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Review

A comprehensive review on integrating sustainable practices and circular economy principles in concrete industry

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ABSTRACT

This comprehensive review explores the integration of circular economy principles into the concrete industry, emphasizing their role in enhancing sustainability and resource efficiency. It covers the fundamental concepts of circular economy and examines the application of Life Cycle Assessment (LCA) in evaluating the environmental impacts of concrete production. The review highlights innovative strategies for recycling, reuse, waste reduction, and resource optimisation, showcasing how these approaches can transform concrete production practices. It also addresses the policy considerations, economic implications, and societal impacts associated with adopting circular economy practices. Furthermore, the review investigates recent technological advancements in circular concrete production, including self-healing concrete and 3D printing. By summarizing these findings and offering practical recommendations, the review aims to support the industry in transitioning towards more sustainable practices. This detailed analysis provides valuable insights into the benefits and challenges of circular economy adoption, helping stakeholders make informed decisions for a greener concrete sector.

1. Introduction

The global construction industry, a cornerstone of economic growth and societal development, heavily relies on concrete as a fundamental building material. Concrete is indispensable in constructing various infrastructures, from residential buildings to roads, bridges, and dams. However, the traditional linear model of concrete production, involving extraction, processing, utilisation, and eventual disposal, has significant environmental and sustainability drawbacks (Liew et al., 2017; Zhao et al., 2021). The extraction of raw materials, particularly sand, gravel, and cement, contributes to habitat destruction, erosion, and alteration of watercourses. Additionally, the production of cement, a key component of concrete, is an energy-intensive process responsible for a substantial share of global carbon dioxide emissions (Worrell et al., 2001; Rehan and Nehdi, 2005; Benhelal et al., 2013; Nie et al., 2022). Furthermore, concrete waste generated during construction and demolition processes poses a significant challenge, occupying landfill spaces and representing lost opportunities for resource recovery (Islam et al., 2019; Ram et al., 2020; Purchase et al., 2021).

The urgency to mitigate these environmental impacts and establish a more sustainable model for the concrete industry has led to the embrace of circular economy principles. The circular economy promotes a regenerative approach, wherein materials and products are kept in use for as long as possible through reuse, recycling, and repurposing. It stands in contrast to the traditional linear "take-make-dispose" model by promoting resource efficiency, waste reduction, and a closed-loop system. Applying circular economy strategies to the concrete industry is a vital step towards sustainable and responsible construction practices. This transformation hinges on a multi-pronged approach that addresses the entire life cycle of concrete, from material acquisition to end-of-life considerations (Deschamps et al., 2018; Adesina, 2020; Huang et al., 2020; Cerchione et al., 2023). Firstly, minimising raw material extraction is essential. This involves exploring alternative sources of aggregates and cement, such as recycled concrete or industrial by-products, to reduce the reliance on virgin resources. Additionally, optimising the mix design ensures that the concrete achieves desired properties with a minimal amount of raw materials. Maximising the reuse and recycling of concrete waste is another critical aspect. Concrete waste generated during construction and demolition can be processed and repurposed as recycled aggregates, diverting materials from landfills and reducing the need for new extraction.

Optimising resource use focuses on efficient material utilisation and

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energy consumption during production, transportation, and construction phases. This includes employing locally sourced materials to minimise transportation emissions. Innovative design and construction practices play a crucial role in extending the life cycle of structures (Wahab et al., 2018; Joensuu et al., 2020; Afzal et al., 2020; KC and Gautam, 2021). Designing for disassembly and reusability allows for the repurposing of components and materials, promoting a circular flow of resources within the construction industry. Collectively, these circular economy strategies encourage a more sustainable concrete industry by reducing environmental impact, conserving resources, and creating a more resilient and efficient built environment.

The application of new technologies, particularly green nanotechnology, is transforming the way we address environmental, economic, and energy challenges. Green nanotechnology leverages eco-friendly materials and processes, such as the use of natural extracts and renewable resources, to develop nanostructures that contribute to sustainability. For instance, the work by Zinatloo-Ajabshir et al. (2019, 2020) explores the eco-friendly synthesis of nanomaterials using natural substances like grape juice and Ficus carica extract. These nanomaterials demonstrate significant potential as photocatalysts for the degradation of hazardous organic pollutants under visible light. Such advancements are crucial in developing sustainable solutions for environmental remediation. In the realm of energy, innovative methods such as the fabrication of sustainable construction materials from industrial waste (Rahimpour et al., 2024a,b) and the development of efficient photocatalysts for clean energy production (Zinatloo-Ajabshir et al., 2024) are essential. These studies highlight the potential of green nanotechnology in producing clean energy through cost-effective and environmentally friendly approaches, contributing to energy sustainability. Furthermore, research on sustainable soda ash production (Rahimpour et al., 2024a,b) and lightweight construction materials (Fahmi et al., 2023) underscores the economic benefits of adopting green technologies, which not only reduce environmental impact but also enhance economic viability through resource efficiency and waste reduction. Overall, these advancements in green nanotechnology and sustainable practices present promising avenues for improving human life and addressing global challenges.

This review aims to provide an extensive exploration of circular economy strategies within the concrete industry. By synthesising existing research, case studies, and successful practices, this review seeks to shed light on the potential benefits and challenges of implementing circular economy principles. The comprehensive analysis intends to equip stakeholders, including policymakers, industry professionals, academics, and environmentalists, with the knowledge needed to drive sustainable and circular transformations in the concrete industry. By doing so, the goal is to forge a path towards a more sustainable, environmentally responsible, and economically viable future for concrete production and construction.

This review is essential as it provides a comprehensive analysis of integrating circular economy principles into the concrete industry, a sector crucial for sustainable development. With concrete production being resource-intensive and environmentally impactful, understanding and adopting circular practices is vital for reducing waste and enhancing resource efficiency. By exploring innovations, evaluating environmental impacts, and discussing policy and economic implications, this review addresses critical knowledge gaps. It offers valuable insights and practical recommendations for industry stakeholders, helping them navigate the transition towards more sustainable and circular concrete practices. Such a review supports informed decision-making and promotes the broader adoption of eco-friendly construction methods.

This paper has presented a novel perspective by integrating circular economy principles specifically tailored to the concrete industry. It has introduced new frameworks for evaluating concrete's sustainability through advanced Life Cycle Assessment (LCA) methods and has explored innovative strategies for recycling and resource optimisation. The paper has highlighted emerging technologies such as self-healing concrete and carbon capture, providing fresh insights into their potential impacts. Additionally, it has discussed the practical implementation of these innovations in policy and economic contexts, offering a forward-looking analysis that addresses current gaps and sets a foundation for future research and development in sustainable concrete practices.

2. Circular economy principles

2.1. Understanding the circular economy concept

The concept of the circular economy (CE) is a fundamental departure from the traditional linear economic model that follows a 'take-make-dispose' pattern. It envisions a restorative and regenerative approach to economic activity. In essence, the idea is to keep resources and products in use for as long as possible, extracting maximum value from them throughout their lifecycle. Once a product reaches the end of its life, the materials it is composed of are reintroduced into the production cycle, reducing waste and minimising the need for new raw materials.

At its core, the CE is underpinned by a few key principles. Firstly, it emphasizes designing products and systems for durability, repairability, and longevity. Products are engineered to last, and repair and maintenance are actively encouraged to extend their lifespan (Tukker, 2015; Wuyts et al., 2019; Foster, 2020; Bakker et al., 2021). Secondly, the focus is on reusing products and components to prevent them from becoming waste (Den Hollander et al., 2017; Zink and Geyer, 2017; Morseletto, 2020). This encourages practices like sharing, refurbishing, and repurposing, allowing products to have multiple lives. Thirdly, recycling plays a critical role. It involves breaking down products and materials at the end of their life and repurposing them to create new products, closing the loop in the material cycle (Di Maio and Rem, 2015; Li et al., 2022; Popović and Radivojević, 2022). Resource efficiency is a fundamental objective. It involves optimising the use of materials, energy, and other resources at every stage of a product's lifecycle. This includes designing for efficiency, minimising waste in production processes, and promoting the responsible consumption of products (Mestre and Cooper, 2017; Geisendorf and Pietrulla, 2018; Hapuwatte and Jawahir, 2021). By using resources more efficiently, the circular economy aims to achieve sustainable growth while reducing environmental impact.

The existing conceptualisation of the CE is illustrated in Fig. 1 within the realm of current practices and business operations. The core message of CE is encapsulated within the inner circles of Fig. 1, namely product reuse, remanufacturing, and refurbishment. These aspects are highlighted for their reduced resource and energy requirements, presenting a more economically viable alternative compared to the conventional recycling of materials into low-grade raw materials. The objective in the inner circles is to maximise the duration of resource value, promoting extensive use and value creation from existing materials.

The CE approach advocates a specific sequence in resource utilisation. Initially, materials should be reclaimed for purposes of reuse, refurbishment, and repair, prioritizing these over remanufacturing, and only then considering raw material utilisation—an approach contrasting traditional recycling which predominantly centres on raw material usage. According to CE principles, energy generation through combustion should stand as the penultimate option, with landfill disposal as the last resort (Iacovidou et al., 2017; Velvizhi et al., 2020; Zębek and Zięty, 2022). By adopting this sequence, the product value chain and its lifecycle preserve the highest possible value and quality, alongside optimised energy efficiency, effectively embodying the essence of CE.

The benefits of adopting a CE approach are extensive. Environmentally, it reduces the strain on natural resources by limiting the extraction of raw materials and lowering pollution levels associated with waste (Quina et al., 2018; Xavier et al., 2021; Zhang et al., 2022). Economically, it fosters innovation, job creation, and economic growth, particularly in the fields of remanufacturing, recycling, and refurbishment

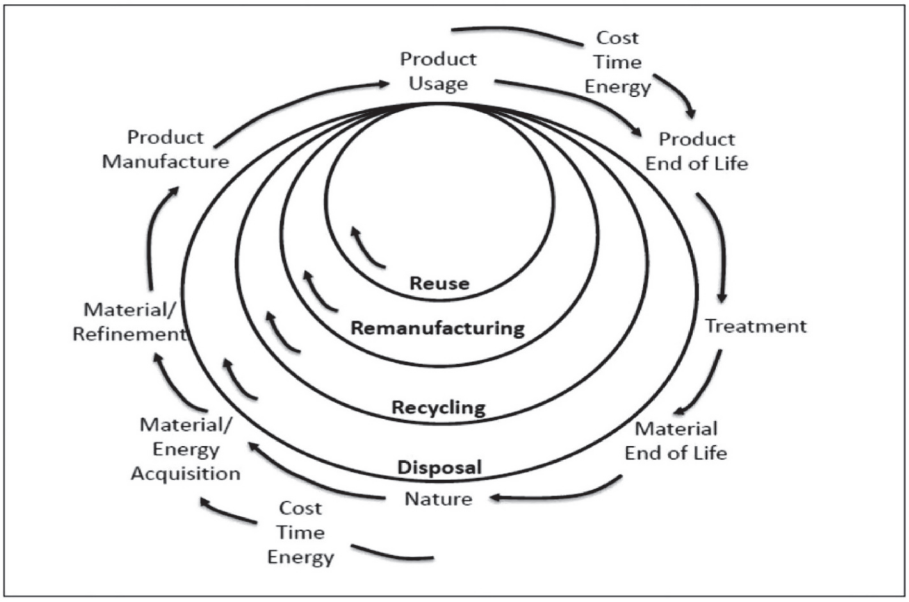

Fig. 1. The concept of circular economy (Korhonen et al., 2018).

(Horbach et al., 2015; Schroeder et al., 2019; Mhatre et al., 2021; Suchek et al., 2021). It also enhances supply chain resilience by reducing dependency on scarce resources (Gaustad et al., 2018; Baars et al., 2021; Dwivedi et al., 2023). Moreover, the CE aligns with societal well-being by promoting access over ownership, encouraging collaboration, and minimising social disparities (Velenturf and Purnell, 2021; Mies and Gold, 2021; Schroder et al., 2020).

2.2. Relevance of circular economy principles to concrete industry

The relevance of CE principles to the concrete industry is profound. Concrete, a cornerstone of construction, traditionally follows a linear model with high resource consumption and waste. Implementing circularity in this industry implies reusing concrete waste, optimising resource usage, and incorporating recycled materials. Recycling concrete reduces landfill burden and curtails the need for raw material extraction. Moreover, designing structures for disassembly and reusing concrete components aligns with circular design principles. By embracing a CE approach, the concrete industry not only minimises its environmental footprint but also fosters sustainability and resource efficiency in construction practices.

Marsh et al.'s study (2022) delved into the practical implementation and integration of circular economy strategies within the concrete domain. It underscores the pressing need to transition from a linear approach to a circular one, significantly diminishing waste production and maximising resource efficiency. By doing so, the concrete industry can contribute to a more sustainable and eco-friendly future. Martínez-Martínez et al. (2023) delved into the development of low-energy cements, aligning with circular economy and low-carbon principles. By exploring new types and dosages for manufacturing these cements from raw materials and industrial waste, the study highlights the potential to markedly reduce energy consumption and the overall environmental impact associated with conventional cement production.

The work by Shehata et al. (2022) showcased the potential of geopolymer concrete as a green building material, demonstrating its alignment with circular economy principles. By utilising industrial waste and minimising the environmental footprint, this approach provides a concrete example of sustainable practices within the construction industry. Deschamps et al. (2018) offered a critical perspective by conducting a life cycle assessment of glass powder usage in concrete, critically evaluating its compatibility within a circular economy framework. This analysis adds depth to the discussion, providing valuable insights into the intricacies and trade-offs associated with specific recycling approaches within the concrete industry. Munaro et al.'s systematic review (2020) presented a comprehensive analysis of how circular economy principles can be effectively integrated into the built environment. It serves as a valuable knowledge synthesis, providing a holistic view of sustainable practices and circularity within the construction sector.

