consider the entire life cycle and multiple environmental indicators.

Beudon et al. [16] focused on the LCA of an innovative hybrid highway bridge composed of an aluminum deck and glulam timber beams. The study demonstrated the environmental benefits of this hybrid structure, including reduced carbon emissions compared to conventional bridge designs. It highlighted the potential for combining different materials to optimise sustainability in infrastructure projects. Ding et al. [53] provided an overview of emerging engineered wood for building applications. While not solely focused on LCA, their review highlighted the sustainable attributes of engineered wood products, including their lower carbon footprint, renewable nature and potential for efficient resource utilization. It emphasised the importance of continued research and innovation in developing sustainable wood-based building materials. Milner [143] explored the sustainability of engineered wood products in construction. The study discussed the environmental benefits of using engineered wood, such as reduced energy consumption, lower greenhouse gas emissions and improved resource efficiency. It emphasised the importance of responsible forest management and the potential for engineered wood products to contribute to sustainable construction practices.

In summary, LCA studies on the structural applications and durability of wood and timber products have provided valuable insights into their environmental performance. These studies have highlighted the benefits of specific applications, such as hybrid CLT structures and innovative bridge designs, in reducing carbon emissions and promoting sustainability. Additionally, the studies emphasised the need for holistic assessments, responsible sourcing and continued research and innovation to further enhance the sustainability of wood and timber products in construction.

4.3.4. Waste and disposal management

Life Cycle Assessment (LCA) plays a crucial role in evaluating the environmental impact of waste and disposal management practices associated with wood and timber products. LCA studies in this field assess various aspects, including waste generation, treatment and final disposal methods. These studies consider the environmental impacts of different waste management options, such as landfilling, incineration, recycling and composting. They also analyse the potential for resource recovery, energy generation and the release of pollutants during waste treatment processes. One important aspect explored in LCA studies is the carbon footprint associated with wood waste management. Wood and timber products have the potential to store carbon and their proper management can contribute to climate change mitigation. LCA helps assess the environmental benefits of recycling or reusing wood waste instead of disposing of it in landfills or incinerators.

Furthermore, LCA studies examine the environmental consequences of different waste management technologies. For instance, they analyse the energy consumption, emissions and resource depletion associated with incineration or composting facilities. These assessments help identify the most environmentally friendly options and guide decision-making towards sustainable waste management practices. Additionally, LCA studies shed light on the potential for circular economy approaches in the wood and timber industry. By assessing the environmental impact of recycling and reusing wood waste, these studies highlight the benefits of diverting materials from landfills and reducing the demand for virgin resources. Moreover, LCA studies inform policymakers, industry stakeholders and waste management professionals about the environmental trade-offs and opportunities associated with different waste management strategies. They provide a quantitative and scientifically grounded basis for decision-making, allowing for informed choices that minimise environmental impacts.

Hossain & Poon [90] conducted a comparative LCA to assess different wood waste management strategies in the context of building construction. Their study highlighted the importance of considering the entire life cycle of wood waste, from generation to final disposal or recycling. The findings emphasised the significance of proper waste management practices in reducing environmental impacts, such as greenhouse gas emissions and energy consumption. Rivela et al. [186] performed a LCA of wood wastes in the context of ephemeral architecture. The study focused on the temporary structures used in events and exhibitions. It provided insights into the environmental implications of wood waste generated in these specific contexts. The findings highlighted the importance of waste prevention and material reuse as effective strategies for minimising the environmental burden associated with wood waste. In the book "Wood Waste Management and Products," Sarmin, et al. [199] discussed the LCA of wood waste. The chapter emphasised the need for proper waste management practices to minimise the environmental impacts of wood waste. It highlighted the potential for recycling, energy recovery and other valorisation methods as sustainable alternatives for wood waste management.

Overall, these studies contribute to our understanding of the environmental implications of wood waste and provide insights into strategies that can be employed to minimise its impact. They underscore the importance of adopting sustainable waste management practices, including recycling and material reuse, to reduce the environmental footprint of the wood and timber industry. However, further research is needed to explore innovative and efficient waste management techniques that can optimise resource utilisation and minimise environmental impacts throughout the life cycle of wood waste.

