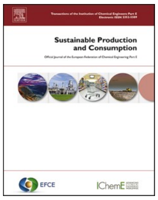
Sustainable Production and Consumption 60 (2025) 245–259

Contents lists available at ScienceDirect

Sustainable Production and Consumption

journal homepage: www.elsevier.com/locate/spc



Enabling circularity in construction: A technology-phase alignment of construction 4.0 and circular economy principles

Sara Rashidian [a,*], SK Tahsin Hossain [a], Kirsty Volz [a], Melissa Teo [a]

[a] School of Architecture and Built Environment, Queensland University of Technology (QUT), 2 George Street, Brisbane, QLD, 4000, Australia

ARTICLE INFO

Editor: Dr Kuishuang Feng

Keywords:
Construction 4.0, circular economy
Technology
Construction phases

ABSTRACT

Integrating Construction 4.0 technologies—the construction-specific application of Industry 4.0—with circular economy (CE) principles presents a transformative opportunity for the construction sector to enhance sustainability, improve resource efficiency, and build long-term resilience. Construction 4.0 refers to the digitalisation and automation of processes through technologies such as Building Information Modelling (BIM), the Internet of Things (IoT), blockchain, digital twins, robotics, and artificial intelligence (AI). Given the construction industry's significant environmental footprint and contribution to global waste, aligning Construction 4.0 with CE principles is essential for shifting from traditional linear practices towards regenerative, closed-loop systems. While sectors such as transport and manufacturing have already demonstrated the benefits of Industry 4.0 technologies in reducing waste and optimising resources, construction has been comparatively slow to embed these innovations across buildings and infrastructure. In addition, despite growing scholarly and industry interest, there remains no comprehensive framework that systematically integrates Construction 4.0 technologies with CE principles across all stages of the construction lifecycle.

This study addresses this gap through a systematic literature review of 58 peer-reviewed articles published between 2015 and 2024, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines. The review focused on English-language publications directly examining the intersection of Construction 4.0 and CE in the construction sector, while excluding non-peer-reviewed studies from unrelated industries. Thematic and co-occurrence analyses were applied to map the alignment of CE principles with Construction 4.0 technologies across seven phases of construction: Planning, Design, Tendering, Manufacturing, Construction, Operation, and End-of-Life. The study contributes a conceptual framework that visualises these alignments and highlights key opportunities and barriers for advancing circularity through digital transformation within the construction industry.

The findings highlight that BIM and IoT play pivotal roles in lifecycle planning, operational efficiency, and resource optimisation, while AI and digital twins support predictive maintenance, material recovery, and closed-loop optimisation. In contrast, robotics and blockchain remain underutilised in manufacturing and deconstruction, representing significant untapped potential to advance circularity. Persistent challenges, including fragmented stakeholder collaboration, siloed practices, and slow technological adoption, continue to impede the sector's ability to fully realise CE ambitions.

Future research should focus on fostering early stakeholder engagement and promoting cross-phase integration of Construction 4.0 technologies to enhance circular outcomes. Further studies are also needed to empirically validate the proposed framework across diverse project contexts and geographical settings. In addition, future research should examine the evolving role of emerging technologies, particularly AI, in accelerating the transition towards circular construction and scaling sustainable innovation across the sector.

---

* Corresponding author.
E-mail addresses: s.rashidian@qut.edu.au (S. Rashidian), tahsin.hossain@qut.edu.au (S.T. Hossain), kirsty.volz@qut.edu.au (K. Volz), melissa.teo@qut.edu.au (M. Teo).

https://doi.org/10.1016/j.spc.2025.10.004
Received 11 June 2025; Received in revised form 12 October 2025; Accepted 13 October 2025

1. Introduction

The global construction industry is facing growing pressure to move away from traditional linear models that rely on intensive resource extraction and waste generation. In response, Circular Economy (CE) principles have gained traction as a transformative approach that seeks to close material loops, reduce environmental impact, and promote long-term sustainability through strategies such as reuse, recycling, repair, and regeneration across the asset lifecycle (Ramakrishna et al., 2020).

Complementing this shift, Construction 4.0, a subset of Industry 4.0, introduces advanced digital technologies that support the transition to circular construction (Nascimento et al., 2019). Technologies such as Building Information Modelling (BIM), the Internet of Things (IoT), Artificial Intelligence (AI), robotics, and blockchain, enhance traceability, automation, data-driven decision-making, and stakeholder collaboration throughout the project lifecycle (Elghaish et al., 2022; Huynh-Xuan et al., 2024; Siriwardhana and Moehler, 2023). These technologies collectively form a digital ecosystem capable of enabling circular construction practices in a more integrated and scalable manner (Talla and McIlwaine, 2024).