The study by Sinoh et al. (2023) specifically explores sustainable aggregates for the Malaysian construction industry, shedding light on the potential of circular economy principles within construction materials. Their work is particularly relevant in the context of emerging economies, underlining the importance of sustainable material choices. Meglin et al.'s assessment (2022) Meglin et al., 2022 at the regional level accentuates the significance of a localized circular economy approach for building materials. Understanding the environmental-economic dynamics within specific regions can inform tailored strategies, optimising the circular transition. The collective findings from these studies provide compelling reinforcement for advocating the adoption of circular economy principles within the concrete industry. This paradigm shift offers substantial benefits, enabling the industry to meaningfully reduce resource consumption, curtail waste generation, and actively contribute to the establishment of a more sustainable and environmentally responsible built environment.

One of the fundamental advantages of embracing circular economy principles in the concrete sector is the notable reduction in resource consumption. By reusing materials, repurposing waste, and employing efficient recycling methods, the industry can significantly decrease its dependence on raw materials. This reduction not only conserves natural resources but also diminishes the environmental impact associated with their extraction and processing. Moreover, integrating circularity within the concrete industry allows for a substantial minimisation of waste. Concrete waste, a prevalent issue in the construction sector, can be repurposed and recycled to create new materials or refurbish existing structures. This approach mitigates the burden on landfills, reduces pollution, and minimises the overall environmental footprint of the industry. Furthermore, transitioning towards a circular economy in the concrete sector contributes to fostering a more sustainable and environmentally responsible built environment. The focus on reusability, recyclability, and efficient resource management aligns with broader global sustainability objectives, including the reduction of greenhouse gas emissions, conservation of biodiversity, and preservation of ecosystem health.

3. Life cycle assessment (LCA) in concrete production

3.1. Overview of LCA

Life Cycle Assessment (LCA) stands as a systematic and vital methodology, meticulously designed to evaluate the environmental footprint of a product, process, or activity throughout its entire life cycle. This holistic approach traverses through the inception, usage, and eventual disposition or recycling, encapsulating a thorough understanding of the sustainability impact. At its core, LCA aims to provide a comprehensive and nuanced comprehension of the environmental implications intricately linked to a specific product or process. This encompasses a multifaceted analysis, delving into resource consumption, energy utilisation, emissions, waste generation, and potential environmental consequences such as climate change, air and water pollution, as well as habitat degradation.

The LCA process unfolds in a structured sequence of steps, commencing with a clear delineation of the study's objectives, system boundaries, functional unit, and pertinent impact categories. Following this, an exhaustive inventory is compiled, meticulously cataloging all inputs, including materials and energy, and outputs, such as emissions and waste, correlated with every life cycle stage of the product or process under scrutiny. Once the life cycle inventory is established, the assessment of potential environmental impacts takes centre stage. This evaluation employs established methodologies like Global Warming Potential (GWP) or Acidification Potential (AP), a step known as Life Cycle Impact Assessment (LCIA). LCIA is pivotal in quantifying the potential environmental burdens associated with the product or process, providing a nuanced understanding of its ecological implications.

Subsequent to the collection of requisite data and the rigorous assessment, interpretation follows suit. This crucial stage involves a profound analysis of the results obtained, pinpointing environmental hotspots and exploring avenues for potential improvements. Sensitivity analysis and comparative evaluation of alternative scenarios are integral components of this interpretive phase, ensuring a robust and comprehensive understanding of the environmental impact. Table 1 presents the steps in LCA, providing descriptions, key activities, and the expected outputs associated with each step in a clear and organized manner.

The applicability of LCA is vast and dynamic, transcending the assessment of individual products. It extends its reach to evaluate organizational or sectoral environmental impacts, serving as a guiding compass for industries. Industries leverage LCA to steer product development, embrace sustainable choices, and minimise their environmental footprint. Equally significant, policymakers draw upon LCA results to craft regulations and incentives, fostering the adoption of sustainable practices within society. Thus, LCA stands as a pivotal tool, driving sustainability and responsible environmental stewardship at various levels of decision-making.

Table 1
Steps in the life cycle assessment (LCA) process.

Step	Description	Key Activities	Outputs
1.	Goal and Scope Definition	Define study objectives, system boundaries, functional unit, and impact categories.	Clearly outlined study objectives and defined scope for the assessment.
2.	Life Cycle Inventory (LCI)	Compile a detailed inventory of inputs (materials, energy) and outputs (emissions, waste) for each life cycle stage.	Comprehensive data on all relevant inputs and outputs throughout the life cycle.
3.	Life Cycle Impact Assessment (LCIA)	Assess potential environmental impacts using established methodologies (e.g., GWP, AP).	Quantified environmental impacts associated with the product or process.
4.	Interpretation	Analyse results, identify environmental hotspots, and explore improvement opportunities. Conduct sensitivity analysis and compare alternative scenarios.	Insights for decision-making, highlighting areas for improvement and potential sustainable strategies.

3.2. LCA application to concrete production

Life Cycle Assessment (LCA) in the context of concrete production involves a thorough analysis of the environmental impact associated with the entire life cycle of concrete. This encompasses raw material extraction, production of concrete components, transportation, construction, usage, and eventual disposal or recycling. LCA evaluates key factors such as resource consumption, energy use, greenhouse gas emissions, air and water pollution, and waste generation. By comprehensively assessing these aspects, LCA allows for informed decision-making to optimise processes, minimise environmental footprint, and enhance the sustainability of concrete production, aligning with global efforts towards a more environmentally responsible construction industry.

The application of LCA to concrete production has garnered considerable attention, reflecting a growing awareness of the environmental impacts associated with the construction industry. Several studies have delved into this domain, employing LCA to analyse the environmental footprints of various concrete manufacturing processes and materials. Vieira et al. (2016) provided a comprehensive review, highlighting the significance of LCA in evaluating both conventional and ecological concrete production. Knoeri et al. (2013) compared recycled and conventional concrete, shedding light on the environmental advantages of recycling in structural applications. Chen et al. (2010) showcased LCA as an indicative method for waste recycling in mineral additions for concrete.

Critically, Gursel et al. (2014) conducted a life-cycle inventory analysis of concrete production, emphasizing its energy and environmental implications. They noted the importance of accurate data and system boundaries for robust LCA results. Mohammadi and South (2017) extended the assessment to benchmark concrete products in Australia, offering region-specific insights. Tinoco et al. (2022) delved into the sustainability of cementitious materials for 3D concrete printing, showcasing LCA as a tool to assess innovative concrete technologies. Hossain et al. (2016) assessed the environmental friendliness of concrete paving eco-blocks, underlining the role of LCA in evaluating eco-friendly construction materials. Colangelo et al. (2020) and Yazdanbakhsh et al. (2018) contributed by comparing concrete with recycled aggregates, aligning with a circular economy approach. Gravina and Xie (2022) explored sustainable concrete development using Crumb Rubber, demonstrating the evolving applications of LCA in novel concrete technologies. Salas et al. (2018) analysed the life cycle of geopolymer concrete, highlighting LCA's role in evaluating alternative concrete formulations.

In the study conducted by Hottle et al. (2022), the defined system boundary for the environmental LCA of concrete is a crucial aspect that shapes the assessment's scope and accuracy. The system boundary adopted for their analysis is cradle-to-gate, encompassing the entire life cycle of concrete production from raw material extraction to the production of wet concrete mix at a batch mixing facility, ready for transport to a construction site as illustrated in Fig. 2. The cradle-to-gate system boundary allows for a comprehensive evaluation, starting with the extraction of raw materials essential for concrete production. This includes the mining or extraction of key components such as limestone, clay, silica, and other essential aggregates. Subsequently, it considers the transportation of these raw materials to the processing facility.

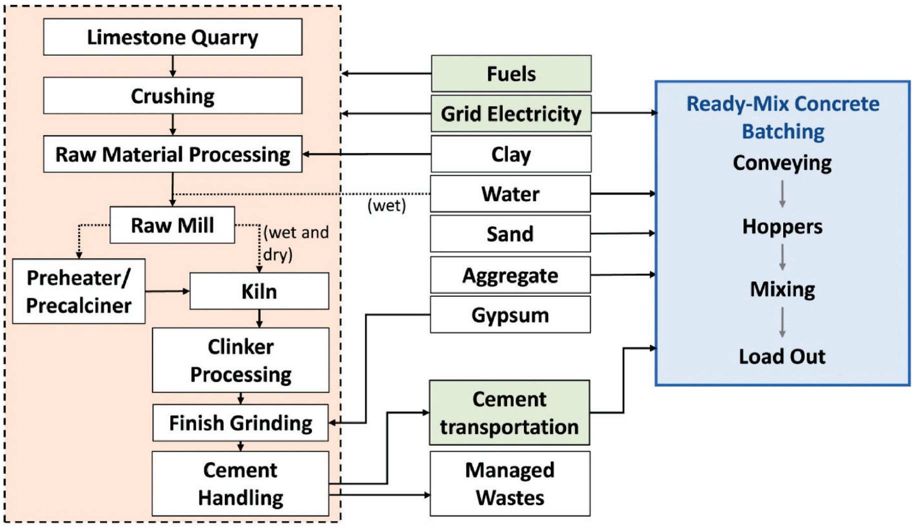

Fig. 2. A diagram delineating the system boundary, encompassing subprocesses within the primary foreground processes of cement and concrete production (Hottle et al., 2022).

Within this system boundary, the authors accounted for the energy-intensive processes involved in cement production, which is a fundamental component of concrete. Cement production involves high-temperature kilning processes, demanding substantial energy inputs and contributing significantly to the overall environmental impact. The assessment also considers the associated emissions and energy usage during this stage. Moving further along the life cycle, the wet concrete mix preparation at a batch mixing facility is integrated into the system boundary. This phase involves blending the cement with aggregates, water, and any required additives to form the concrete mix, representing a critical transition point where the raw materials take on their intended form for construction purposes.

The collective body of research underscores the crucial role that LCA plays in the meticulous evaluation of the environmental repercussions stemming from concrete production. LCA, as a methodological framework, illuminates a comprehensive pathway towards the achievement of environmentally sustainable concrete manufacturing. Through in-depth analyses, it serves as a powerful tool, shedding light on critical areas within the production process that can be optimised and refined to minimise environmental impact.

One of LCA’s significant strengths is its ability to guide stakeholders in the construction industry towards adopting eco-conscious practices. The insights garnered from an LCA facilitate informed decision-making, encouraging a proactive approach to sustainability. Stakeholders, armed with the knowledge of the ecological footprint of concrete production, are empowered to make strategic choices that steer the industry towards greener and more environmentally responsible methodologies. In essence, this approach instigates a paradigm shift within the concrete sector, aligning its practices with broader sustainability objectives. It underscores the imperative of not only focusing on the end product but on the entire life cycle, fostering a sustainable ethos that resonates with the urgent global need for environmentally conscious practices across all industrial domains. The integration of LCA into the fabric of concrete production is instrumental in paving the way towards a greener, more sustainable future.

3.3. Environmental impact analysis of concrete production

Traditional concrete production poses significant environmental challenges. Foremost is carbon dioxide emissions during clinker production, a major constituent of cement, contributing substantially to global warming. Extraction of raw materials, an energy-intensive process, depletes finite resources and disrupts ecosystems. Moreover, energy-intensive clinker production heavily relies on fossil fuels. Water usage, waste generation, and transportation also contribute to the environmental burden. Sustainable alternatives, like using alternative cementitious materials, enhancing energy efficiency, and embracing circular economy principles, are vital for mitigating these impacts and fostering a more eco-conscious concrete industry.

The environmental impact analysis of concrete production is a critical research area due to the significant ecological footprint of the concrete industry. Research in this domain aims to understand and mitigate the environmental challenges posed by traditional concrete production. Several studies explore alternative materials, production processes, and technologies to reduce the environmental burden. Studies like Bajpai et al. (2020) and Morsali and Yildirim (2023) investigated the use of alternative materials like fly ash, silica fume, and red mud in concrete production and evaluate their environmental impact through life cycle assessment (LCA). They highlighted the potential for reducing environmental impact by utilising industrial by-products as substitutes for traditional raw materials.

Other studies, such as by Van den Heede and De Belie (2012) and Gursel and Ostertag (2017), compared the environmental impact of traditional and ’green’ concretes using LCA. They emphasized the importance of considering the entire life cycle of concrete, including raw material extraction, production, construction, and disposal, to comprehensively assess environmental impacts. Furthermore, research like that of Manjunatha et al. (2022) and Serres et al. (2016) focused on incorporating waste materials, such as PVC waste powder and recycled concrete aggregate, into concrete production. These studies advocate for a sustainable approach to concrete manufacturing by reducing waste and reusing materials, thereby lessening the ecological footprint.

Ingrao et al. (2014) and Faleschini et al. (2014) explored the use of basalt aggregates and recycled concrete containing electric arc furnace (EAF) slag, respectively, in concrete production. They conducted environmental assessments using LCA to quantify the benefits of incorporating these materials in terms of reduced environmental impact. Table 2 provides a summary of various studies, their environmental focus, methods used for analysis, and key findings, offering an overview of their contributions to the environmental impact analysis of concrete production. It is important to note that each study uses different methodologies and materials, making direct comparisons challenging. The diversity in geographical contexts, technological advancements, and material availability necessitates a case-by-case evaluation. Overall, these studies collectively emphasize the importance of adopting sustainable practices and alternative materials to mitigate the

Table 2
Environmental impact analysis of concrete production - A summary of key studies.