5. Recent advances and emerging trends in LCA of construction materials

In recent years, there have been significant advances and emerging trends in the field of Life LCA applied to construction materials. One prominent trend is the incorporation of circular economy principles, which focus on minimizing waste and promoting resource efficiency throughout the life cycle of construction materials. This involves strategies such as recycling, reusing and remanufacturing to reduce environmental impacts. Additionally, there is a growing emphasis on exploring renewable and low-carbon alternatives to traditional construction materials, aiming to mitigate carbon emissions and promote sustainability. Technological innovations and process optimisation also play a crucial role, enabling the development of more efficient and environmentally friendly manufacturing processes. Lastly, policy implications and regulatory frameworks are being established to incentivize sustainable practices and ensure compliance with environmental standards in the construction industry. These recent advances and trends in LCA hold great promise for promoting sustainable construction practices and informing decision-making processes.

5.1. Incorporating circular economy principles

The integration of circular economy principles in the LCA of construction materials represents an important and dynamic field of study with the aim of advancing sustainability in the construction industry. The concept of a circular economy seeks to shift away from the traditional linear model of resource consumption and disposal towards a more circular approach that prioritises resource efficiency, waste reduction and the preservation of materials within the economic system [142,153]. While traditional LCA of construction materials primarily focuses on assessing the environmental impacts across the various life cycle stages, including extraction, production, use, and disposal, incorporating circular economy principles expands the scope of analysis to include additional considerations such as material reuse, recycling and recovery. This broader perspective enables a more comprehensive evaluation of the environmental implications and opportunities associated with different materials, promoting a more sustainable and circular approach to construction practices.

The integration of circular economy principles into LCA involves a focus on material circularity and longevity, aiming to prolong the lifespan of construction materials and minimise waste generation [123,3,91]. This approach entails exploring strategies such as material reuse, refurbishment, remanufacturing, and recycling, as well as optimising material selection and design for circularity. By keeping materials within the economic system for as long as possible, the reliance on new resource extraction is reduced, resulting in environmental benefits. The incorporation of circular economy principles in LCA provides valuable insights into the potential environmental advantages and challenges associated with different material choices and management practices. It helps identify opportunities to mitigate the environmental impact of construction materials throughout their life cycle, including assessing the energy and emissions savings achieved through the use of recycled or reclaimed materials compared to virgin materials.

Incorporating circular economy principles in LCA not only provides valuable insights into environmental benefits but also informs decision-making processes. It guides the selection of materials and strategies that align with circularity goals and support sustainable development objectives. LCA offers quantitative data and indicators to compare materials, identify life cycle hotspots, and assess the potential benefits of implementing circular practices [120,141]. To fully integrate circular economy principles in LCA, collaboration among stakeholders is crucial, including designers, manufacturers, contractors, waste management entities, policymakers, and researchers. By working together, innovative approaches, technologies, and policies can be developed to promote circularity in the construction industry. Challenges remain, such as data availability, data quality, standardised methodologies, and the consideration of social and economic aspects alongside environmental factors, which require further development to ensure a comprehensive assessment.

5.2. Renewable and low-carbon alternatives

Renewable alternatives, such as bamboo, straw, timber, and bio-based polymers, are derived from rapidly renewable or regenerative resources, offering the construction industry an opportunity to decrease dependence on non-renewable resources and foster a more sustainable supply chain. Simultaneously, low-carbon alternatives like recycled concrete, recycled wood, and low-carbon cement substitutes possess lower carbon footprints in comparison to conventional options. By integrating these materials, construction activities can mitigate greenhouse gas emissions [122,166,237,45]. Embracing renewable and low-carbon alternatives aids in achieving environmental sustainability goals and contributes to the reduction of the industry’s carbon impact.

LCA studies on renewable and low-carbon alternatives cover multiple dimensions, including energy consumption, greenhouse gas emissions, water usage, and resource depletion. Through these assessments, valuable insights are gained regarding the environmental advantages of adopting these alternatives, such as lower carbon emissions, energy efficiency, and reduced dependency on finite resources. Furthermore, LCA aids in identifying any potential trade-offs or unintended environmental consequences, fostering a comprehensive comprehension of the environmental impacts associated with the use of these materials [78,231]. To conduct LCA studies on renewable and low-carbon alternatives, meticulous and comprehensive data collection is vital. This entails gathering information on the production processes, energy inputs, emissions and resource utilisation associated with these materials. Factors such as the availability and sustainability of renewable resources, technical feasibility, market acceptance, and cost considerations are also taken into account to provide a holistic assessment. Integrating renewable and low-carbon alternatives within the LCA framework promotes sustainable design and construction practices. It equips decision-makers with the necessary information to make well-informed choices aligned with sustainability goals. The insights gained from LCA studies can also shape the development of policies, regulations, and certifications that encourage the widespread adoption of renewable and low-carbon materials in the construction industry.