Despite increasing interest, a major gap remains; there is currently no comprehensive framework that maps how Construction 4.0 technologies can support CE principles across all phases of the construction lifecycle. This lack of structured guidance limits both theoretical insight and practical application for stakeholders. This study addresses that gap by proposing a structured, lifecycle-oriented framework that links CE principles to Construction 4.0 technologies—highlighting their individual and synergistic potential to promote circularity in construction.

The study is guided by the following research questions:

1) How are the phases of the construction lifecycle examined in the context of circular economy principles within the existing literature?
2) What phase-specific strategies for circular economy implementation are identified in construction research, and how do these strategies support the core principles of circularity?
3) How do Construction 4.0 technologies correspond with circular economy principles throughout the construction lifecycle as reflected in the scholarly discourse?

The remainder of this article is structured as follows: Section 2 reviews the relevant literature, highlighting gaps in existing CE frameworks and Construction 4.0 integration. Section 3 describes the methodology used in the system review. Section 4 presents and discusses the findings, starting with an analysis of research trends and progressing to the core principles of the circular economy and their integration into distinct phases of construction. It further explores actionable circular economy strategies and examines the transformative role of Construction 4.0 technologies in enhancing circularity through efficiency, transparency, and sustainability. Section 5 concludes the paper by summarising the key contributions and outlining directions for future research.

2. Literature review

Circular economy in the construction context refers to a regenerative model that aims to eliminate waste, extend the lifecycle of building components, and maximise resource efficiency by applying strategies such as reuse, repair, recycling, and recovery across all stages of the built environment (Akomea-Frimpong et al., 2024; Minunno et al., 2018). Unlike linear models, CE promotes closed material loops and systemic design thinking to minimise environmental impact and preserve embodied value. Over the past decade, CE has been increasingly explored in the built environment, focusing on strategies such as modular construction, design for disassembly, material recovery, and sustainable procurement (Charef and Emmitt, 2021; Qazi and Appolloni, 2022; Sadeghi et al., 2023; Shashi et al., 2023; Spisáková et al., 2022). Studies by Minunno et al. (2018) and She et al. (2024) have catalogued a range of actionable CE strategies, including reuse of by-products, prefabrication, digital tracking, and early-stage design optimisation for adaptability and longevity.

Although the literature has made notable contributions to both CE and Construction 4.0, existing studies tend to focus on general CE principles or isolated practices, such as waste minimisation or end-of-life strategies, without examining how these principles interact across the full construction process (Benachio et al., 2020; Shooshtarian et al., 2022). Similarly, research on Construction 4.0 often explores individual technologies like BIM or AI applied to specific project phases such as design or demolition (Akanbi et al., 2019; Charef and Emmitt, 2021; Shojaei et al., 2021), offering limited insight into how digital tools can collectively support circularity across the entire lifecycle.

While frameworks have been proposed to address circularity in construction (e.g., Charef, 2024; Hosseini et al., 2023), these are often limited in scope—focusing either on CE principles in general or on the application of a single technology within specific phases. They do not provide a phase-by-phase mapping of how multiple Construction 4.0 technologies can enable a full spectrum of CE strategies across the lifecycle (Sajid et al., 2024). The identified gap not only restricts theoretical advancement but also hinders practical adoption, as stakeholders lack a structured model that connects CE principles with Construction 4.0 capabilities across planning, design, manufacturing, construction, operation, and end-of-life stages (Chen et al., 2022; Illankoon and Vithanage, 2023; Yu et al., 2022). This study addresses this gap by offering a more integrated approach: a structured, lifecycle-oriented framework that defines distinct phases of circular construction and systematically links them with enabling technologies such as BIM, IoT, AI, blockchain, AI-enabled BIM and digital twins. In this context, the term "framework" refers to a model that connects CE principles with Construction 4.0 technologies across all construction phases, highlighting their combined and synergistic potential in practice.

Moreover, existing studies highlight significant barriers to CE adoption, including limited technological access, fragmented stakeholder collaboration, and a general lack of awareness or skills related to digital tools in the industry (Fig. 1).

By bridging the gap between CE theory and Construction 4.0 application, the framework offers both strategic guidance and practical insights for industry stakeholders aiming to implement circular practices effectively.