Study	Environmental Impact Focus	Methods Used	Key Findings
Bajpai et al. (2020)	Fly ash and silica fume based geopolymer concrete	Environmental Impact Assessment	Highlighted the environmental impact of fly ash and silica fume based geopolymer concrete.
Manjunatha et al. (2022)	Green concrete prepared with PVC waste powder	Engineering Properties and Environmental Impact Assessment	Demonstrated the potential of using PVC waste powder for creating sustainable green concrete.
Habert et al. (2012)	Reducing environmental impact by increasing concrete strength	Quantification and Assessment	Quantified the environmental improvements achieved by enhancing concrete strength.
Morsali and Yildirim (2023)	Red mud utilisation in concrete production	Life Cycle Assessment	Studied the environmental impact of incorporating red mud in concrete production using life cycle assessment.
Van den Heede and De Belie (2012)	Comparison of environmental impact between traditional and ’green’ concretes	Literature Review and Theoretical Calculations	Emphasized the importance of considering the environmental impact of both traditional and ’green’ concretes.
Ingrao et al. (2014)	Use of basalt aggregates in concrete production	Environmental Impact Assessment	Explored the environmental benefits of using basalt aggregates in concrete.
Chottemada et al. (2023)	Alkali-Activated Concrete with Fibre Reinforcement	Environmental Impact Analysis	Investigated the environmental impact of alkali-activated concrete with fibre reinforcement.
Serres et al. (2016)	Concrete made from recycled concrete aggregate	Life Cycle Assessment and Environmental Evaluation	Showed the positive environmental implications of using recycled concrete aggregate.
Gursel and Ostertag (2017)	Comparative life-cycle impact assessment of concrete manufacturing in Singapore	Comparative LCA	Compared the environmental impact of concrete production methods in Singapore.
Faleschini et al. (2014)	Recycled concrete containing EAF slag	Environmental Assessment through LCA	Demonstrated reduced environmental impact with the use of recycled concrete containing electric arc furnace (EAF) slag.

environmental impact of concrete production and move towards a more eco-conscious construction industry.

4. Recycling and reuse in concrete production

4.1. Concrete recycling techniques and technologies

Concrete recycling involves employing various techniques and technologies to repurpose waste concrete, contributing to sustainability in construction. The process begins with crushing and screening the waste concrete to create smaller, reusable fragments. These fragments can be reconstituted with hydraulic binders or used in producing precast concrete for new applications. Thermal methods like pyrolysis and high-temperature reclamation, biological approaches such as bioremediation, and wet grinding are employed to further recycle the concrete. Additionally, smart demolition techniques and alkali activation play crucial roles. Implementing concrete recycling helps reduce the demand for virgin resources and minimises environmental impact, promoting a circular economy in construction. Table 3 provides a comprehensive overview of various concrete recycling techniques, highlighting their descriptions, advantages, and challenges.

Concrete recycling, as illuminated by the array of studies, stands at the frontier of sustainable construction practices. The cultural comparison of concrete recycling decision-making by Tam et al. (2010) is a captivating exploration that brings into focus the impact of cultural dynamics on recycling strategies. It underscores the necessity for tailored approaches, accounting for diverse cultural attitudes towards recycling. This insight suggests that effective implementation strategies must consider the cultural context for maximum efficacy and acceptance. The study by Everaert et al. (2019) delved into the novel use of microwave radiation as a pre-treatment for concrete recycling. This innovative approach offers the promise of significantly enhancing recycling efficiency. Yet, its viability on a larger scale and cost-effectiveness need careful evaluation. The potential benefits, if realized, could revolutionize concrete recycling practices by improving the process’s efficiency and reducing its environmental footprint.

Gebremariam et al. (2020) brought forward the imperative of innovative technologies in managing end-of-life concrete waste. This aligns with the broader sustainability goals of the construction industry. It advocates for embracing technological advancements to minimise waste and promote the principles of a circular economy. However, the successful implementation and adoption of these technologies need to be accompanied by supportive policies and industry collaboration. The waste-free technology proposed by Kalinowska-Wichrowska et al. (2020) introduces an intriguing concept in concrete recycling. By minimising waste in the recycling process, this approach aligns with the ethos of sustainability and resource optimisation. Further exploration is warranted to understand the scalability and adaptability of this technology across diverse construction scenarios. Ménard et al. (2013) presented innovative process routes to ensure high-quality recycled concrete. This addresses a common concern about the structural and functional performance of recycled concrete, a key consideration for its widespread acceptance and use. By emphasizing quality, this study advances the case for recycled concrete as a viable alternative in construction projects.

Tam et al.’s (2020) critical review of CO_2 technologies for recycled aggregate concrete is particularly timely considering the global focus on reducing carbon emissions. Utilising CO_2 in concrete recycling not only reduces environmental impact but also aligns with sustainability objectives. Future research and practical applications will likely reveal the true potential of CO2-based technologies in enhancing concrete recycling processes. The scrutiny of fine recycled concrete aggregates by Nedeljković et al. (2021) underscores the need for a balanced approach. While striving for environmental benefits through the use of recycled aggregates, it is crucial to optimise their incorporation without compromising concrete performance. This delicate balance is central to

Table 3
Techniques and technologies for concrete recycling and reuse.

Technique/Technology	Description	Advantages	Challenges	Reference
Crushing and Screening	Breaking down waste concrete into smaller fragments for reuse.	Reduces landfill waste, conserves resources.	Requires energy for crushing and transportation.	Chen et al., (2003); Cakır, 2014; Gomes et al., (2015); Lotfi et al., (2015)
Thermal Methods (e.g., pyrolysis)	Applying heat to break down concrete into its components, often for energy or material recovery.	Energy recovery, resource reuse.	High energy input, potential emissions.	Lee et al., (2020); Rani et al., (2021)
Biological Approaches (e. g.,bioremediation)	Using microorganisms to break down concrete and recover materials.	Environmentally friendly, potential for material recovery.	Slow process, specific environmental conditions.	Al-Salloum et al., (2017); Kadapure (2021)
Alkali Activation	Reacting waste concrete with alkaline solutions to produce a new binding material.	Reduces cement use, enhances material properties.	Requires proper mix design, technical expertise.	Ahmari et al., (2012); Abdel-Gawwad et al., (2019); Ho et al., (2021)
Electrochemical Methods	Using electric current to dissolve concrete, separating it into its components.	Efficient separation, potential for material recovery.	Limited to specific types of concrete.	Ménard et al. (2013); Shirole et al., (2023)
Abrasion Technologies	Employing mechanical processes like milling or grinding to break down concrete for reuse.	High production rate, resource recovery.	Produces fine dust, equipment wear and tear.	Lotfi et al., (2014); Lotfi et al., (2017); Dilbas et al., (2019)
Hydro-demolition	High-pressure water jets used to break down and remove deteriorated or old concrete.	Selective removal, less damage to reinforcement.	Generates wastewater, high water usage.	Tanikura et al. (2018)
Carbonation	Exposing waste concrete to CO_2 to convert calcium hydroxide back to calcium carbonate.	Carbon sequestration, reduces need for cement production.	Long curing time, challenges in full-scale adoption.	Iizuka et al., (2004); Van der Zee and Zeman (2016)
Concrete Reclamation Systems	Advanced systems that sort, clean, and recover aggregates from waste concrete for reuse.	Efficient material recovery, potential for high purity products.	Initial investment, maintenance complexities.	Zhang et al., (2019); Gebremariam et al., (2020)

promoting sustainable practices in concrete recycling. Lotfi et al. (2015) delved into performance-based concrete recycling technology, showcasing its potential to enhance the quality of recycled aggregate concrete. While promising, challenges such as cost and accessibility might restrict its widespread implementation. Further research and cost-effective solutions are needed to bridge this gap and make performance-based technologies more accessible and feasible for the industry.

Tam’s comparative analysis of concrete recycling implementation across different countries (2009) provides a broader perspective. Learning from diverse experiences and sharing best practices globally can drive concrete recycling towards a standardized and universally applicable practice. This comparative outlook fosters collaboration and mutual learning for a sustainable construction industry. Badraddin et al. (2021) keenly identify and present the challenges facing concrete recycling in practice. Acknowledging these challenges is the first step towards overcoming them. Addressing issues like lack of awareness and infrastructural limitations is pivotal for the successful and widespread adoption of concrete recycling technologies. Policymakers, industry stakeholders, and researchers should join forces to devise strategies that mitigate these challenges and drive sustainable concrete recycling practices forward.

These studies collectively highlight the critical role of concrete recycling as a sustainable practice. They introduce innovative technologies and techniques, setting the stage for a more sustainable and environmentally responsible approach in the construction industry. However, concerted efforts, further research, and policy support are essential to address challenges and promote the wide-scale adoption of concrete recycling technologies. Concrete recycling holds immense promise in significantly reducing the environmental impact of construction, and realizing this potential is crucial for a sustainable future.

4.2. *Use of recycled aggregates in concrete*

The integration of recycled aggregates in concrete marks a crucial stride towards sustainable construction practices. By repurposing materials from demolished structures or industrial by-products, recycled aggregates mitigate the strain on natural resources and diminish waste in landfills. Furthermore, this approach curtails the energy-intensive extraction of virgin materials, lowering the overall carbon footprint of concrete production. While challenges like variable quality and potential contaminants persist, advancements in processing and quality control are progressively addressing these issues. Overall, the use of recycled aggregates embodies an eco-conscious shift in the construction industry, aligning with global sustainability imperatives. Due to both human-made and natural disturbances on our planet, numerous cities, settlements, and homes have been ravaged. For a visual representation of the production of waste from destroyed buildings, refer to Fig. 3, which illustrates the process of creating Recycled Concrete Aggregates.

Ravindrarajah and Tam (1987) presented pioneering research, examining the viability of recycled concrete as both fine and coarse aggregates. This early investigation laid the foundational understanding of the potential for recycled materials in concrete, sowing the seeds for further exploration into sustainable alternatives. Taking a regional approach, Poon and Chan (2007) investigated the use of recycled aggregates in the specific construction context of Hong Kong. Their study emphasized the importance of considering localised practices, available materials, and unique needs when implementing sustainable construction techniques. This regional perspective underscores the necessity of adapting sustainable practices to diverse contexts. In 2016, De Brito and Silva critically reviewed the current state of recycled aggregate use in concrete, offering insights into the path forward. By analysing progress and identifying challenges, their work stressed the need for strategic planning and ongoing research to advance the integration of recycled aggregates, promoting sustainable concrete production on a broader scale.

Tam et al. (2018) provided a detailed review, summarizing developments in recycled aggregate applications from 2000 to 2017. Their comprehensive work shed light on emerging trends, showcasing the potential for recycled aggregates in various applications. They emphasized the importance of standardisation to optimise the advantages of recycled aggregates across diverse applications. Collery et al. (2015) advocated for a performance-related approach when utilising recycled aggregates in concrete. Ensuring that the inclusion of recycled aggregates doesn’t compromise the structural and functional performance of concrete, they emphasized that sustainability should be achieved without compromising the quality and durability of the structures. This performance-centric perspective is crucial for garnering wider acceptance of recycled aggregates.

Addressing durability, Kou and Poon (2012) explored strategies to enhance concrete durability through the incorporation of coarse recycled aggregates. Durability is a vital factor in ensuring the longevity and

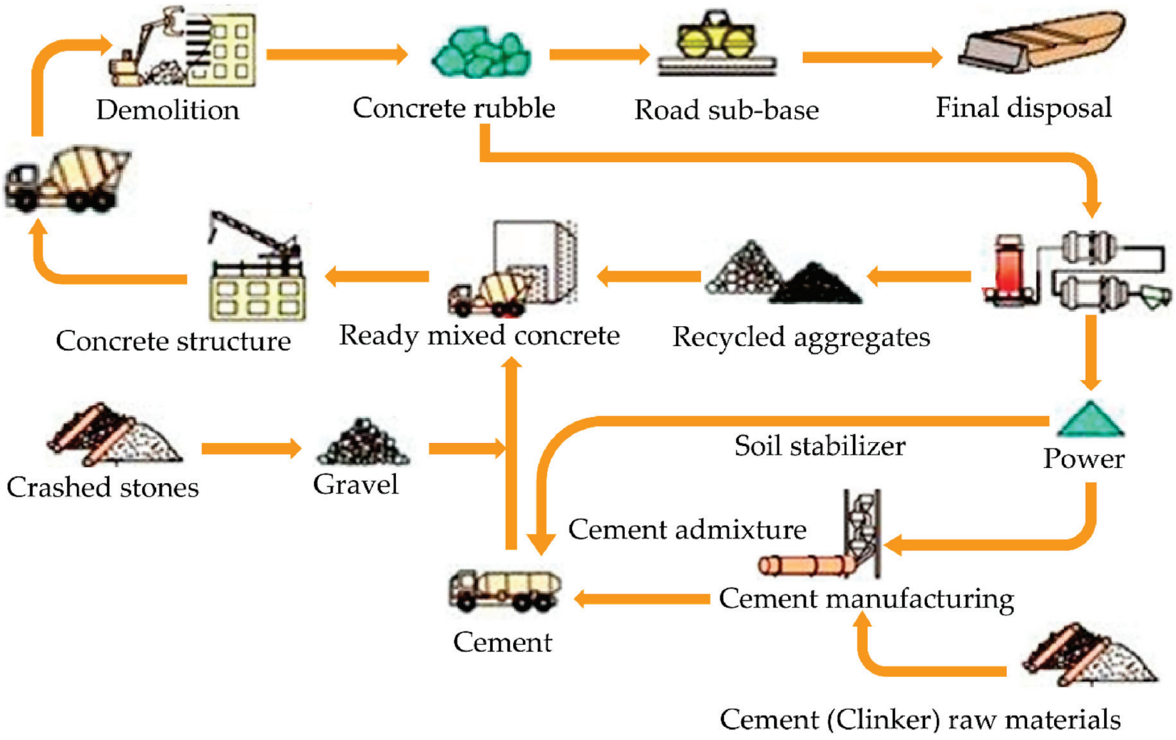

Fig. 3. Process of destroyed buildings wastes production as RCAs (Makul et al., 2021).

performance of structures. By addressing this aspect, the research promotes the viability of recycled aggregates as a sustainable construction material. Koulouris et al. (2004) presented practical case studies illustrating the application of recycled aggregates in concrete. These real-world projects demonstrated the feasibility and advantages of integrating recycled materials into construction, substantiating the environmental benefits while meeting performance requirements. Practical case studies provide tangible evidence of the viability and advantages of incorporating recycled aggregates. Tam et al. (2016) introduced a novel concept of carbon-conditioned recycled aggregates, showcasing innovative approaches to enhance the sustainability of concrete production. Their work underscored the potential of unconventional methods to contribute to sustainable practices in the construction industry, paving the way for innovative, eco-friendly approaches. Table 4 provides a comprehensive overview of the main focus, key findings, and implications of each discussed research paper regarding the use of recycled aggregate in concrete.