While renewable and low-carbon alternatives offer significant advantages, their widespread adoption faces certain challenges. Cost considerations, technical limitations, and market acceptance can hinder their implementation in construction projects. Moreover, the availability of reliable and standardised data for these materials can be a limitation in conducting robust LCA assessments [234,42]. Overcoming these challenges requires collaborative efforts among industry stakeholders, researchers, and policymakers. By working together, innovative solutions can be developed to address cost concerns, overcome technical limitations, and promote market acceptance of renewable and low-carbon alternatives. Additionally, efforts should be made to improve data availability and standardization, enabling more accurate and comprehensive LCA assessments.

5.3. Technological innovations and process optimisation

Technological innovations drive progress in the construction industry by introducing improvements in various areas, such as manufacturing processes, material formulations, energy efficiency, and waste reduction. These innovations are crucial for developing more sustainable alternatives to conventional construction materials and methods. For instance, the advancements in composite materials, which offer enhanced strength and durability, have the potential to replace traditional materials like steel or concrete [134,178]. This substitution can result in reduced energy consumption and lower carbon emissions throughout the life cycle of construction projects. By embracing and implementing these technological innovations, the construction industry can significantly contribute to sustainability goals and promote a more environmentally friendly built environment.

Process optimisation plays a crucial role in the construction industry by identifying opportunities to streamline production processes, minimise waste generation, and improve resource efficiency. By analysing and optimising energy use, water consumption, and raw material utilisation, environmental impacts associated with the manufacturing and production of construction materials can be reduced. Implementing lean manufacturing principles, for example, can lead to more efficient resource utilisation, waste reduction, and improved overall productivity [189,221,69]. Through process optimisation, the construction industry can enhance sustainability by minimising resource depletion, reducing emissions, and promoting more efficient and environmentally friendly practices throughout the production phase.

LCA studies on technological innovations and process optimisation play a crucial role in evaluating the environmental performance of new materials and processes compared to conventional ones. These assessments consider key factors such as energy consumption, greenhouse gas emissions, water usage, waste generation, and resource depletion throughout the life cycle [108,183,207]. By conducting LCA, the environmental benefits and potential trade-offs associated with adopting these innovations can be quantified and assessed. This information enables stakeholders to make informed decisions, prioritise sustainable alternatives, and drive the adoption of more environmentally friendly technologies and practices in the construction industry.

Technological innovations and process optimisation have the potential to yield significant environmental benefits. For instance, the implementation of energy-efficient manufacturing processes can result in reduced energy consumption and greenhouse gas emissions. Utilising recycled materials or waste by-products as inputs for construction materials can contribute to waste reduction and resource conservation [162,206,216]. Additionally, the adoption of modular construction techniques and prefabrication methods can lead to minimised material waste, shorter construction time, and improved energy efficiency in building operations. These advancements in technology and process optimisation are instrumental in promoting sustainability and driving positive environmental outcomes in the construction industry.

Nonetheless, there are challenges associated with implementing technological innovations and process optimisation in LCA for construction materials. These challenges include high initial costs, technical feasibility, market acceptance, and regulatory barriers. The adoption of new technologies and processes often requires substantial investments and may encounter resistance due to unfamiliarity or skepticism. It is essential to address these challenges through collaborative efforts among industry stakeholders, researchers, and policymakers. Regulatory frameworks and incentives can play a significant role in encouraging the adoption of innovative technologies and promoting sustainable practices in the construction industry. By overcoming these challenges, the construction sector can unlock the full potential of technological advancements and process optimisation to achieve a more sustainable and environmentally friendly built environment.

5.4. Policy implications and regulatory frameworks

Policy implications and regulatory frameworks are crucial for guiding the application of LCA in the context of construction materials. These frameworks establish guidelines, standards, and incentives that promote sustainable practices, encourage the adoption of environmentally friendly materials, and drive the transition toward a more sustainable construction industry. By setting clear objectives and requirements, policies can influence decision-making processes, promote the integration of LCA into construction projects, and create a supportive environment for sustainable development. They can also facilitate the harmonisation of LCA methodologies and ensure the consistency and comparability of LCA results across different projects and regions.