3. Methods

The methodology for this study follows a Systematic Literature Review (SLR) approach, using both thematic and descriptive analysis to synthesise and interpret the findings. Systematic literature reviews are an established method for comprehensively identifying, selecting, synthesising, and appraising high-quality evidence related to a specific research question, ensuring transparency and minimising bias through a structured and systematic process (Hossain et al., 2024; Regona et al., 2022; Zoleykani et al., 2024). To begin the review, the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework was employed, ensuring a transparent and replicable process (David et al., 2023; Moher et al., 2009). Four-stage process—identification, screening, eligibility, and inclusion—guided the selection of relevant studies (Khan et al., 2021). The literature search was conducted across three major databases: Scopus, Web of Science (WOS), and Google Scholar. Scopus was prioritised due to its extensive coverage of academic publications, followed by cross-checking with WOS and Google Scholar to ensure comprehensive coverage of all relevant sources.

The search was conducted using a combination of keywords related to Construction 4.0, technology, and the circular economy in construction. The search used for this systematic review was: "Construction 4.0"

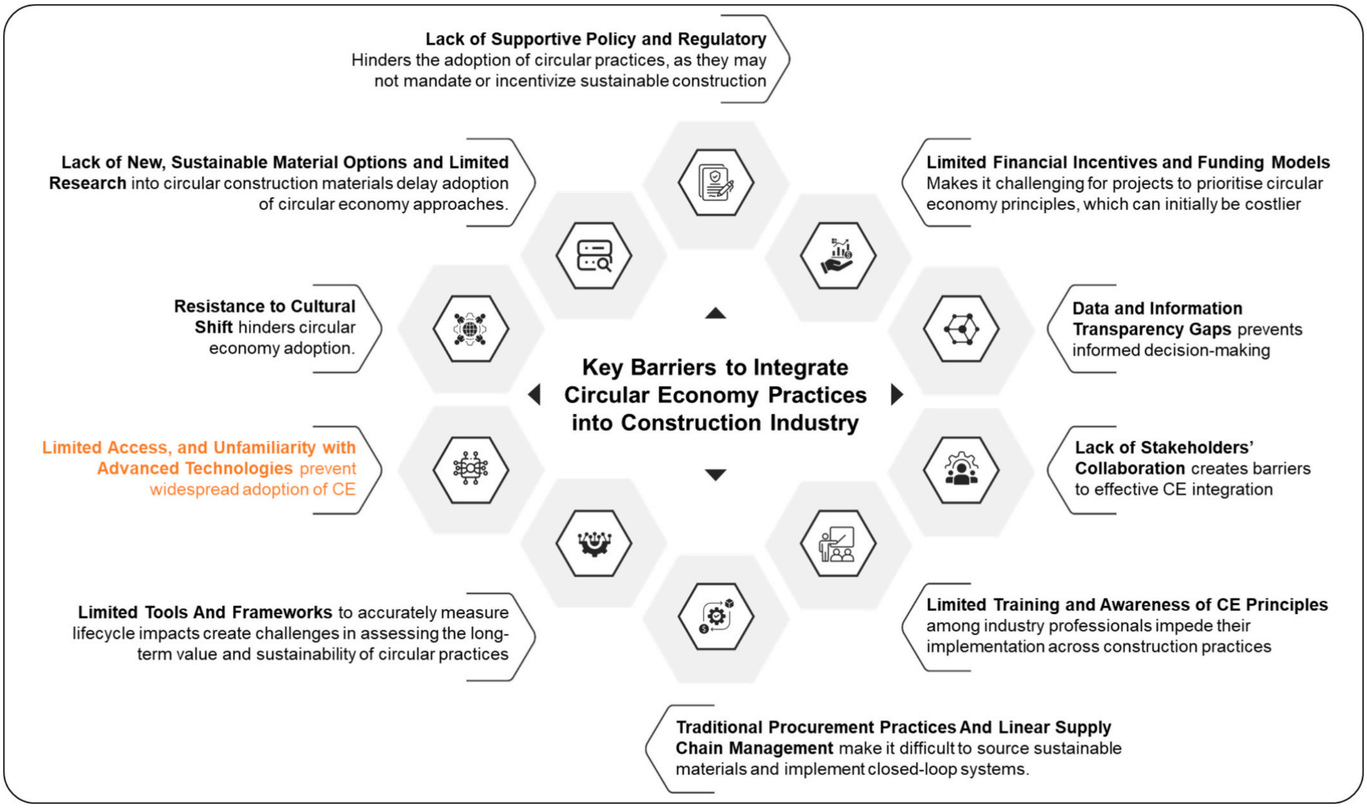


Fig. 1. Key challenges in implementing CE principles in the construction industry, identified from existing literature.

