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Integrating circular economy principles and life cycle assessment into cement manufacturing: A systematic review.

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Abstract

The cement industry contributes significantly to global construction and economic development but presents significant environmental challenges. When one ton of cement is produced, approximately the same amount of carbon dioxide (CO₂) is released into the atmosphere, from the quarry to packaging for sale or from cradle-to-gate. This exacerbates environmental concerns on ecosystems and human health. Given the increasing demand for cement and increasing environmental awareness, the construction industry is looking for resource-efficient solutions. Tackling these challenges necessitates a transition to sustainable practices through the integration of circular economy (CE) principles and life cycle assessment (LCA) methodologies. LCA offers a comprehensive framework for evaluating and quantifying the environmental impacts of cement production from a cradle-to-grave perspective, while CE complements this approach by embedding sustainability into the process through innovative resource utilization. This review emphasizes significant advancements in reducing clinker consumption in concrete by incorporating supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag and other agricultural waste. Additionally, it explores the potential of biomass and biomass residues as alternative fuels for kilns, fostering greater sustainability in cement manufacturing. These eco-friendly strategies not only improve material performance but also reduce the industry's carbon footprint. By systematically analyzing the existing literature, this paper identifies critical gaps in LCA standardization, the application of CE in cement production, and the introduction of alternative materials. It provides actionable recommendations for future research and practical industry implementation, contributing to the global transition to sustainable construction.

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1. Introduction

The cement industry is a critical driver of global construction and economic growth, yet its environmental footprint poses significant challenges like air pollution [1], [2] and respiratory diseases [3], [4]. The production of cement is resource-intensive and contributes to considerable carbon dioxide (CO₂) emissions, exacerbating climate change [5] and environmental degradation [6]. One tonne of cement produced generates nearly an equivalent tonne of CO₂ [7]. This environmental

burden is exacerbated by the growing global demand for cement [8], [9], driven by rapid urbanization [10] and infrastructure development [11].

As the demand for cement continues to rise, there is an urgent need for the construction industry to adopt more sustainable practices [12]. Consequently, there is a growing interest in integrating circular economy (CE) principles and life cycle assessment (LCA) methods into the environmental assessment of cement production processes [13], [14]. The goals of the CE are waste reduction and increased resource

efficiency [15], whereas LCA offers a framework for assessing the environmental effects of cement production [16]. To lessen dependency on traditional cement in the face of these climate change difficulties, researchers have investigated substitute materials like fly ash [17], coffee husks [18], biochar in Ghana [19], risk husks usage in rural housing in Kerala, a southern state of India [20], almond shell ash [21], sugarcane bagasse ash in Pakistan [22]. Despite these efforts, the practical application of LCA in assessing the scalability and trade-offs between environmental impacts and material circularity remains complex.

With alternative fuels and supplemental cementitious materials, this systematic review explores the body of existing literature with the main research question being how can life cycle assessment methodologies and circular economy principles be successfully incorporated into cement manufacturing to improve sustainability and lessen environmental impacts?

2. Methodology

Different literature databases were explored, including Web of Science, JSTOR, ScienceDirect and Google scholar. More research articles were identified by screening the citation and references of the papers obtained from the search results (see Figure 1.). The keywords applied were “circular economy,” “cement,” “construction industry,” “environmental impact,” “environmental assessment,” “life cycle assessment,” and “sustainability”. A range of vocabulary and Boolean operators were used to find the literature selected for this research. The initial search of the databases used a combination of “life cycle assessment” (or “LCA”), “cement,” “circular economy,” and “construction” to determine the focus words for this study. Further searches included variations of both singular and plural terms.

Studies indicating risk of bias, inconsistency, imprecision and unclear methodology, indirectness, and uncollaborated conclusions were not included in this review. Data collected included the article title, authors, country where the study was performed, study period and year of publication.

3. Results

3.1. Synthesis of Findings

The reviewed studies produced varying conclusions in terms of how well circular economy principles and life cycle assessment can be integrated into the cement and construction industry. Research has shown that blending supplementary cementitious materials (SCMs) into clinker can significantly lower CO₂ emissions [23], [21], [12], [24]. Examples of real-world case studies where cement plants have successfully integrated circular economy principles include Lafarge Holcim’s Geocycle Waste Management [25]. Heidelberg’s Norcem Brevik plant in Norway is a pioneer in carbon capture, utilization, and storage (CCUS). The plant integrates waste from construction and demolition (C&D) sites by recycling concrete aggregates and using them in cement production [26]. Dangote Cement plants in Nigeria have adopted biomass fuels, such as palm kernel shells and rice husks, to substitute for coal in kiln operations [27]. These real-life cases demonstrate that by partially replacing Portland cement with SCMs, the cement industry’s carbon dioxide emissions are lowered since SCMs typically have a lower carbon footprint compared to traditional cement production [28], [29].