The progression of research in recycled aggregate use, as evidenced by the discussed references, showcases the evolving understanding of the potential and practicality of recycled materials in concrete. From foundational research to localized applications, performance-driven methodologies, and innovative concepts, the movement towards

Table 4
Summary of studies on recycled aggregate applications in concrete.

Reference	Main Focus	Key Findings	Significance and Implications
Sri Ravindrarajah et al. (1987)	Recycled Concrete as Aggregates	Viability of recycled concrete as fine and coarse aggregates.	Pioneering study, laying the foundation for recycled materials in concrete.
Poon and Chan (2007)	Use of Recycled Aggregate in Hong Kong	Context-specific implementation of recycled aggregates in Hong Kong.	Regional perspective emphasizing adaptation to local contexts.
De Brito and Silva (2016)	Current State and Future Prospects	Critical review and future outlook of recycled aggregate use in concrete.	Identifies progress, challenges, and the need for strategic planning.
Tam et al. (2018)	Review of Recycled Aggregate Applications	Comprehensive review of recycled aggregate applications from 2000 to 2017.	Highlights trends and potential applications, emphasizing standardization.
Collery et al. (2015)	Performance-related Use of Recycled Aggregates	Focus on rational use of recycled aggregates in concrete based on performance.	Promotes a methodical approach to optimising recycled aggregate use.
Kou and Poon (2012)	Enhancing Durability with Recycled Aggregate	Techniques to improve durability properties of concrete using coarse recycled aggregate.	Addresses concerns regarding durability, enhancing the application of recycled aggregates.
Koulouris et al. (2004)	Case Studies on Recycled Aggregate Use	Demonstrates real-world applications of recycled aggregate in concrete.	Provides practical insights and encourages industry adoption.
Etxeberria et al. (2007)	Recycled Aggregate Concrete as Structural Material	Examines the use of recycled aggregate concrete as a structural material.	Advances the understanding of structural applications of recycled aggregate concrete.
Paine and Dhir (2010)	Performance-related Approach to Recycled Aggregates	Performance-based assessment and approach to the use of recycled aggregates.	Proposes a performance-centric methodology for recycled aggregate utilisation.
Bostanci et al. (2018)	Low Carbon and Cost-effective Concrete	Emphasizes the use of recycled aggregates for low carbon and cost-effective concrete.	Addresses sustainability and cost concerns in the concrete industry.
Tam et al. (2016)	Carbon-conditioned Recycled Aggregate	Evaluates carbon-conditioned recycled aggregate in concrete production.	Offers an innovative approach to improve the properties of recycled aggregate concrete.
Tam et al. (2007)	Proportion Optimisation using Recycled Aggregate	Two-stage mixing approach for optimised proportioning using recycled aggregate.	Enhances the efficiency of recycled aggregate utilisation in concrete.

sustainable, performance-enhanced concrete using recycled aggregates is evident. Continued research and industry-wide adoption are imperative to maximise the benefits of this eco-friendly practice and transform it into a mainstream construction approach. The collective effort in this direction is fundamental for a sustainable and greener future in the construction sector.

4.3. *Recycled cementitious materials*

Recycled cementitious materials, often referred to as recycled cement or recycled concrete, are a sustainable alternative in the construction industry. These materials are derived from the recycling of waste concrete and sometimes other construction materials. The process involves collecting waste concrete from demolition sites or construction leftovers and processing them to produce a useable product. The recycling process includes crushing the waste concrete into smaller pieces, removing impurities such as steel reinforcement, and then grinding it into a fine powder. This resulting powder can replace a certain percentage of traditional cement in new concrete mixes, reducing the overall demand for virgin raw materials.

The utilisation of recycled cementitious materials offers several benefits. First and foremost, it promotes sustainability by reusing waste materials and reducing the burden on natural resources. It helps in managing construction and demolition waste, diverting it from landfills. Moreover, using recycled cement can lead to a reduction in carbon emissions associated with cement production, contributing to a lower carbon footprint. However, challenges exist, including the need to ensure the quality and consistency of recycled materials, potential variability in properties, and limitations in the replacement percentage due to performance requirements. Overcoming these challenges requires ongoing research, standardized production processes, and a deeper understanding of the behaviour of recycled cementitious materials in various applications.

Carriço et al. (2020) provided an in-depth analysis and evaluation of thermoactivated cementitious materials, elucidating their fundamental properties and potential applications. This review serves as a foundational resource for comprehending the intricacies of the thermoactivation process and its profound effects on recycled cementitious materials. The insights offered in this study open up avenues for further research and practical utilisation of these materials in sustainable construction practices. In their study, Kalinowska-Wichrowska et al. (2019) delved into the properties of composites incorporating recycled cement mortar, highlighting the considerable potential of these materials as supplementary cementitious elements. A comprehensive understanding of the supplementary role played by recycled cement mortar is crucial for maximising its effective use, thereby contributing to sustainable and eco-conscious concrete production. Li et al. (2021) conducted an investigative study on the use of recycled powder derived from the preparation of recycled aggregate as a supplementary cementitious material. The findings of this research provide valuable insights into the effective utilisation of recycled powder, thus making significant strides toward sustainable concrete production and resource optimisation. In their research, Wang et al. (2022) placed a notable emphasis on the eco-friendly treatment of recycled concrete fines, positioning them as supplementary cementitious materials. This study delves into sustainable treatment methodologies for recycled concrete fines, aligning with the growing momentum of environmentally conscious practices within the construction industry.

The pivotal research by Rashad (2014) centred on the substitution of fine aggregates with recycled waste glass within cementitious materials. This study plays a critical role in broadening our understanding of how recycled glass can be effectively harnessed to augment the sustainability of concrete production, encouraging a more circular approach to waste management. Serpell and Lopez (2013) explore reactivated cementitious materials sourced from hydrated cement paste wastes, presenting innovative solutions for repurposing waste materials within the realm of concrete production. Such innovative approaches stand as indispensable pillars in advancing sustainable waste management practices. Qian et al. (2020) proposed a groundbreaking advancement in the form of green ultra-high performance concrete (UHPC), premised on the judicious application of recycled cementitious material. This pioneering study showcases inventive applications of recycled cementitious materials, particularly in the realm of high-performance concrete, hinting at exciting prospects for sustainable construction materials.

Zajac et al. (2023) delved into supplementary cementitious materials founded on recycled concrete paste, providing critical insights into the judicious utilisation of recycled concrete paste. This research substantially expands the scope of sustainable supplementary materials in concrete production, advancing the discourse on eco-friendly practices within the construction domain. Faneca et al. (2018) presented a notable advancement by demonstrating the development of conductive cementitious materials utilising recycled carbon fibers. This innovative approach not only underscores the potential for integrating recycled materials into advanced applications but also accentuates the symbiosis of sustainability and innovation. In their study, Oksri-Nelfia et al. (2016) focused on the reutilisation of recycled crushed concrete fines as a mineral addition in cementitious materials, championing a sustainable approach to waste management and concrete production. The insights garnered from this research significantly contribute to promoting circularity in the construction industry.

Yu and Shui (2014) underscore the critical importance of efficiently reusing recycled construction waste cementitious materials. A robust understanding of efficient utilisation becomes instrumental in unlocking the true sustainability potential embedded in recycled construction waste materials. Zhou et al. (2021) proposed an innovative approach for recycling engineering sediment waste as sustainable supplementary cementitious materials, further emphasizing the vast potential in leveraging a diverse array of waste materials for sustainable concrete production. This study points to a future where waste materials play a vital role in advancing sustainable construction practices. Fig. 4 illustrates the closed-loop process of cement recycling aimed at mitigating the carbon footprint associated with the manufacture of thermally-activated recycled cement (Lei Xu et al., 2022).

A thorough examination of these studies underscores the considerable promise held by recycled cementitious materials in reshaping the construction industry towards a more sustainable future. The key lies in harnessing innovative methodologies and gaining a profound comprehension of the properties and versatile applications of these recycled materials. Their effective integration into concrete production processes not only signifies a breakthrough in sustainable construction practices but also ushers in an era of eco-conscious building. Several groundbreaking approaches come to light in these studies, among them thermos-activation processes that unlock the latent potential of waste materials. This transformational method paves the way for optimising the use of recycled cementitious materials, a pivotal strategy for reducing the ecological footprint of construction activities. Furthermore, the repurposing of waste materials, as revealed in these research works, showcases the transformative potential of circular economy principles within the construction sector. Ultimately, these studies collectively offer a roadmap for maximising the utilisation of recycled cementitious materials, underscoring their indispensable role in advancing a greener and more sustainable construction industry.

5. Waste reduction and resource optimisation

5.1. *Minimising waste in concrete production*

Minimising waste in concrete production is vital for sustainable construction practices. Employing optimised mix designs and efficient raw material management reduces excess usage, ensuring accurate proportions. Integrating recycled aggregates and supplementary cementitious materials lowers reliance on virgin resources.

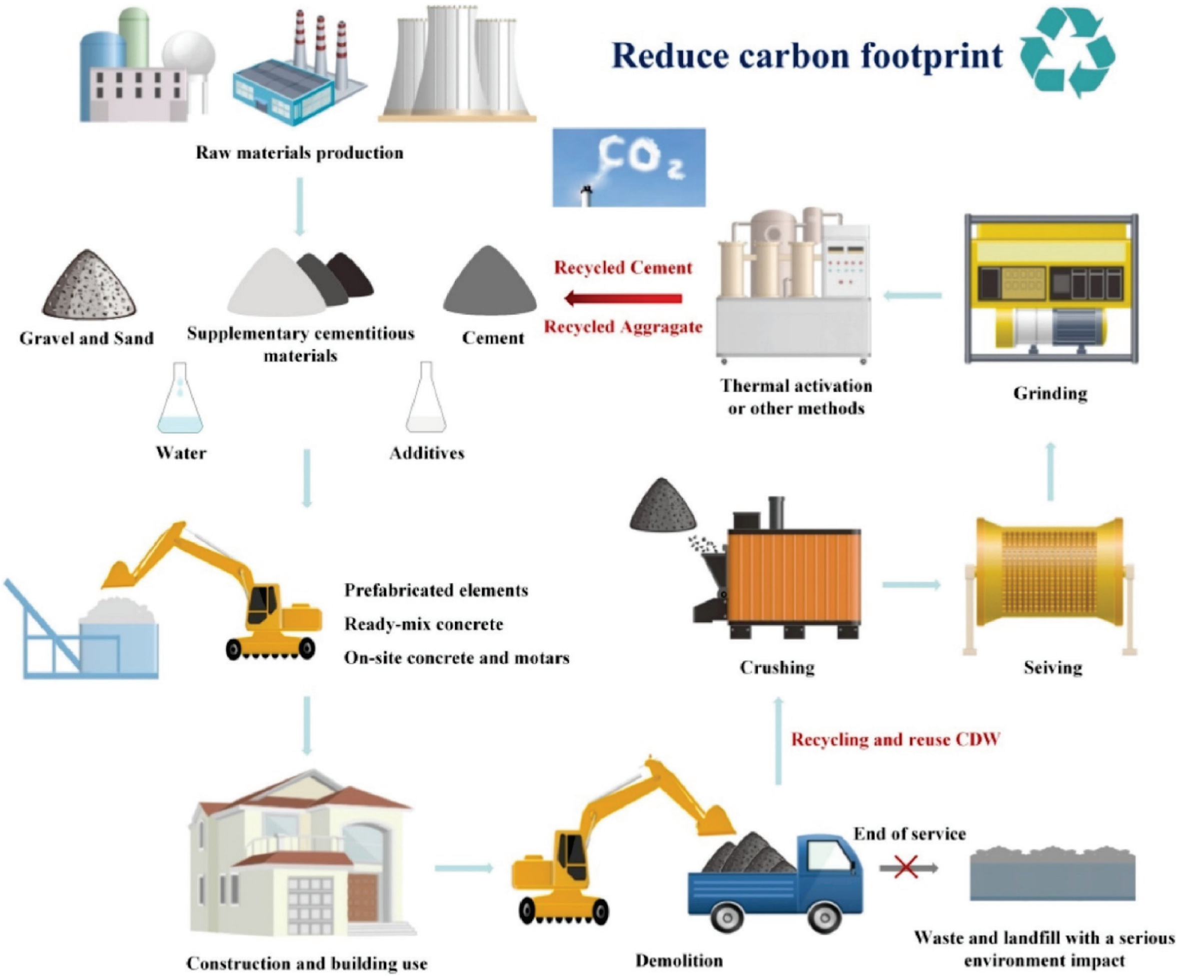

Fig. 4. Closed-loop of recycling cement to reduce carbon footprint (Lei Xu et al., 2022).