or "Digital Construction" or "Smart Construction" or "Building Information Modelling" or "BIM" or (("Internet of Things" or "IoT" or "Artificial Intelligence" or "AI" "Robotics" or "Cobots" or "Automation" "Digital Twin" or "Extended Reality" or "XR" or "3D" or "Additive Manufacturing" or "Big Data" or "Machine Learning" or "Cloud Computing" or "Blockchain") and "Construction") and ("Circular Economy" or "Material Reuse" or "Waste Reduction" or "Green Building" or "Eco-Friendly Construction" or "Zero-Waste" or "Zero Waste" or "SDG" or "Sustainable Construction" or "Sustainability in Construction"). The keywords relevant to Construction 4.0 and circular economy were extracted from the literature and several review papers (Alcalde-Calonge et al., 2022; van der Heijden, 2023). The initial search identified 2135 articles (Scopus = 1276; Web of Science = 859). The search criteria used to gather these records included a combination of article titles, abstracts, and keywords relevant to the subject matter, with an open-ended publication date range up to 30 September 2024. First, titles, abstracts, and keywords were reviewed using primary inclusion criteria: (i) peer-reviewed journal articles, (ii) available in full-text in English, and (iii) directly relevant to Construction 4.0 or CE in construction. This process reduced the list to 1136 articles. Duplicate entries were identified and removed using manual review, resulting in 748 unique articles.

These articles were subjected to a secondary screening, which evaluated relevance based on alignment with the research aim and guiding questions of this study. Studies were excluded if they: (i) focused solely on general sustainability without reference to CE or Construction 4.0; (ii) targeted sectors outside construction (e.g., manufacturing, agriculture); or (iii) were conceptual pieces without methodological or empirical insights. After this step, 192 articles remained for further evaluation.

During the eligibility stage, the full texts of 192 articles were reviewed using tertiary exclusion criteria, including those with insufficient methodological detail. This process reduced the pool to 91 articles. In accordance with the PRISMA protocol, a further refinement was then conducted to assess the depth and relevance of each study. Articles were excluded if they provided only broad discussion without analytical depth, and/or addressed circularity as a peripheral rather than integrated concern. This rigorous screening yielded 58 articles that were retained for in-depth review. The process of selecting articles, as outlined in the PRISMA protocol, is illustrated in Fig. 2.

Following the identification and selection of relevant data and publications, a thematic analysis was undertaken. This method is widely acknowledged as a robust and reputable qualitative data analysis technique that enhances the methodological rigour of research (Rashidian et al., 2023). This approach was particularly suited to identifying recurring patterns and synthesising diverse findings, allowing for a deeper understanding of how Construction 4.0 technologies align with CE principles.

4. Results and discussion

This section presents the key findings from the systematic literature review and provides an integrated discussion of emerging patterns, thematic insights, and conceptual developments. The analysis is structured around several core dimensions, including research trends, keyword associations, foundational principles of the circular economy, construction phases, strategic CE approaches, and the role of Construction 4.0 technologies. Each subsection highlights critical aspects identified through thematic and co-occurrence analysis to support a comprehensive understanding of how CE and Construction 4.0 intersect in the built environment.

4.1. *Trends and insights in circular economy research within construction 4.0*

The first part of this section explores the evolving research landscape at the intersection of circular economy and Construction 4.0. It begins by analysing publication trends to demonstrate the increasing academic