Other studies on the contrary indicated lack of standardized methodologies for applying LCA to circular economy practices in cement manufacturing as a challenge, which complicated the comparison of results across different studies [13], [30]. Different studies and industries used varying LCA methodologies, leading to inconsistent results. For instance, some studies used a cradle-to-grave approach [31], [32], focusing on the entire lifecycle from raw material extraction to disposal, while others used a cradle-to-gate approach [33], which only considers impacts up to the point where the product leaves the manufacturing facility. Other studies conducted LCA using an inventory analysis only [35] and others used a the detailed four stage approach that included goal scope, inventory analysis, impact assessment and interpretation [30], [36]. Lack of standard LCA methodologies made it difficult to assess the impact accurately.

Finally some studies also revealed the trade-offs, such as increased energy consumption and emissions during the production and transportation of SCMs [37], [38], [39]. For example, grinding slag into ground granulated blast furnace slag or processing fly ash requires energy, which can contribute to additional greenhouse gas emissions if fossil fuels are used [40], [41]. SCMs are often transported from their production sites to cement plants. This transportation could add to the overall carbon footprint, especially if SCMs are sourced from distant locations [42].

Several studies explored the use of supplementary cementitious materials since these materials offer the triple benefits of circular economy principles by improving the performance of concrete and improving resource efficiency during production while reducing the amount of clinker used in cement, which is the primary source of CO₂ emissions. For instance, fly ash, a by-product of coal combustion, when recycled has been shown to improve the durability and

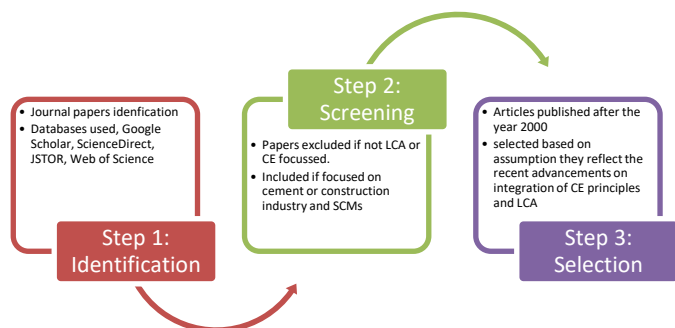


Figure 1: Flow diagram of the study selection process

workability of concrete while reducing environmental impacts [43].

3.2. Integrating Circular Economy and Life Cycle Assessment

One important technique for assessing how products and processes affect the environment from cradle to grave is by using LCA. LCA makes it possible to evaluate all environmental impacts, associated with energy use, raw material extraction, emissions, and waste management, in the context of cement manufacturing [32], [30], [44]. LCA facilitates a comprehensive approach of various cement production methods and materials as well as the identification of opportunities to enhance environmental performance.

Several studies applied LCA to assess the environmental performance of alternative cement formulations. For example, Santos et al., (2020) conducted an LCA study comparing conventional Portland cement with fly ash and ground granulated blast furnace slag -blended cements [45]. The results showed that using these alternative materials could reduce CO₂ emissions by up to 30%. However, trade-offs between environmental impacts and material circularity must be considered. For instance, while SCMs reduce CO₂ emissions, their extraction and transportation may introduce other environmental impacts such as land use change and energy consumption [6].

Table 1 provides a summary of alternative approaches identified in the literature for integrating LCA and implementing CE principles through the life cycle of cement. This table is significant because it highlights the diverse strategies and methodologies that researchers have explored to merge these two important concepts. The variety of approaches documented reflects the complexity and multifaceted nature of combining LCA with CE. Each approach offers unique insights, demonstrating that there is no single solution but rather a range of options that can be tailored to different contexts and objectives.

Table 1. Alternative approaches identified in the literature integrating LCA and CE.

Cement Life Cycle Stage	Practical Circular Economy practices
Raw material extraction	Refuse the linear model "take, make, dispose" economy, which assumes that there will always be new materials to use and places to dispose of waste.
Manufacturing stage	Reuse materials directly within a plant or indirectly by other industrial plants and/or recycle (onsite) the waste stream resource
Packaging & Distribution of cement	Regulation on marketing of resources mixed with another industrial waste to produce a valuable product.
Design of Buildings	Rethink Eco designs for transformable buildings, apply building information modelling (BIM) for

	construction waste minimization.
Construction phase	Recycle wastewater, after suitable treatments to obtain a drastic reduction of the clear water amount used for industrial purposes.
End of life	Recover: Demolition waste minimization and analyze the potential reuse or recycling of existing materials and if it is feasible comparing to using new materials.
Beyond building life	Rethink: Use of Life-cycle analysis to find the benefits of reusing different types of materials in the design stage of a new building.