Implementing precise batching, utilising concrete reclaimers, and managing returned concrete efficiently further minimise waste. Lean manufacturing principles and regular training on waste reduction techniques are key. Continuous monitoring and improvement ensure ongoing progress towards minimising waste and promoting eco-friendly practices in the concrete production industry.

Table 5 elucidates strategies to curtail waste in concrete production. It delineates diverse actions like optimal mix design, waste recycling, and efficient resource utilisation. Each strategy is succinctly described, portraying its essence and execution. The benefits of these strategies encompass diminished waste, cost-effectiveness, and environmental friendliness. Additionally, the table evaluates the feasibility of implementing each strategy, categorizing it as easy, moderate, or challenging. It offers a comprehensive and accessible reference, empowering industry professionals to adopt prudent measures and foster waste reduction in their concrete manufacturing endeavours.

Minimising waste in concrete production is a multifaceted challenge that demands innovative solutions and a shift in the way we approach construction. Vieira et al. (2019) brought attention to the critical issue of waste generation in the production of ready-mixed concrete. By identifying the key sources of waste, this study underlines the necessity of adopting more sustainable practices within the concrete industry. Waste minimisation can lead to reduced environmental impacts, such as lower energy consumption and decreased landfill usage. This, in turn, can translate into cost savings for concrete producers while promoting environmental responsibility.

The review by Xuan et al. (2018) extends the conversation by exploring the management and sustainable utilisation of processing wastes from ready-mixed concrete plants. They emphasize that addressing waste is not just a matter of disposal but an opportunity to

Table 5
Strategies for waste minimisation in concrete production.

Stage of Concrete Production	Waste Minimisation Strategies	Benefits	Implementation Challenges
Raw Material Procurement	Efficient inventory management, precise forecasting, use of recycled aggregates.	- Reduced raw material waste - Environmental benefits	- Establishing reliable forecasting systems - Procurement costs
Mix Design and Batching	Optimised mix designs, accurate batching systems, incorporation of supplementary cementitious materials.	- Lowered material waste - Improved concrete quality	- Technical expertise - Initial setup costs
Formwork and Construction	Reusable formwork systems, efficient construction planning, regular training on waste reduction.	- Reduced formwork waste - Time and cost savings	- Initial investment in reusable formwork - Training and adaptation period
Concrete Curing and Finishing	Efficient curing processes, controlled finishing to avoid overuse of materials.	- Lesser material wastage - Enhanced surface quality	- Skill and labour requirements - Balancing efficiency with quality

follow the principles of a circular economy. Instead of considering waste as something to discard, these materials can be treated as valuable resources. Strategies like recycling waste products or repurposing them in construction can help achieve this circular economy mindset. The innovative work of Xuan et al. (2016) introduces the concept of carbon dioxide sequestration in concrete waste. Concrete manufacturing is known for its carbon emissions, and this study suggests that these emissions can be mitigated by trapping CO_2 in concrete waste, effectively turning it into a carbon sink. Additionally, their exploration of using concrete slurry waste in construction products demonstrates that waste materials can have a second life as inputs for new structures. This circular approach not only reduces waste but also decreases the demand for fresh raw materials. Martins et al. (2022) shift the focus to a specific geographic context, Belo Horizonte, Brazil, where they manage and characterize concrete wastes from concrete batching plants. This localized perspective is crucial, as waste management practices can vary widely across regions. Understanding local waste generation and disposal dynamics is essential for optimising waste reduction efforts.

Closed-loop recycling of construction and demolition waste for concrete is a sustainable practice with a significant environmental impact (Fig. 5). This approach involves the collection, sorting, and processing of waste materials from demolished structures and construction sites, transforming them into recycled aggregates and other components used in concrete production. By diverting this waste from landfills and reusing it, not only are valuable resources conserved, but the environmental footprint of concrete manufacturing is significantly reduced. Closed-loop recycling minimises the need for new raw materials, curbing energy consumption and greenhouse gas emissions. It promotes resource efficiency, making concrete production more sustainable and aligned with circular economy principles.

The central theme that reverberates throughout these studies is the fundamental importance of waste minimisation within concrete production, as it represents a cornerstone of sustainable construction practices. It necessitates a paradigm shift, transforming the perception of waste from a cumbersome by-product to a valuable resource in its own right. This shift in mindset aligns closely with the principles of the circular economy, where resources are conserved, reused, and repurposed in a closed-loop system. By recognizing that what was once considered waste can be a valuable input into concrete production, the construction industry stands to reap multiple benefits. Firstly, the reduced disposal of waste materials translates into less strain on landfills and a significant reduction in environmental pollution. Additionally, it contributes to the conservation of raw materials, a precious resource in an era of increasing scarcity. This reimagining of waste materials as valuable resources symbolizes a revolutionary approach in the construction sector. It not only lessens the ecological footprint of concrete production but also propels the industry toward a more sustainable, responsible, and environmentally friendly future. By adopting the principles of the circular economy, the concrete industry embarks on a transformative journey, paving the way for a more resilient and resource-efficient construction landscape.

5.2. *Resource efficiency through material optimisation*

Resource efficiency through material optimisation in concrete production is pivotal for sustainable construction. It involves smart material choices, such as utilising local or recycled aggregates and supplementary cementitious materials. Precision in mix design, water conservation, and waste handling further enhance resource efficiency. Prefabrication and precast components minimise material waste, while life cycle assessment tools guide eco-friendly choices. Embracing innovative technologies, optimising transportation, and designing for durability reduce resource consumption and environmental impact. This holistic approach aligns concrete production with sustainability goals, addressing both resource scarcity and environmental concerns in the construction industry.

Table 6 provides a comprehensive overview of strategies for enhancing resource efficiency in concrete production, crucial for sustainability in the construction industry. Each strategy is accompanied by a succinct description of its benefits and key considerations, offering practical insights for concrete manufacturers and construction professionals. Selecting optimal aggregates, substituting cement with supplementary materials, and adopting precise mix designs optimise material usage, reduce waste, and cut costs. Efficient water conservation, waste handling, and the use of prefabricated components further enhance resource efficiency. Additionally, life cycle assessments, innovative technologies, optimised transportation, and durable design strategies contribute to a more sustainable concrete production process.

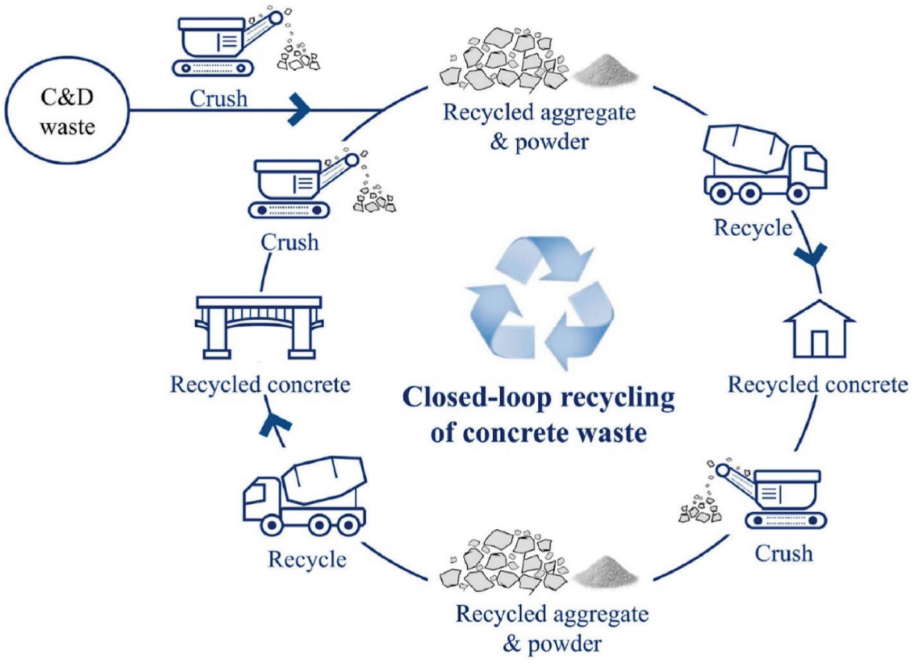

Fig. 5. Closed-loop recycling of construction and demolition waste for concrete (Kim and Jang, 2022).

Table 6
Strategies for resource efficiency in concrete production.

Strategy	Benefits	Key Considerations
Selecting Optimal Aggregates	Diminished resource consumption and lowered carbon emissions.	Availability of suitable local aggregates and quality control for recycled materials.
Substituting Cement	Lowered carbon footprint and decreased cement usage.	Compatibility of supplementary materials with concrete mix and project specifications.
Precision in Mix Design	Efficient use of materials, reduced waste, and cost savings.	In-depth knowledge of concrete mix design and strict adherence to project requirements.
Water Conservation	Significant water conservation and improved concrete quality.	Precise measurement and consistent application of water-to-cement ratio and additives.
Effective Waste Handling	Reduced waste and the potential for cost-effective recycling.	Adequate facilities for waste handling and recycling, along with staff training.
Prefabrication and Precast Components	Controlled production, reduced waste, and faster construction.	Design and production capabilities for prefabricated elements, transportation logistics.
Life Cycle Assessment	Informed decision-making, reduced environmental impact.	Availability of LCA data, expertise in interpreting results.
Incorporation of Innovative Technologies	Pioneering solutions with potential for substantial resource savings.	Investment in research and development, compatibility with existing processes.
Optimising Transportation	Lowered transportation-related resource consumption.	Effective supply chain management, transportation fleet optimisation.
Durable Design	Extended lifespan of structures, decreased maintenance needs.	Material durability, construction techniques, and long-term maintenance planning.

These strategies empower the construction industry to minimise waste and environmental impact while securing a competitive edge.

The drive for resource efficiency through material optimisation in concrete production is an essential response to the growing environmental and economic challenges facing the construction industry. Concrete, a foundational component of modern infrastructure, is notorious for its substantial resource requirements, energy consumption, and waste generation. To mitigate these adverse impacts, researchers and practitioners have explored various approaches to refine concrete mix designs and construction processes, maximising performance while minimising resource consumption.

In recent years, advancements in computational design optimisation have revolutionized concrete mixtures. DeRousseau et al. (2018) showcased the power of advanced computing and simulation, enabling precise customization of concrete for specific applications. Zahid et al. (2018) emphasized statistical modeling, demonstrating its efficacy in optimising fly ash-based geopolymer composites. Yildizel et al. (2020) integrated experimental data and mathematical modeling to optimise glass fiber-reinforced concrete, enhancing both structural integrity and resource conservation. Shobeiri et al. (2022) proposed a holistic framework considering environmental, financial, and mechanical factors in concrete mix design. Sharifi et al. (2020) focused on high-strength self-consolidating concrete, demonstrating tailored designs for resource efficiency and high performance.

Habibi and Ghomashi (2018) introduced an optimal mix design method for self-compacting concrete, streamlining processes and reducing material waste. R. Zhao et al. (2023) explored multi-objective mix design optimisation for self-compacting concrete with recycled aggregates, promoting sustainability. Bourchy et al. (2019) addressed challenges in mix design for massive structures, minimising waste and energy consumption. Bhuva and Bhogayata (2022) utilized artificial intelligence for self-compacting concrete mix design, showcasing the role of emerging technologies in resource efficiency. Collectively, these studies reflect the concrete industry's commitment to strategic optimisation, minimising resource consumption, waste generation, and enhancing overall performance.

Fig. 6 illustrates a conceptual diagram outlined in the study by Shen et al. (2021) depicting the physics-guided multi-objective optimisation process for formulating cementitious composites that incorporate Microencapsulated Phase Changing Materials (MEPCMs). This figure visually conveys the multi-objective optimisation procedure for crafting cementitious composites that integrate MEPCMs to enhance their functionality. The authors emphasize a physics-guided methodology, which underlines the importance of leveraging fundamental physical principles in optimising material composition. By utilising MEPCMs, these composites can achieve specific properties and functions, such as improved thermal performance or energy efficiency. The diagram suggests that this optimisation process is multi-objective, implying that it seeks to balance multiple performance criteria simultaneously. This approach aligns with the growing demand for construction materials that not only meet structural requirements but also offer advanced functionalities and sustainability benefits.

5.3. Innovative approaches for waste reduction

Innovative approaches for waste reduction in concrete production are crucial for advancing sustainability in the construction industry. As demand for more eco-friendly practices grows, these methods provide effective solutions that extend beyond traditional concrete production techniques, focusing on optimising resource use and minimising environmental impact. One significant advancement involves integrating recycled materials and specialized additives into concrete mix designs. By incorporating industrial by-products such as fly ash, slag, or recycled concrete aggregates, this approach reduces the need for virgin materials and lowers the energy consumption associated with production. These recycled materials not only help conserve natural resources but also enhance the performance and durability of concrete, leading to fewer repairs and replacements over time.

The advent of 3D printing technology in construction allows for highly accurate, on-site creation of concrete structures. This method reduces material waste by producing only what is necessary and permits intricate designs that might be impractical with traditional methods. By minimising off-cuts and leftover materials, 3D printing significantly lowers the environmental footprint of construction projects. Self-healing concrete represents another groundbreaking development. This technology incorporates microcapsules or bacteria that activate when cracks form, automatically repairing minor damages. This capability extends the lifespan of structures and reduces the need for costly and resource-intensive repairs, thereby minimising overall waste associated with maintenance and reconstruction.