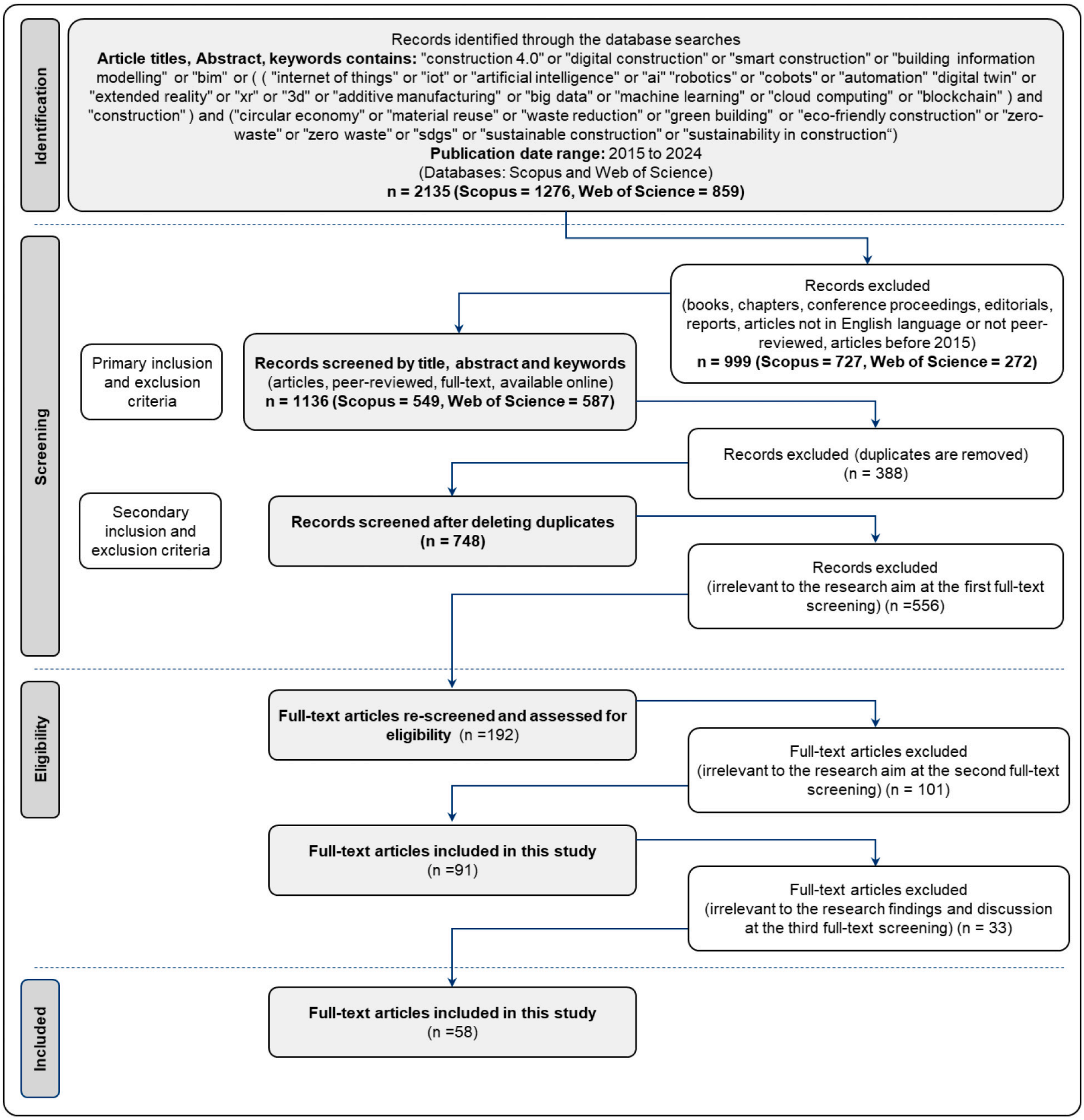


Fig. 2. Article selection process using the PRISMA method.

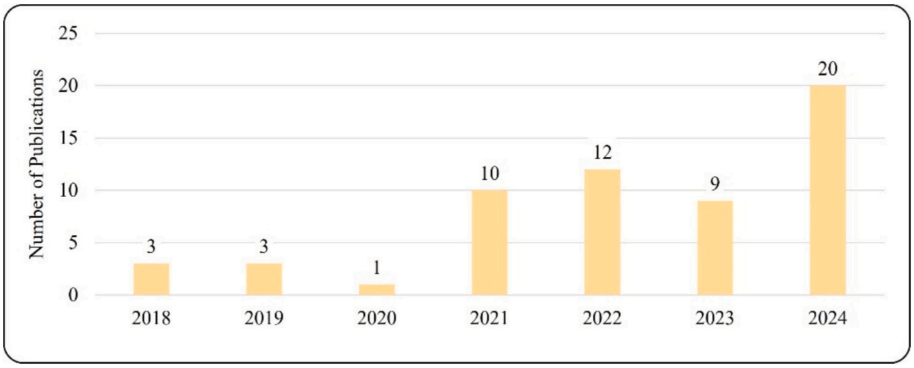


Fig. 3. Yearly publication trend of reviewed articles.

interest in this area over the past decade. This is followed by a keyword co-occurrence analysis, offering insights into the main themes, terminologies, and emerging research directions within the selected literature.