Policy implications related to LCA in the construction sector revolve around the establishment and enforcement of regulations, guidelines, and standards that govern the environmental performance of construction materials [26,41,65]. These policies are designed to ensure that materials used in construction meet specific sustainability criteria, such as lower carbon emissions, resource efficiency, and waste reduction. They may involve mandatory LCA studies for construction projects, the adoption of environmentally friendly materials or technologies, and the implementation of sustainable construction practices. By integrating LCA requirements into policies, decision-makers can drive the adoption of more sustainable materials and practices, ultimately leading to a greener and more sustainable construction industry.

Regulatory frameworks offer a systematic and standardised approach to addressing environmental considerations and advancing sustainable practices within the construction industry. These frameworks encompass various tools such as building codes, environmental certifications, and rating systems that integrate principles of LCA. For instance, renowned green building certification systems like LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method) incorporate LCA assessments as part of their evaluation criteria [15,68,200]. By incorporating LCA, these frameworks incentivize the use of sustainable construction materials and practices, promoting the development of environmentally responsible buildings and infrastructure.

Policy implications and regulatory frameworks have the potential to drive the widespread adoption of renewable and low-carbon alternatives in construction materials. Governments and regulatory bodies can play a crucial role by offering incentives, subsidies, or tax credits to promote the use of sustainable materials. They can also implement measures such as taxes or levies on high-carbon materials to discourage their usage. By creating a supportive policy environment, governments can stimulate market demand for sustainable materials and encourage industry stakeholders to incorporate LCA in their decision-making processes. These policies not only contribute to environmental sustainability but also foster innovation and economic growth in the construction sector.

Policy implications and regulatory frameworks play a crucial role in addressing the challenges of implementing LCA in the construction industry. They can promote data standardisation to ensure consistency and reliability in LCA assessments. These frameworks can also address data accessibility and transparency, facilitating the exchange of information among stakeholders. Furthermore, policies can support the development of industry-wide databases or platforms that store LCA data for various construction materials, simplifying the assessment process and promoting data sharing [157]. By fostering a supportive policy environment, governments can encourage widespread adoption of LCA and facilitate the integration of sustainability considerations in construction decision-making processes.

Effective policy development and implementation require collaboration among policymakers, industry stakeholders, and researchers. Policymakers should engage with industry professionals and researchers to gain a comprehensive understanding of the environmental impacts of construction materials and identify areas where policy interventions can be effective. Industry stakeholders play a vital role in providing practical insights and feedback on the feasibility and effectiveness of policies. Researchers contribute by providing scientific evidence, conducting studies on the environmental performance of materials, and evaluating the impact of policy interventions. This collaborative approach ensures that policies are informed by scientific knowledge, consider practical implications, and are effectively implemented to drive positive change in the construction industry.

6. Challenges and future directions

6.1. Data availability and quality

Data availability and quality are crucial aspects of conducting LCA for construction materials. Here are some considerations regarding data availability and quality in LCA:

1. Data Sources: Availability of relevant data sources is essential for conducting accurate LCA studies. These sources may include industry databases, environmental product declarations (EPDs), literature, governmental reports and specific research studies. Access to reliable and up-to-date data is necessary to ensure the credibility and accuracy of LCA results.
2. Data Collection: Collecting primary data can be time-consuming and expensive. Therefore, using secondary data from reputable sources is often preferred. However, it is important to critically evaluate the relevance and reliability of the data sources to ensure their applicability to the specific context and system being assessed.
3. Data Completeness: LCA studies require comprehensive data covering all life cycle stages of construction materials, including raw material extraction, manufacturing, transportation, use and end-of-life scenarios. Incomplete data can lead to biased or incomplete assessments. Efforts should be made to collect data for all relevant life cycle stages to ensure a comprehensive analysis.
4. Data Quality: The quality of data used in LCA studies is crucial. Data quality can be assessed based on parameters such as representativeness, accuracy, precision and reliability. Transparent documentation of data sources, assumptions and uncertainties is necessary to ensure the reproducibility and reliability of LCA results. Peer-reviewed data and data quality assessments can provide additional credibility.
5. Data Transparency and Validation: Openness and transparency in data reporting are important for LCA studies. It allows for verification, replication and comparison of results by other researchers or stakeholders. Data validation techniques, such as sensitivity analysis and uncertainty assessment, help evaluate the robustness and reliability of LCA findings.
6. Industry Collaboration: Collaboration with industry stakeholders, manufacturers and trade associations can improve data availability and quality. Industry-specific data, such as production processes, energy consumption and emissions, can be obtained through collaboration, ensuring more accurate and context-specific assessments. Collaborative efforts can also help address data gaps and improve the representation of construction materials' life cycles.
7. Improving Data Availability: Efforts should be made to enhance data availability for construction materials. This includes promoting data sharing, encouraging the development and use of standardized data formats and establishing industry-wide databases. Increased transparency and accessibility of data can support more consistent and reliable LCA studies.
8. Continuous Improvement: Regular updates and improvements in data collection methods, data sources and data quality assessment techniques are necessary to enhance the accuracy and relevance of LCA for construction materials. Incorporating new scientific findings, technological advancements and industry practices into data collection processes ensures that LCA studies remain up-to-date and reflective of the current state of the industry.