Carbon capture and utilisation (CCU) systems are designed to capture CO_2 emissions generated during concrete production and repurpose them into useful products or store them safely. This process helps mitigate the significant greenhouse gas emissions associated with cement production, which is a major contributor to global CO_2 levels. Additionally, using durable and reusable formwork and moulds reduces the amount of waste generated from disposable materials. This practice supports a circular economy by ensuring that formwork is used multiple times before being retired, thus reducing both material consumption and disposal issues. Implementing waste recycling and lean construction practices streamlines the construction process, reducing excess material and improving efficiency. Recycling construction debris into new materials or products helps close the loop of material usage, while lean practices focus on minimising waste through better planning and process optimisation. Advanced monitoring systems, such as smart concrete technologies and digital twins, also play a pivotal role in enhancing construction efficiency. Digital twins create virtual replicas of physical structures, enabling real-time monitoring and predictive analysis. This

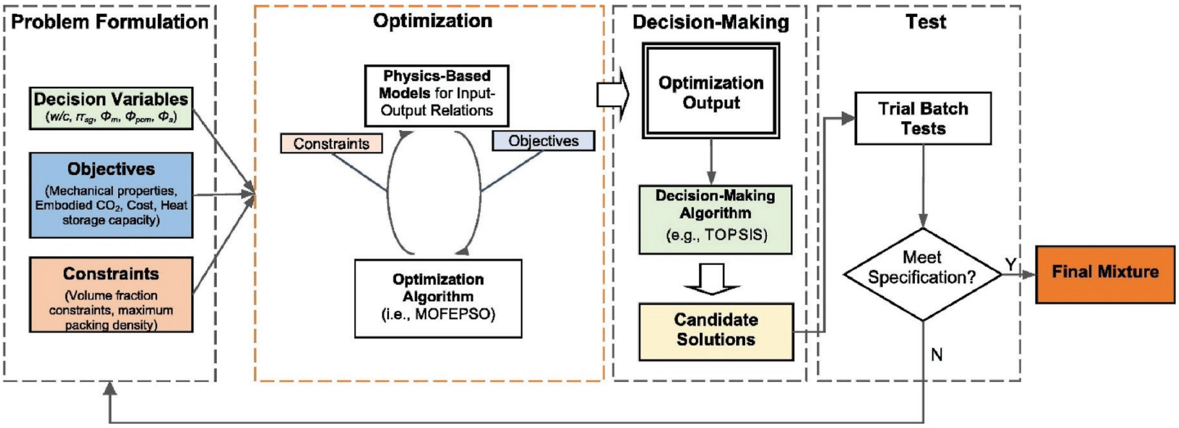

Fig. 6. Conceptual diagram of physics-guided optimisation for MEPCM-Enhanced cementitious composites (Shen et al., 2021).

helps identify potential issues early, allowing for timely interventions and reducing the risk of material waste due to errors or unforeseen problems. Overall, these innovative approaches are transforming concrete production, making it more sustainable and resource-efficient. By leveraging advanced technologies and practices, the construction industry can significantly reduce its environmental impact, paving the way for a more sustainable future.

Table 7 highlights innovative strategies aimed at reducing waste and improving resource efficiency in concrete production. Each approach is described with its benefits and key considerations, providing a concise reference for industry professionals and researchers. Advanced mix designs optimise resource use, while 3D printing enables precise construction with minimal waste. Self-healing concrete and carbon capture technologies extend structural lifespan and reduce environmental impact. Reusing formwork and embracing the circular concrete economy further minimise waste. Recycling construction waste on-site and adopting lean construction practices enhance resource efficiency. Smart concrete technologies, digital twins, and references promote the use of data-driven solutions to reduce waste and optimise processes, fostering sustainability in the construction industry.

6. Policies and regulations for circular concrete practices

6.1. Overview of existing policies and regulations

Existing policies and regulations for circular concrete practices play a pivotal role in promoting sustainability within the construction industry. These guidelines aim to reduce waste generation, conserve resources, and minimise the environmental footprint of concrete production. Key measures include requirements for using recycled materials, responsible waste management, and promoting circular economy principles. Furthermore, policies emphasize the importance of life

Table 7
Innovative approaches for waste reduction.

Innovative Approach	Description	Benefits	Key Considerations	Reference
Advanced Mix Designs	Development of concrete mixes with recycled materials and additives to optimise resource use.	Improved resource efficiency, low-impact concrete.	Compatibility with project requirements, material sourcing.	Sohail et al., (2018); Kurda et al., (2022)
3D Printing	Precise on-site construction with minimal material wastage, using only the required amount of concrete.	Reduced material waste, efficient use of resources.	Adaptation to project scale and technology requirements.	Buswell et al., (2018); Khan et al., (2020); Xiao et al., (2021)
Self-Healing Concrete	Technologies embedding capsules or vascular networks to extend structural lifespan, reducing replacements.	Longer-lasting structures, less material waste.	Compatibility with project needs, maintenance procedures.	Wang et al., (2014); Vijay et al., (2017); Qian et al., (2021)
Carbon Capture and Utilisation (CCU)	Capturing and repurposing CO_2 emissions generated during concrete production, reducing the environmental footprint.	Reduced carbon emissions, eco-friendly concrete.	Integration of CCU systems, environmental monitoring.	Hasanbeigi et al., (2012); Skocek et al., (2020); Hanifa et al., (2023)
Reuse of Formwork and Moulds	Employing durable and reusable formwork and moulds to minimise waste and reduce the need for disposable materials.	Minimised waste, cost savings.	Proper maintenance and storage of formwork, adaptability to varying project designs.	Li et al., (2022); Mei et al., (2022); Liebringshausen et al., (2023); Mei et al., (2023)
Circular Concrete Economy	Implementing a closed-loop system for concrete materials, including recycling and reusing concrete waste.	Reduced waste generation, sustainable material use.	Collaborative partnerships in the concrete supply chain, quality control of recycled materials.	Colangelo et al., (2020); Caldas et al., (2021); Mostert et al., (2021); Marsh et al., (2022)
Construction Waste Recycling	On-site recycling of construction waste materials, including concrete, for reuse in the same or other projects.	Waste reduction, cost savings, resource efficiency.	Proper handling and sorting of waste materials, adherence to recycling regulations.	Tam and Tam (2006); Liu et al., 2020; He and Yuan (2020); Omer et al., (2022)
Lean Construction Practices	Streamlining construction processes, including concrete placement, to reduce material waste and improve efficiency.	Minimised waste, increased project efficiency.	Comprehensive project planning, efficient coordination among stakeholders.	Salem et al., (2006); Pheng et al., (2016); Babalola et al., (2019); Xing et al., (2021)
Smart Concrete Technologies	Integration of sensors and data analytics to monitor concrete performance, allowing for early detection of issues and reducing the need for replacements.	Longer-lasting structures, reduced material waste.	Investment in sensor technology, data management and analysis.	Sun et al., (2000); Makul (2020); Nilimaa (2023); Yang et al., (2023)
Digital Twins for Construction	The use of digital twins—virtual replicas of construction projects—to optimise design and construction processes, reducing errors and waste.	Improved project planning, waste reduction, cost savings.	Digital twin technology adoption, data integration, skilled workforce.	Greif et al., (2020); Zhang et al., (2022); Zhao et al., (2023)

cycle assessments to understand the environmental impact of concrete projects from extraction to disposal. Compliance with these policies ensures a more responsible and eco-friendly approach to concrete production, aligning with global efforts to combat climate change and promote sustainable construction practices.

Table 8 provides an overview of existing policies and regulations aimed at promoting circular concrete practices in the construction industry. These measures are crucial for reducing waste, conserving resources, and fostering sustainability. The outlined policies encompass waste management regulations, environmental certification programs, resource efficiency directives, circular economy strategies, material standards and guidelines, tax incentives, extended producer responsibility laws, construction and demolition waste regulations, green public procurement criteria, and research and development funding. Each policy or regulation serves specific objectives, such as minimising waste, encouraging material recycling, and stimulating circular economy practices. These policies are supported by relevant references that offer detailed insights into their implementation and impacts. Together, these measures play a pivotal role in advancing the adoption of circular concrete practices and enhancing the sustainability of construction projects.

Table 8
Overview of policies and regulations promoting circular concrete practices.

Policy/ Regulation	Description	Key Objectives	References
Waste Management Regulations	Regulate the disposal and management of construction waste, including concrete.	Reduce landfill waste, promote recycling, and reuse of concrete materials.	Sealey et al., (2001); Lu and Tam, 2013; Yuan (2013)
Environmental Certification Programs	Certification schemes like LEED incentivize sustainable construction practices, including circular concrete.	Encourage the use of recycled and reclaimed concrete materials.	Cidell and Cope (2014); Lu et al., (2019); Chi et al., (2020)
Resource Efficiency Directives	Set targets for recycling and reusing construction materials to reduce the environmental impact of construction activities.	Promote resource efficiency and waste reduction in the construction sector.	Kylili and Fokaides (2017); Gálvez-Martos et al., (2018); Ghaffar et al., (2020)
Circular Economy Strategies	National and regional strategies promoting resource efficiency and sustainable practices in the construction industry, including circular concrete solutions.	Foster a circular economy, reduce waste, and encourage sustainable practices.	Hossain et al., (2020); Bonoli et al., (2021); Marsh et al., (2022)
Material Standards and Guidelines	Development of standards and guidelines for incorporating recycled and alternative materials in concrete mixes.	Ensure concrete produced with recycled content meets specific performance requirements.	Oikonomou (2005); Maier and Durham (2012); Tam et al., (2018)
Tax Incentives	Provide tax incentives to construction companies adopting circular concrete practices, such as recycling concrete waste or using alternative materials.	Encourage the adoption of sustainable construction methods.	Ghisellini et al., (2018); Ghisellini and Ulgiati (2020); Munaro and Tavares (2023)
Extended Producer Responsibility (EPR) Laws	Require manufacturers and producers of concrete and construction materials to take responsibility for the end-of-life disposal of their products.	Encourage design for recycling and reusability.	Acree Guggemos and Horvath, 2003; Milanez and Bührs, 2009; Shooshtarian et al., (2021)
Construction and Demolition Waste Regulations	Regulations governing the sorting and disposal of construction and demolition waste, including concrete.	Promote concrete recycling and divert waste from landfills.	Clark et al., (2006); Yuan (2017); Blaisi (2019); Shooshtarian et al., (2022)

(continued on next page)

6.2. Potential policy frameworks to encourage circular concrete practices

Policy frameworks hold the key to driving the adoption of circular concrete practices in the construction industry. As sustainability and resource efficiency become paramount concerns, governments and regulatory bodies can enact policies that incentivize and enforce circular principles. These frameworks may encompass mandatory recycling targets, tax incentives, eco-labelling, research grants, extended producer responsibility programs, and public procurement policies. By introducing these measures, policymakers aim to reduce waste, promote the use of recycled materials, and lower the environmental footprint of concrete production. Such policies not only contribute to a more sustainable construction sector but also align with global efforts to combat climate change and encourage innovation in materials and practices.

Table 9 provides an overview of key policy elements that can encourage and support the adoption of circular concrete practices within the construction industry. These policies are essential for driving the shift towards more sustainable and environmentally responsible construction methods. They encompass a wide range of strategies, from mandatory recycling requirements to extended producer responsibility, resource taxation, and incentives, as well as certifications, waste tracking, and circular procurement. Additionally, the integration of life cycle assessments, research and development funding, education and training programs, and public awareness campaigns form a holistic policy framework. Together, these measures can significantly reduce waste, promote resource efficiency, and advance the circular economy within the concrete sector.

6.3. Stakeholder involvement and policy implementation challenges

In the pursuit of advancing circular concrete practices within the construction industry, active stakeholder involvement plays a pivotal role. Collaborative efforts, awareness campaigns, education, and coordinated action are essential components of driving sustainable construction methods (Mousa, 2015; Sharma, 2018; Negash et al., 2021). Engaging a diverse set of stakeholders is fundamental. This includes construction companies, suppliers, governmental bodies, environmental organizations, and local communities. Such collaboration promotes shared responsibility and resource-sharing, creating a collective commitment to embracing circular concrete practices. Effective communication is indispensable to inform stakeholders about the merits of circular concrete practices. Workshops, training programs, seminars, and awareness campaigns serve as valuable tools for conveying the benefits of sustainable construction. These educational efforts ensure

Table 8 (*continued*)

Policy/ Regulation	Description	Key Objectives	References
Green Public Procurement (GPP)	Use GPP criteria that favour contractors and suppliers employing circular concrete and sustainable construction practices in public projects.	Drive sustainable public procurement and promote circular practices.	Alhola et al., (2019); Braulio-Gonzalo and Bovea (2020)

Table 9

Policy framework for advancing circular concrete practices.