4.1.1. Research landscape

This systematic review encompassed a total of 58 articles focusing on the intersection of Construction 4.0 technologies, CE, in the construction industry. The publication timeline of these articles is shown in Fig. 3, revealing a notable growing research interest and output trend over the past seven years. The number of publications increased significantly in subsequent years, with 10 articles published in 2021, 12 in 2022, 9 in 2023, and 20 articles published by October 2024. The low number of publications during 2018–2020 may indicate that this research area was still in its early stages, as the concepts of circular economy and digital transformation in construction were just beginning to gain attention and develop momentum (Ferdosi et al., 2023; Ullah et al., 2024; Yevu et al., 2021). The sharp rise in publications from 2021 onward likely corresponds to an increasing global focus on sustainability and resource efficiency in construction (Hentges et al., 2022; Shashi et al., 2023). In recent years, and particularly in the first ten months of 2024, 20 articles were published, indicating a growing awareness among stakeholders of the potential for digital technologies to integrate CE principles.

4.1.2. Keywords co-occurrence analysis

To identify the main trending topics in the selected articles, a keyword co-occurrence analysis was performed using VOSviewer (Zoleykani et al., 2024), with the resulting network displayed in Fig. 4. The minimum threshold for keyword occurrences was set to three, allowing the identification of significant keywords while filtering out generic terms and those with interchangeable meanings (Siriwardhana and Moehler, 2023). Interchangeable keywords were standardised into a single common keyword to enhance clarity and minimise redundancy, as presented in Table 1. For example, keywords such as BIM, building information model–BIM, building information modelling, even though structured differently, all represent building information modelling. Similarly, the term life cycle assessment was treated as a keyword for life cycle, life cycle analysis, and life cycle assessment (LCA), as they all referred to the same concept.

After standardisation, 421 keywords remained, of which 32 keywords that appeared at least three times were selected for analysis. The connections between these keywords are illustrated in Fig. 4, where the size of each node represents the frequency of keyword occurrence, and the lines indicate co-occurrences between terms. The proximity of