By addressing data availability and quality challenges in LCA for construction materials, researchers and practitioners can improve the reliability, credibility and usefulness of sustainability assessments. This, in turn, enables informed decision-making, promotes sustainable practices and supports the development of more environmentally friendly construction materials and processes.

6.2. Standardisation and harmonisation of LCA methods

Standardisation and harmonisation of LCA methods for construction materials is essential to ensure consistent and reliable sustainability assessments across the industry. Here are some key considerations for achieving standardisation and harmonisation in LCA methods:

1. Methodological Consistency: Establishing consistent methodologies for LCA studies is crucial. This includes defining common system boundaries, functional units, impact assessment methods and data quality requirements. Harmonised guidelines and standards, such as ISO 14040 and ISO 14044, provide a foundation for methodological consistency and should be followed.
2. Inventory Data Collection: Standardisation of data collection methods is important to ensure the accuracy and comparability of LCA results. Developing industry-wide databases and reference data for construction materials can facilitate consistent data collection. Harmonisation efforts should focus on defining parameters, units and data sources to ensure compatibility and comparability of inventory data.
3. Impact Assessment Methods: Harmonising impact assessment methods is necessary to enable meaningful comparisons across different LCA studies. Developing consensus-based impact categories, characterization models and weighting factors for construction materials can enhance consistency and transparency. Collaborative efforts among researchers, industry experts and stakeholders can contribute to the development of harmonised impact assessment methods.
4. Data Transparency and Accessibility: Standardisation should also address data transparency and accessibility. Making LCA data openly available and using common formats and platforms can promote data sharing and facilitate comparisons. Encouraging the use of open-source LCA software and promoting data interoperability can support harmonisation efforts.
5. Stakeholder Involvement: Engaging stakeholders from industry, academia and relevant organizations is crucial for achieving harmonisation in LCA methods. Collaboration and dialogue among stakeholders can help identify common goals, address challenges and drive consensus on methodological approaches. Involving stakeholders in standardisation initiatives and establishing multi-stakeholder platforms can foster harmonisation.
6. Continuous Improvement and Updating: LCA methods for construction materials should be subject to continuous improvement and updating to reflect advances in science, technology and best practices. Regular reviews, feedback mechanisms and revision processes can ensure that LCA methods remain relevant, robust and aligned with evolving industry needs.
7. International Collaboration: International collaboration is vital to achieving global harmonisation of LCA methods for construction materials. Collaboration among different countries, research institutions and industry associations can facilitate the exchange of

knowledge, experiences and best practices. Harmonisation efforts should aim for convergence and alignment with international standards and guidelines.

By promoting standardisation and harmonisation of LCA methods for construction materials, the industry can benefit from consistent and comparable sustainability assessments. This enables informed decision-making, facilitates benchmarking and supports the development of more sustainable construction practices and materials.