Policy Element	Description	Key Benefits
Mandatory Recycling Requirements	Regulations mandating the use of recycled aggregates and materials in concrete production.	Reduction of resource consumption and waste generation.
Extended Producer Responsibility	Shifting responsibility for managing construction waste to manufacturers, promoting design for reuse and recycling.	Encourages sustainable product design and end-of-life recycling.
Resource Taxation and Incentives	Introducing taxes on virgin materials and providing financial incentives for recycled and sustainable alternatives.	Encourages the use of eco-friendly concrete materials.
Certification and Standards	Developing industry-specific certifications and standards for circular concrete materials and practices.	Ensures quality and sustainability of circular materials.
Waste Tracking and Reporting	Requiring construction companies to track and report the source, quantity, and destination of construction waste.	Enhances transparency and accountability in waste management.
Circular Procurement	Encouraging organizations to prioritize circular and sustainable concrete materials in their procurement processes.	Fosters the market for circular concrete materials.
Life Cycle Assessment Integration	Promoting the use of LCAs as a decision-making tool for concrete projects to assess environmental impact from cradle to grave.	Supports informed decision-making for sustainable concrete.
Research and Development Funding	Allocating funding for research and development of innovative concrete recycling and circular practices.	Stimulates innovation in circular concrete technologies.
Education and Training	Providing training and education programs for construction professionals on circular concrete practices and their benefits.	Builds a skilled workforce for circular construction.
Public Awareness Campaigns	Raising public awareness about the importance of circular concrete practices in reducing waste and environmental impact.	Fosters community support for circular construction efforts.

that stakeholders are well-informed and motivated to participate actively in the adoption of circular concrete practices.

Governments and regulatory bodies can encourage stakeholder participation by providing incentives such as tax benefits, subsidies, or grants for sustainable construction projects (Olubunmi et al., 2016; Rana et al., 2021; Díaz-López et al., 2021). These financial incentives motivate stakeholders to invest in circular concrete practices. Clear and consistent regulations are crucial. Policies and guidelines must be well-defined and uniformly enforced to ensure that stakeholders understand their roles and responsibilities. Ambiguity or policy inconsistencies can lead to confusion and hinder compliance. Encouraging research and development in circular concrete technologies can lead to innovative, cost-effective solutions. This not only benefits construction companies but also suppliers and manufacturers, fostering an environment of continuous improvement and innovation. Engaging the public through media, community outreach, and educational programs is vital. Public awareness can create a demand for sustainable construction practices. When customers, investors, and local communities advocate for eco-friendly construction, stakeholders are more likely to respond positively. However, the successful implementation of policies to promote circular concrete practices is not without its challenges. These challenges must be effectively addressed to ensure the seamless transition towards sustainability in the construction industry.

Resistance to change is a common barrier, particularly among stakeholders accustomed to traditional construction practices (Chan et al., 2017; Darko et al., 2017). The perception of increased costs or complexity associated with circular practices may hinder their adoption. Overcoming this resistance requires a focus on demonstrating the long-term benefits and cost savings associated with sustainability. A significant challenge lies in addressing the knowledge gap regarding the environmental implications of construction activities. Comprehensive awareness campaigns and educational efforts are necessary to close this gap and ensure that all stakeholders understand the critical importance of circular concrete practices. Weak enforcement of policies can undermine compliance. For policies to be effective, consistent monitoring and penalties for non-compliance are crucial. Enforcement mechanisms must be in place to encourage adherence to circular practices.

Smaller construction companies may face financial constraints when transitioning to more sustainable methods and materials. Access to funding, incentives, or cost-sharing initiatives can help overcome this challenge and facilitate their engagement in circular concrete practices. The transition to circular practices often requires specialized technical expertise that not all stakeholders possess. Providing training and capacity-building programs can address this knowledge gap and ensure that stakeholders have the necessary skills to implement circular concrete practices. Comprehensive data collection and reporting systems are often necessary for policy monitoring. This can be logistically challenging and requires significant investments in technology and human resources to establish effective data management and reporting mechanisms. Balancing stakeholder involvement with the resolution of policy implementation challenges is essential for the successful promotion of circular concrete practices in the construction sector. These efforts are foundational for enhancing sustainability, reducing environmental impact, and fostering resilience in the construction industry, contributing to a more sustainable and eco-friendly future.

7. Economic and social implications of circular economy in concrete industry

7.1. Economic viability and cost considerations

The incorporation of circular economy principles in the concrete industry is increasingly recognized for its potential to enhance economic viability while simultaneously addressing environmental concerns. Circular economy practices, which emphasize resource efficiency, waste reduction, and the reintegration of materials into the production cycle, hold the promise of positively impacting the concrete sector's cost considerations. A fundamental aspect of the circular economy is optimising resource use. By reusing and recycling materials, the concrete industry can reduce its dependence on virgin resources. This not only conserves natural resources but also diminishes the expenses associated with their extraction and transportation.

Circular economy practices aim to minimise waste generation. In the concrete industry, this means finding innovative ways to repurpose or recycle waste materials, such as concrete rubble. Reduced waste disposal costs contribute to cost savings. Designing durable concrete structures with extended lifespans is a key circular economy concept. While initial construction costs may be slightly higher, the long-term savings in maintenance and repair can be substantial. Using advanced mix designs and incorporating supplementary materials like fly ash, slag, or silica fume can enhance material efficiency. These materials often come at a lower cost than pure cement and reduce the carbon footprint, a win-win for both economic and environmental aspects.

Governments and regulatory bodies can introduce economic incentives such as tax benefits, subsidies, or grants for construction projects that adopt circular practices. These incentives make circular economy principles financially appealing to stakeholders. Increasingly, consumers, investors, and local communities are demanding eco-friendly and sustainable construction practices. Meeting this demand can provide a competitive advantage and potentially command premium pricing. However, it is important to acknowledge that transitioning to a circular economy in the concrete industry may involve initial investments and adjustments in construction processes. Resistance to change, knowledge gaps, and the need for training are among the challenges to overcome. The adoption of circular economy principles in the concrete industry has the potential to bring about economic viability and significant cost benefits. By focusing on resource optimisation, waste reduction, and the creation of durable structures, concrete manufacturers can align economic and environmental interests. To ensure the success of circular practices, it's imperative to address the challenges and provide incentives for stakeholders to embrace this transformative approach, ultimately leading to a more sustainable and economically viable concrete industry.

Ghisellini et al. (2018) provided a comprehensive literature review on the environmental and economic costs and benefits of a circular economy approach in the construction and demolition sector. Their analysis highlighted the potential cost savings and reduced environmental impact through recycling and reusing construction materials. However, the economic feasibility of circular practices could be hindered by initial investment requirements and the need for changes in construction processes. Muñoz-Vélez et al. (2023) offered a unique perspective by demonstrating how circular practices could add value to post-industrial waste, specifically aluminium dross, for cement matrix applications. Their study showcased the economic benefits of repurposing waste materials, as it could lead to cost reduction and resource optimisation in the concrete industry.

Uddin et al. (2023) presented a case study focused on implementing the circular economy in the cement industry in Pakistan. They discussed the economic implications of transitioning to circular practices and underscored the importance of supportive policies and incentives to make circularity economically viable. Hossain et al. (2020) examined the existing trends and challenges in adopting circular practices in the construction industry. Their research emphasized the economic advantages of extending the life cycle of construction materials, reducing waste generation, and fostering sustainability. However, they also acknowledged the need for overcoming barriers such as higher initial costs and resistance to change. La Scalia et al. (2021) contributed to the discussion by addressing the transition from lab-scale green geopolymeric mortar production to large-scale industrial manufacturing. They highlighted the economic feasibility of upscaling circular practices, especially in the context of geopolymeric mortars, which could lead to both cost savings and environmental benefits.

The economic viability of the circular economy in the concrete industry is a complex and multifaceted issue. While there are clear economic advantages in terms of resource optimisation, reduced waste, and potential cost savings, the successful implementation of circular practices requires overcoming challenges related to initial investments, policy support, and industry-wide adoption. A holistic and coordinated approach is needed to ensure that circular practices not only benefit the environment but also make economic sense in the long run.

7.2. Job creation and skill development opportunities

The adoption of circular economy principles in the concrete industry goes beyond just environmental benefits; it fosters substantial opportunities for job creation and skill development throughout the sector. Recycling facilities and upcycling plants need a skilled workforce. These workers are responsible for sorting and processing materials, ensuring their quality, and creating innovative ways to repurpose materials. This includes concrete recycling, where trained personnel sort and process old concrete to produce high-quality recycled aggregates. Circular concrete practices require continuous innovation (Joensuu et al., 2020; Adesina, 2020). Research scientists, engineers, and development experts specialize in creating sustainable materials and construction methods. They are responsible for developing new materials, optimising existing ones, and exploring innovative ways to reduce waste.

Architects and engineers play pivotal roles in designing structures with circular principles (Dokter et al., 2021; Victar et al., 2023). They must integrate recycled materials, optimise designs for resource efficiency, and reduce waste during the construction phase. This involves a deep understanding of sustainable construction materials and practices. As the industry shifts towards circular practices, new businesses emerge, focusing on recycling, upcycling, and eco-friendly construction solutions. These businesses require professionals in management, marketing, logistics, and business development to thrive. A skilled workforce is essential for repurposing and reusing concrete elements. Demolition crews, concrete cutters, and technicians play key roles in safely deconstructing old structures and preparing materials for reuse. The adoption of circular initiatives necessitates experts who can assess the environmental impact of construction activities. Environmental consultants, auditors, and sustainability experts are vital to ensure compliance with eco-friendly standards and regulations.

Skill development programs and workforce training are essential for preparing individuals for roles in the circular concrete economy (Govindan and Hasanagic, 2018; Schroeder et al., 2019). These programs teach workers how to handle recycled materials, operate machinery in recycling facilities, and implement sustainable construction practices safely and effectively. A new category of professionals, known as circular concrete technicians, is emerging. They specialize in handling recycled materials, optimising concrete mixes to include recycled components, and ensuring compliance with circular principles. This role focuses on the technical aspects of circular concrete production. The industry's adoption of innovative technologies and machinery for recycling and reusing materials requires technicians and operators to maintain and operate this equipment efficiently. These roles ensure the smooth operation of recycling and upcycling facilities. Educators, trainers, and communicators are vital for raising awareness about circular concrete practices. They educate both the public and industry professionals, deepening understanding of the benefits of circular economy principles and promoting sustainable practices.

The transition to a circular economy in the concrete industry not only reduces environmental impact but also offers substantial opportunities for job creation and skill development. This transition is reshaping the industry and nurturing a skilled and diverse workforce committed to resource efficiency and environmental responsibility. It is a pivotal step towards a more sustainable and eco-friendly future in construction.

7.3. Social and community benefits

The transition to a circular economy within the concrete industry brings forth a range of social and community benefits that are instrumental in shaping more sustainable, inclusive, and prosperous societies (Purchase et al., 2021; Maury-Ramírez et al., 2022). Circular economy practices promote job creation within local communities. Recycling centres, upcycling facilities, and sustainable construction projects require a workforce, offering employment opportunities. The concrete industry, which traditionally relies on manual labour, can particularly benefit from increased job opportunities, which, in turn, enhance local economic stability. Circular practices often encourage smaller-scale, community-based initiatives. These initiatives stimulate local economic growth as they generate a demand for materials, labour, and services within the community. Smaller businesses engaged in recycling, repurposing, and sustainable construction contribute to the economic vitality of their surroundings.

Transitioning to circular practices necessitates a skilled workforce with expertise in recycling, sustainable construction, and materials repurposing (De los Rios and Charnley, 2017; Mahpour, 2018; Awan and Sroufe, 2022). This requirement encourages investments in vocational training programs. These programs equip individuals with valuable skills, making them more employable, and enhancing the overall competence of the local workforce. The circular economy fosters closer collaboration between circular initiatives and local communities. Communities may become actively involved in recycling programs, waste management, or even in decision-making processes related to circular projects. This engagement cultivates a sense of ownership and responsibility, as community members actively participate in shaping their local environment. Circular concrete practices reduce the environmental footprint of construction. This contributes to cleaner air, reduced pollution, and less stress on local ecosystems. These environmental improvements lead to an enhanced quality of life for community residents, as they breathe cleaner air and enjoy a healthier and more attractive local environment.

The reuse and recycling of materials in circular practices reduce the demand for natural resources (Yong, 2007; Goyal et al., 2018). This resource conservation ensures that communities have access to essential resources for longer periods, thereby promoting resource security and sustainability. Circular practices alleviate the burden on local governments to manage and dispose of construction waste. This can lead to lower waste disposal costs, which, in turn, benefit taxpayers and local budgets, freeing up resources for other community needs. Sustainable construction practices often involve the use of safer and healthier building materials. Communities gain from living or working in structures that are constructed with materials that are less harmful to health. This enhances the well-being and safety of community members. Participating in circular initiatives can foster a sense of pride within the community. Community members take pride in the knowledge that they are actively contributing to a more sustainable and eco-friendly local environment. This pride can lead to a stronger community identity.

The circular economy encourages educational programs and awareness campaigns related to sustainable practices. These initiatives empower individuals with knowledge about the environmental benefits of circular concrete, enabling them to make more informed choices in their daily lives. Sustainable construction practices can lead to more cost-effective housing solutions. This makes affordable housing more accessible to a broader segment of the population, thereby addressing a pressing community need. Circular economy projects often serve as hubs for innovation and entrepreneurship. These hubs can attract researchers, startups, and businesses, enriching the local innovation ecosystem. They become sources of new ideas, technologies, and opportunities for the local community.

Sustainable construction practices, often associated with circular initiatives, can result in more resilient structures (Munaro et al., 2020; Foster, 2020; Díaz-López et al., 2021). These buildings are better equipped to withstand natural disasters, thus enhancing community safety and reducing the impact of such events. Circular initiatives frequently involve public education and community involvement. This increases awareness about sustainable practices, leading to a more informed and engaged community. As community members become more knowledgeable about the benefits of circular practices, they are more likely to adopt eco-friendly behaviours and demand sustainable construction solutions. The adoption of circular economy practices within the concrete industry plays a pivotal role in building healthier, more sustainable, and economically resilient communities. These practices empower individuals, create opportunities for growth, and foster a sense of community well-being, making them a crucial step towards a brighter and more sustainable future for societies at large.