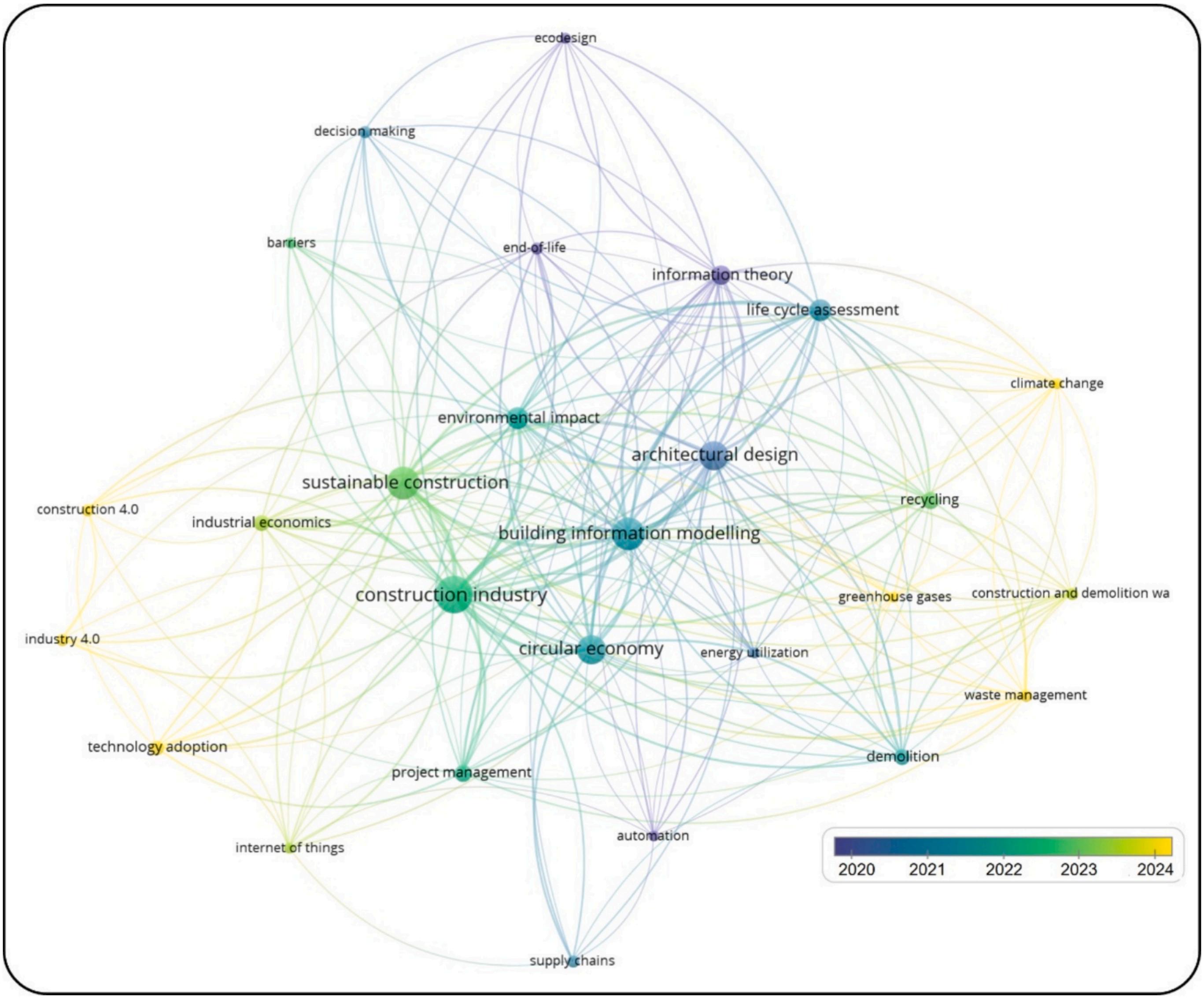


Fig. 4. Keyword co-occurrence in the reviewed articles.

Table 1

List of emerging keywords from co-occurrence analysis.

Actual keywords from articles	Standardised term used for analysis
BIM, building information model – BIM, modelling, building information modelling, building information modelling (BIM), building information modelling, building information modelling (BIM)	Building Information Modelling
construction, construction industry, construction projects, building construction building industry	construction industry
construction and demolition, demolition	demolition
digital technologies, technology adoption	technology adoption
economics, industrial economics,	industrial economics
end of lives, end-of-life	end-of-life
environmental impact, environmental technology	environmental impact
gas emissions, greenhouse gases	greenhouse gases
life cycle, life cycle analysis, life cycle assessment, life cycle assessment (LCA)	Life Cycle Assessment
sustainability, sustainable construction, sustainable development	sustainable construction

keywords indicates their relative co-occurrence: closely positioned keywords frequently appear together in publications, while those positioned further apart are less cited together. Centrally located keywords such as building information modelling, circular economy, and construction industry indicated strong connections, suggesting these terms were focal points in the literature, often central to discussions. Other central terms, such as sustainable construction and architectural design, also highlight core aspects of research related to circular economy integration in the built environment. Keywords with high occurrences and strong link strength reflect the primary areas of interest in the field.

Keywords like Industry 4.0, Internet of Things, technology adoption, and automation form a distinct cluster, linking the adoption of advanced digital technologies to the transition towards Construction 4.0. The relative distance of these keywords from circular economy suggests less frequent co-occurrence highlighting potential gaps in research connecting circular economy with emerging technologies. Operational aspects such as supply chains and project management appear at the periphery indicating these areas are relevant to automation and circular economy yet are not investigated in the literature presenting further research opportunities in terms of the role of stakeholders in circular economy transition through Construction 4.0

The colour gradient in the map (from blue to yellow) represents a temporal trend, where blue signifies older research (closer to 2020) and yellow represents newer research (closer to 2023). Established topics such as BIM and circular economy appear in the blue and green range, suggesting they have been consistently discussed over recent years. In contrast, keywords with a yellow tint, like technology adoption, Construction 4.0, and automation, reflect emerging areas of interest, indicating a shift towards digitalisation in newer publications. The emergence of keywords such as AI, digital twin, and big data alongside circular economy signals a growing research interest in the combined use of these technologies to support lifecycle thinking and CE strategies—indicating a clear trajectory towards more integrated, intelligent systems. While these specific terms are not directly visible in Fig. 4, they are conceptually embedded within broader clusters such as technology adoption, industry 4.0, construction 4.0, and internet of things. In addition, their influence can also be traced through adjacent themes of automation, supply chains, project management, and building information modelling, all of which represent the digital transformation pathways through which AI-driven and data-intensive approaches enter circular construction research. Thus, even though the terminology may not appear explicitly in the keyword network, the underlying technological shift they represent is clearly captured in the thematic structure of the field.