6.3. Incorporating social aspects and human health impacts

Incorporating social aspects and human health impacts in LCA for construction materials is crucial for a comprehensive understanding of their sustainability performance. Here are some key considerations for integrating these aspects into LCA:

1. Social Life Cycle Assessment (SLCA): SLCA is an approach that assesses the social and socio-economic impacts associated with the life cycle of a product or material. It evaluates aspects such as human rights, labour conditions, community well-being and stakeholder engagement. Integrating SLCA into LCA studies can provide insights into the social implications of construction materials, including impacts on workers, local communities and society at large.
2. Stakeholder Engagement: Inclusion of relevant stakeholders throughout the LCA process can help identify and prioritize social aspects and human health impacts. Engaging workers, local communities, NGOs and other relevant groups can provide valuable insights into the social challenges and concerns associated with construction materials. Their input can guide the selection of impact categories and indicators that capture human health impacts and social well-being.
3. Impact Categories: Consideration of impact categories related to human health and social aspects is essential. These may include occupational health and safety, worker exposure to hazardous substances, community health and well-being, social equity and human rights. Developing specific impact assessment methodologies and indicators that capture these dimensions can enable a more comprehensive evaluation of construction materials' sustainability performance.
4. Data Availability: Availability of reliable and context-specific data on social aspects and human health impacts is a challenge in LCA studies. Collaborative efforts between researchers, industry stakeholders and relevant organisations can help improve data availability and quality. Building databases that capture social performance indicators and human health data for construction materials can support more robust assessments.
5. Methodological Development: Further development of impact assessment methodologies that incorporate social aspects and human health impacts is necessary. This involves refining characterization models, toxicity indicators and exposure assessment methods for substances of concern in construction materials. Integrating epidemiological data and risk assessment approaches can enhance the understanding of potential health impacts.
6. Integration of Multiple Perspectives: Considering diverse perspectives and values is crucial in assessing social aspects and human health impacts. Engaging with impacted communities, health experts, social scientists and other relevant stakeholders can help ensure that a broad range of concerns and values are taken into account. Incorporating participatory approaches and including qualitative data in LCA studies can capture local knowledge and social experiences.

By incorporating social aspects and human health impacts into LCA for construction materials, a more holistic assessment of their sustainability performance can be achieved. This integration helps to inform decision-making, promote responsible practices and contribute to the development of more socially sustainable and health-conscious construction materials and processes.

6.4. Bridging the gap between LCA research and industry practices

Bridging the gap between LCA research and industry practices is essential for the effective integration of sustainability principles in real-world decision-making. Here are key aspects that can help bridge this gap:

1. Standardisation and Harmonisation: Standardisation of LCA methodologies, data collection protocols and reporting formats is crucial for enhancing the comparability and credibility of LCA studies. Efforts should be made to develop industry-specific guidelines and standards that align with international frameworks, such as ISO 14040 and ISO 14044. Harmonisation among different LCA practitioners and organizations can facilitate knowledge sharing and ensure consistent application of LCA in industry practices.
2. Data Availability and Accessibility: Access to reliable and up-to-date data is vital for conducting meaningful LCA studies. Collaboration between researchers, industry stakeholders and data providers is crucial for improving data availability, quality and transparency. Efforts should be made to establish open-access databases and platforms that facilitate data sharing and enable industry professionals to access relevant information for LCA assessments.
3. Simplified Tools and Decision Support Systems: LCA can be perceived as complex and time-consuming, which may discourage its adoption in industry practices. Developing simplified tools and decision support systems that incorporate LCA results into user-friendly interfaces can help bridge this gap. User-friendly software, integrated with industry-specific databases, can enable practitioners to conduct streamlined LCA assessments and make informed sustainability decisions without requiring in-depth expertise in LCA methodology.

4. Training and Capacity Building: Providing education, training and capacity building initiatives on LCA to industry professionals can enhance their understanding of LCA concepts and methodologies. Workshops, webinars and training programs can help bridge the knowledge gap and empower professionals to integrate LCA into their decision-making processes. Collaboration between academia and industry in developing tailored training programs can ensure the practical relevance and applicability of LCA knowledge.
5. Stakeholder Engagement: Engaging industry stakeholders, including designers, manufacturers, policymakers and consumers, is crucial for successful implementation of LCA in industry practices. Stakeholders' involvement in the LCA process can help identify relevant sustainability indicators, set meaningful goals and prioritise improvement opportunities. Regular communication channels, such as industry forums, conferences and sustainability networks, should be established to foster dialogue, knowledge exchange and collaboration between researchers and industry practitioners.
6. Demonstrating Business Value: Highlighting the business value and competitive advantages associated with LCA adoption can motivate industry stakeholders to integrate LCA into their practices. Demonstrating the positive impacts of LCA on resource efficiency, cost savings, market differentiation and stakeholder engagement can help overcome perceived barriers and encourage industry-wide adoption. Case studies and success stories showcasing the tangible benefits of LCA can serve as powerful tools to bridge the gap between research and industry practices.