8. Technological innovations and future prospects

8.1. Emerging technologies in circular concrete production

Emerging technologies are driving a profound transformation in the concrete industry, enabling the alignment of concrete production with circular economy principles. These innovations are revolutionizing the way concrete is designed, manufactured, and used, offering significant benefits for sustainability, efficiency, and waste reduction. One groundbreaking technology is self-healing concrete. This innovation integrates capsules or vascular networks within the concrete matrix, allowing it to autonomously repair cracks and damages. This self-repair capability not only extends the lifespan of concrete structures but also reduces the need for frequent maintenance or replacements. It is a prime example of how technology can contribute to circularity by ensuring the longevity of concrete products.

3D printing is another game-changing technology in concrete production. This method enables the precise layering of concrete, ensuring that material is applied only where needed. It minimises waste by avoiding overuse of concrete and can be particularly advantageous in complex architectural designs or in situations where customization is required. 3D printing can significantly reduce material waste and lead to more resource-efficient construction practices. Carbon capture and utilisation (CCU) technologies are transforming concrete production by repurposing CO_2 emissions generated during the process. These innovations capture CO_2 and turn it into a resource, reducing the carbon footprint of concrete. By incorporating captured CO_2 into concrete formulations, the industry not only reduces environmental impact but also effectively "upcycles" a waste product. Digital twins are virtual replicas of construction projects. They facilitate optimal design and construction processes, reducing errors and waste. By simulating and optimising construction in a virtual environment, digital twins enhance project planning and management, leading to more efficient resource utilisation and minimised material waste.

These technologies have the potential to revolutionize the concrete industry, making it more sustainable, resource-efficient, and environmentally responsible. By embracing these innovations, the concrete industry can align itself more closely with the principles of the circular economy, ultimately contributing to a greener, more sustainable future for construction. Table 10 highlights a range of emerging technologies poised to revolutionize circular concrete production. These innovations offer sustainable solutions by conserving resources, reducing waste, and improving concrete properties. Self-healing concrete repairs cracks autonomously, extending the lifespan of structures. 3D printing enables precise construction with minimal material waste. Carbon capture and utilisation (CCU) repurposes CO_2 emissions, curbing the carbon footprint. Digital twins optimise design and construction, reducing errors and waste. While these technologies promise numerous benefits, including enhanced durability and resource efficiency, their implementation may entail challenges like initial costs and technical expertise. Nevertheless, they represent a forward-looking approach to revolutionizing the concrete industry in line with circular economy principles.

8.2. Future trends and prospects for circular economy in concrete industry

The future of the circular economy in the concrete industry is poised for a transformative shift towards sustainability and responsible construction. Advanced recycling technologies will revolutionize waste processing, efficiently returning concrete waste to the production cycle as recycled aggregates. Circular design principles will become standard, embedding circular economy principles in construction projects and

Table 10
Emerging technologies for circular concrete production: Description, benefits, and key considerations.

Technology	Description	Benefits	Key Considerations	Reference
3D Printing	Utilises 3D printing technology for precise on-site construction, reducing material waste.	Minimal material waste, customized structures, and accelerated construction.	Adaptation to project scale and technology requirements.	Buswell et al., (2018); De Schutter et al., (2018); Khan et al., (2020)
Self-Healing Concrete	Integrates capsules or vascular networks for in-situ crack repair, extending structural lifespan.	Longer-lasting structures, reduced maintenance, and improved resource efficiency.	Compatibility with project needs and maintenance procedures.	Wiktor and Jonkers (2011); Li and Herbert (2012); Vijay et al., (2017); Qian et al., (2021)
Carbon Capture and Utilisation (CCU)	Captures and repurposes CO_2 emissions from concrete production, mitigating environmental impact.	Reduced carbon emissions, eco-friendly concrete, and carbon utilisation.	Integration of CCU systems and environmental monitoring.	Lim et al., (2019); Chai et al., (2022)
Recycled Aggregates and Industrial By-Products	Incorporates recycled aggregates and industrial waste materials into concrete production.	Diminished demand for natural resources, reduced waste generation, and lowered environmental impact.	Efficient sorting, processing, and quality control of recycled materials.	Pellegrino et al., (2016); Silva et al., (2014); Chinnu et al., (2021)
Precast Concrete	Utilises prefabrication techniques to manufacture concrete components off-site, reducing material waste.	Controlled production conditions, minimised material waste, and accelerated construction.	Transportation logistics, design capabilities, and quality control.	Mao et al., (2013); Arashpour et al., (2017); Guo et al., (2023)
Smart Concrete Technologies	Integrates sensors and data analytics to monitor concrete performance, enabling early issue detection.	Longer-lasting structures, reduced material waste, and proactive maintenance.	Investment in sensor technology, data management, and analysis.	Gunay et al., (2019); Taheri (2019); Qiu et al., (2021); Pickard et al., (2023)
Low-Carbon Clinker Substitutes	Replaces traditional clinker with low-carbon alternatives to reduce CO_2 emissions during cement production.	Lower carbon footprint, eco-friendly concrete, and reduced environmental impact.	Compatibility of substitutes with concrete mix and project requirements.	Maddalena et al., (2018); Gartner and Sui (2018); Schneider (2019); Malacarne et al., (2021)
Digital Twins for Construction	Utilises digital twins—virtual replicas of construction projects—to optimise design and reduce errors.	Improved project planning, waste reduction, cost savings, and enhanced accuracy.	Adoption of digital twin technology, data integration, and skilled workforce.	Greif et al., (2020); Opoku et al., (2021); Zhang et al., (2022); Zhao et al., (2023)

facilitating easier deconstruction and material repurposing. Material passport systems will enhance transparency, allowing stakeholders to track and identify reusable components, while sustainable cement alternatives will focus on low-carbon binders, reducing the environmental impact of concrete. Eco-labeling and certification will provide standardized information, guiding consumers towards sustainable choices. Government regulations and incentives will encourage circular practices, while global collaboration will foster knowledge sharing and technology transfer. Education and awareness campaigns will equip the workforce with circular construction knowledge. As circular concrete practices become economically viable, waste reduction targets will drive industry-wide commitment to sustainability, promising a dynamic future of eco-friendly and resilient construction practices.

9. Challenges and limitations

9.1. Technical and technological challenges

The integration of circular economy principles into the concrete industry presents a transformative journey laden with technical and technological challenges. Ensuring the consistent quality of recycled materials, enhancing structural durability, reducing energy consumption in recycling technologies, implementing effective data management, developing low-carbon binders, optimising waste sorting, and adopting circular design principles are critical challenges. Overcoming these hurdles demands interdisciplinary collaboration, research and development, innovation, supportive policies, and industry-wide commitment. Consistent material quality and performance are crucial for recycled and alternative materials, necessitating comprehensive testing and certification standards. Achieving durability and longevity in circular concrete requires advanced research into formulations, mix designs, and protective coatings. Innovations in recycling technologies, including advanced crushing and selective separation, are essential to close the loop efficiently.

Digitalization and data management are key, demanding standardized systems and robust cybersecurity. Adoption of alternative binders like geopolymers requires further research, while waste sorting and collection must leverage automated technologies and effective waste policies. Design and engineering challenges call for interdisciplinary collaboration and educational programs promoting circular design principles. Energy efficiency in production involves implementing renewable sources and efficient processes. Regulatory hurdles require collaborative efforts to establish clear, supportive policies. While challenging, these obstacles present opportunities for advancing sustainability, resource efficiency, and responsible construction practices in the concrete industry.

9.2. Economic and financial challenges

Transitioning to a circular economy in the concrete industry poses significant economic and financial challenges that must be effectively tackled for a successful shift. Initial capital investment stands out as a primary hurdle, requiring companies to upgrade facilities, implement new technologies, and invest in research and development. Smaller companies may particularly struggle with these substantial upfront costs. The perception of increased expenses is another challenge, as stakeholders may view circular practices as more costly than traditional approaches. Convincing them that these investments lead to long-term cost savings and substantial sustainability benefits is crucial. Economic incentives, such as government support and tax benefits, play a pivotal role in fostering circular practices. The absence of these incentives can impede widespread adoption.

Calculating and realizing the return on investment for circular practices is challenging, given the emphasis on immediate financial gains. Market demand for circular concrete products is intricately linked to economic viability, highlighting the need to stimulate demand for eco-friendly construction materials. Additionally, resource scarcity puts economic pressure on the industry to adopt circular practices, but concerns about supply chain stability and material costs arise. To effectively address these economic challenges, a comprehensive approach is necessary. This involves creating supportive economic policies and incentives, raising industry awareness about the long-term financial benefits, fostering a market for circular products, and incentivizing sustainable choices. Collaboration among industry stakeholders, government entities, and financial institutions is crucial for overcoming these challenges and propelling the concrete industry towards a more sustainable and economically viable future.

9.3. Social and behavioural challenges

Transitioning to a circular economy in the concrete industry encounters formidable social and behavioural challenges. Deep-rooted resistance to change at individual and organizational levels poses a significant hurdle, necessitating extensive awareness campaigns and education to showcase the long-term benefits of sustainability. Knowledge and awareness gaps among stakeholders, including professionals and the general public, impede progress, emphasizing the need for education on the environmental implications of construction activities and circular concrete practices. Cultural norms prioritizing cost and speed over sustainability present challenges, requiring a transformation in values and practices. Motivating stakeholders to adopt circular practices, especially when perceived as more expensive, demands a mix of financial and non-financial incentives. Stimulating consumer demand for circular concrete products relies on raising public awareness through educational campaigns.

The adoption of circular practices requires specialized skills, necessitating training programs to bridge the skill gap. Stakeholder collaboration is essential but complex, demanding effective alignment among construction companies, suppliers, regulatory bodies, and local communities. Government policies must facilitate circular practices, emphasizing collaboration to establish comprehensive and consistent regulations. Transparent data collection mechanisms are crucial for overcoming resistance to accountability throughout the supply chain. Addressing these multifaceted challenges demands a comprehensive strategy encompassing education, awareness, incentives, regulations, and collaborative efforts to build a socially responsible and environmentally conscious concrete industry committed to circular practices.

10. Concluding Remarks

The adoption of circular economy principles presents a compelling solution. It represents a shift towards a more sustainable and efficient era in concrete production and construction. By aligning with the principles of circularity, the industry can realize several key advantages. It will minimise the depletion of finite resources, reduce emissions, and diminish the environmental impact throughout the concrete life cycle. Moreover, the transition to circular practices not only mitigates environmental harm but also promotes economic viability by minimising waste and optimising resource use. This shift also fosters social well-being by generating employment opportunities and contributing to more resilient and eco-friendly communities.

The circular economy (CE) shifts from a ’take-make-dispose’ model to one that emphasizes durability, repair, reuse, and recycling to minimise waste and resource use. In concrete production, CE principles advocate for reusing concrete, optimising resources, and reducing landfill waste. Life Cycle Assessment (LCA) evaluates environmental impacts throughout concrete’s lifecycle, aiming to enhance sustainability by incorporating alternative materials and reducing emissions. Studies highlight LCA’s role in optimising concrete production practices and advancing eco-friendly technologies. Concrete recycling employs various techniques to repurpose waste, including crushing, thermal methods, and bioremediation. It reduces the need for virgin materials and environmental impact. The use of recycled aggregates and cementitious materials in new concrete helps conserve resources and lower carbon emissions. Advances in technology and research continue to enhance these sustainable practices.

Policies and regulations for circular concrete practices focus on enhancing sustainability in construction by promoting waste reduction, resource conservation, and the use of recycled materials. They include waste management rules, environmental certifications, and tax incentives. Future frameworks could enforce recycling, offer financial incentives, and support research. Challenges include stakeholder resistance and policy enforcement, but these practices can drive economic, job creation, and community benefits. Emerging technologies like self-healing concrete, 3D printing, and carbon capture are transforming concrete production towards circular economy principles, enhancing sustainability and efficiency. Future trends include advanced recycling, circular design, and material passports. Challenges involve technical, financial, and social barriers, such as high initial costs and resistance to change, necessitating comprehensive strategies and collaboration for successful implementation.

In essence, embracing the circular economy within the concrete industry is not merely an option; it is a necessity. It represents a collective commitment to responsible practices that align with global sustainability goals. The transformation towards circular concrete production is pivotal for reducing environmental harm, fostering economic sustainability, and enhancing social welfare. As stakeholders recognize these imperatives and act upon them, the concrete industry can indeed herald a more sustainable and eco-friendly future.

While the review provides a detailed exploration of circular economy principles in concrete production, it has some limitations. It may not fully address the practical challenges of implementing these principles at scale or the specific economic impacts on various industry sectors. Additionally, it might overlook regional variations in regulations and market conditions that affect adoption. The review focuses on current technologies and strategies but may not sufficiently account for emerging innovations or future developments. Lastly, the review’s emphasis on theoretical aspects may limit its applicability to real-world scenarios and practical implementation challenges in the concrete industry.

The practical application of this paper lies in its comprehensive framework for integrating circular economy principles into concrete production. It provides actionable insights into sustainable practices, including advanced recycling methods, innovative material technologies, and policy recommendations. These guidelines are designed to help industry professionals, policymakers, and researchers adopt more resource-efficient and eco-friendly concrete solutions. By implementing the strategies and technologies discussed, stakeholders can enhance sustainability, reduce environmental impacts, and drive the concrete industry towards a more circular economy. This paper thus serves as a valuable resource for advancing practical, real-world applications in sustainable construction.

CRediT authorship contribution statement

Salim Barbhuiya: Writing – review & editing, Writing – original draft, Formal analysis, Data curation, Conceptualization. **Bibhuti Bhusan Das:** Writing – review & editing. **Dibyendu Adak:** Writing – review & editing.

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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