4. Opportunities in Integrating Circular Economy and Life Cycle Assessment

The use of supplementary cementitious materials reduces reliance on virgin materials while maintaining concrete's structural integrity. For example, sugarcane bagasse ash has been shown to enhance concrete performance [13]. With increased funding for research and development, SCMs could achieve quality similar to Portland cement through optimized blends and formulations.

Secondly, public-private partnerships [46], [47], can support the development of a circular supply chain by fostering collaboration among builders, cement manufacturers, and waste producers (e.g., steel plants, agriculture). Governments can aid this effort by establishing local recycling facilities to ensure a steady supply of alternative materials for cement production.

Thirdly, expanding and localizing green building certification programs, such as Leadership in Energy and Environmental Design (LEED) from America [48] or the European Building Research Establishment Environmental Assessment Methodology (BREEAM) [49] in developing economies can incentivize the use of sustainable materials. Higher certification levels could encourage builders and developers to adopt circular economy principles in construction projects.

Fourthly, eco-designs by architects can minimize waste, optimize resource efficiency, and enable recycling at a building's end-of-life. Pilot projects showcasing the integration of circular economy and life cycle assessment principles can help persuade reluctant stakeholders of their practical and financial benefits [50]. Tools like Building Information Modeling (BIM) [12] can further reduce waste, while advanced recycling technologies, such as robotic sorting and chemical recycling, improve material recovery.

Finally, developing clearer national and regional roadmaps are needed to guide the transition to a circular economy. Policies mandating the use of recycled materials in cement and construction, alongside long-term goals to reduce material waste and emissions, will provide stakeholders with the structure and incentives to adopt sustainable practices [51].

5. Challenges in Integrating Circular Economy and Life Cycle Assessment

Despite the potential of integrating CE and LCA in the cement industry, several challenges hinder full adoption. One major hurdle is the complexity of evaluating trade-offs between environmental impacts and material circularity [52], [28]. For instance, while recycling reduces raw material use and waste, it can also increase energy consumption and emissions during the recycling process [53].

Lack of standardized LCA methodologies for CE practices poses another barrier. Variations in system boundaries, functional units, and impact categories make it difficult to compare results and establish industry-wide best practices. Economic and regulatory factors, such as limited incentives for low-carbon materials and slow policy implementation, further delay progress [54], [55].

Managing supplementary cementitious materials (SCMs) is another challenge [39]. Processing SCMs can impact cement performance, and determining whether to recycle, reuse, or safely dispose of materials at the end of their life cycle adds complexity. Recycling, while reducing waste, may still have significant environmental costs, such as high energy usage. Without clear plans for end-of-life material handling, the environmental benefits of CE practices can diminish [56], [37].

Finally, using unconventional materials can introduce uncertainty. Stakeholders may hesitate to adopt new approaches without strong evidence of long-term benefits [38]. Shifting from linear to circular models, as seen in India, requires not just technical changes but also a significant transformation in mindset and organizational culture [57]. Overcoming these challenges is key to advancing sustainability in the cement sector.

6. Conclusion

The cement industry faces a critical challenge in balancing economic growth with sustainable development. Achieving sustainability and meeting net-zero targets requires integrating life cycle assessment (LCA) techniques and circular economy (CE) concepts. However, addressing challenges such as trade-offs and the lack of standardized procedures is crucial for the effective adoption of these approaches. Accelerating the use of CE and LCA is essential for reducing the environmental footprint of the cement industry and fostering a sustainable future.. Public-private partnerships (PPPs) can bridge knowledge and resource gaps. Governments can offer incentives, such as tax breaks, grants, or subsidies, to promote the adoption of circular practices like using recycled materials and sustainable manufacturing processes. Private companies can contribute innovations and research to tackle industry-specific sustainability challenges. Collaboration platforms involving manufacturers, builders, architects, and engineers can further drive knowledge-sharing and best practices, with industry associations playing a pivotal role in fostering these partnerships.

Future research should prioritize the development of standardized LCA methodologies tailored to circular economy

principles. This would enable consistent environmental impact assessments and facilitate comparisons across innovative cement production processes. Additionally, exploring alternative materials, such as construction and demolition waste, holds significant potential for advancing sustainable cement production..

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CRedit authorship contribution statement

S Onsongo: Conceptualization, Writing - Original Draft, Methodology, Investigation, Formal analysis, Data curation. **J. Olukuru:** Conceptualization, Writing - Review & Editing, Methodology, Validation, Supervision. **O Mwabonje:** Conceptualization, Writing - Review & Editing, Data curation, Visualization, Supervision.

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