By addressing these aspects and fostering collaboration between researchers, industry professionals and other stakeholders, the gap between LCA research and industry practices can be effectively bridged. This integration can lead to more informed and sustainable decision-making across various sectors, driving the transition towards a more sustainable future.

6.5. Future research priorities

Identifying future research priorities in the field of LCA of construction materials is crucial for advancing sustainable practices in the construction industry. Here are some key areas that warrant further investigation:

1. Methodological Advancements: Future research should focus on developing and refining LCA methodologies specific to construction materials. This includes addressing data gaps, improving inventory modelling techniques and enhancing impact assessment methods. Advanced modelling approaches, such as hybrid LCA and consequential LCA, should be explored to capture the dynamic and interconnected nature of construction material systems.
2. Integration of Social and Economic Aspects: To achieve a comprehensive sustainability assessment, future research should aim to integrate social and economic aspects into LCA frameworks for construction materials. This entails considering factors such as worker health and safety, socio-economic impacts on local communities and life cycle cost analysis. The development of comprehensive impact assessment methods that incorporate these dimensions is essential.
3. Life Cycle Optimisation: Future research should focus on optimising construction material life cycles through LCA-driven decision-making. This involves developing decision-support tools and frameworks that consider LCA results in combination with other performance criteria, such as structural integrity, durability and energy efficiency. Integrated approaches that combine LCA with Building Information Modelling (BIM) and other design tools can enable real-time evaluation and optimisation of construction material choices.
4. Regionalisation and Contextualisation: Construction materials' environmental impacts can vary significantly across regions due to differences in energy sources, transportation distances and waste management practices. Future research should emphasise regionalised LCA approaches that account for these variations, enabling more accurate and context-specific assessments. This includes developing regionalized life cycle inventories and impact assessment factors.
5. Data Availability and Transparency: Continued efforts are needed to enhance the availability, quality and transparency of data for construction material LCA. Future research should focus on developing standardized data collection protocols, establishing open-access databases and promoting data sharing among stakeholders. Improving the transparency and reliability of data sources will contribute to more robust and credible LCA studies.
6. Circular Economy and Material Recovery: As the construction industry moves towards a circular economy approach, future research should explore the LCA implications of material recovery, reuse and recycling strategies. This includes assessing the environmental benefits and trade-offs associated with different recycling technologies, developing guidelines for designing recyclable materials and quantifying the environmental impacts of circular economy practices.
7. Stakeholder Engagement and Decision-Making: Future research should emphasise the involvement of stakeholders, including designers, manufacturers, policymakers and end-users, in the LCA process. This includes developing effective communication strategies to bridge the gap between LCA research and practical decision-making. Collaborative platforms that facilitate knowledge exchange and stakeholder engagement can contribute to informed decision-making and promote the adoption of sustainable construction practices.

By addressing these research priorities, the LCA of construction materials can continue to evolve and provide valuable insights for sustainable decision-making in the construction industry.

7. Concluding remarks

This review paper has provided valuable insights into the methodologies, comparative analysis and future directions of LCA in the context of construction materials. The paper has highlighted the importance of LCA in evaluating the environmental impacts associated with construction materials throughout their life cycle. Various LCA methodologies and tools have been discussed, emphasising the need for standardised approaches to ensure consistency and comparability of results.

Looking ahead, the paper has identified several future directions for LCA research in the field of construction materials. These include the integration of LCA with Building Information Modelling (BIM) to enhance decision-making at early design stages, the development of regionalized impact assessment methods and the incorporation of social and economic aspects into LCA frameworks. Additionally, the paper emphasises the importance of addressing data gaps and improving the transparency and accessibility of LCA databases.

Overall, this review paper serves as a comprehensive resource for researchers, practitioners and policymakers involved in sustainable construction. It highlights the need for continued efforts to advance LCA methodologies, foster cross-disciplinary collaborations and promote the widespread adoption of LCA as a fundamental tool for evaluating and improving the environmental performance of construction materials. By embracing these recommendations, the construction industry can move towards more sustainable practices and contribute to a greener and more resource-efficient built environment.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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