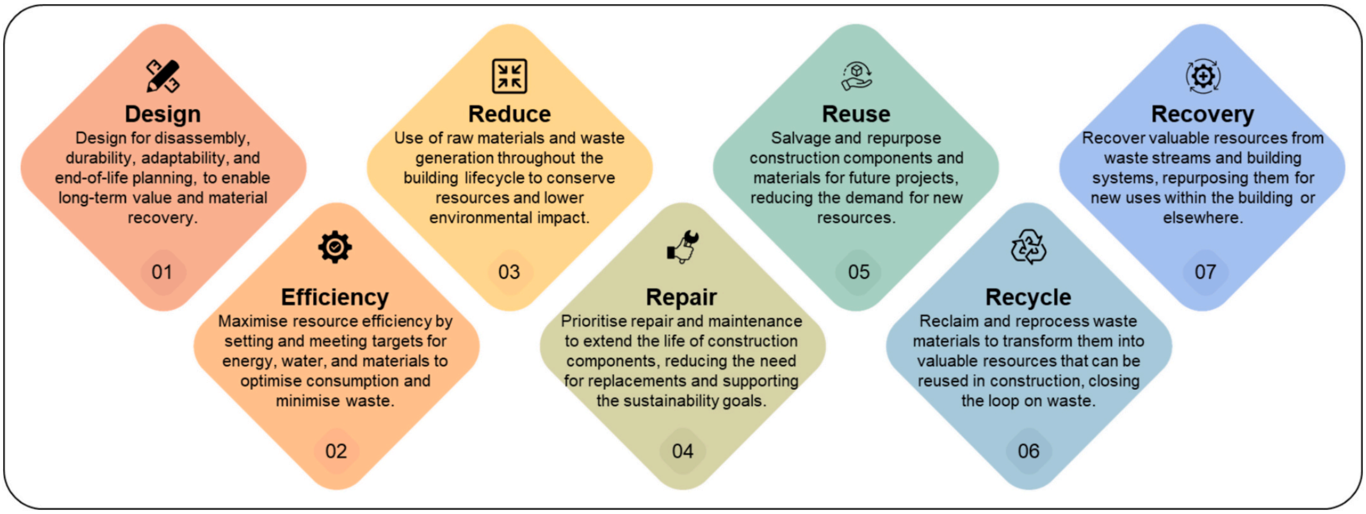
It is worth noting that Life Cycle Assessment (LCA) appeared as a recurring keyword in the co-occurrence analysis, even though it was not part of the initial search string. However, only a few reviewed studies applied LCA in depth, highlighting a gap in assessing the environmental trade-offs of CE principles. LCA is widely recognised as the established tool for measuring CE capacities in the built environment and is increasingly linked to Building 4.0 technologies through BIM and plug-in analysis software such as OneClick. Future research should explore both the barriers and enablers to adopting LCA within Building 4.0 tools and examine its effectiveness in advancing CE outcomes in construction practices and operations, using methods such as case studies and stakeholder interviews.

4.2. Core principles of circular economy in construction

The construction sector is progressively acknowledging the significance of implementing CE principles to optimise resource utilisation (Dongez et al., 2021; Saradara et al., 2024; Torgautov et al., 2021). Despite increasing interest, this SLR revealed that an industry-specific framework detailing the core principles of circularity was lacking, which reveals a significant research gap. While numerous studies discussed various principles of CE for construction, each typically focused on a few principles, often determined by the particular research perspective or context (Akanbi et al., 2019; Elghaish et al., 2023; Hentges et al., 2022; Qazi and Appolloni, 2022; Sadeghi et al., 2023). For instance, Dongez et al. (2021) examined the overarching context of the circular economy and its transition from a linear model, highlighting the principles of reduction, reuse, and recycling. In their investigation of CE strategies to minimise construction and demolition waste, She et al. (2024) also highlighted reducing consumption and promoting the reuse and recycling of materials. Furthermore, they have recognised the recovery of materials as a core principle. Shashi et al. (2023) explored the learnings and benefits of circular construction in their research, emphasizing the importance of extending the lifespan of buildings through sustainable design, maintenance, and repair. In their research on the application of BIM and blockchain in circular construction supply chains, Elghaish et al. (2023) emphasised principles including design for disassembly and deconstruction, waste and consumption reduction, and maximisation of resource efficiency.

The existing literature exhibits a fragmented approach, frequently discussing relevant CE principles specific to a research aim, rather than forming a cohesive, standard framework. The consolidation of these principles is important for a consistent and sector-wide implementation of the circular economy in construction. This study identified the seven core principles of the circular economy in construction: design, efficiency, reduce, repair, reuse, recycle, and recovery, illustrated in Fig. 5. The development of a consolidated framework in this study provides a structured basis for advancing circular economy practices in construction, offering a unified reference that can facilitate more systematic and holistic implementation and encourage consistency across the industry.

The foundation of circular construction lies in planned and thoughtful **design**. This principle includes considerations for adaptability (Banihashemi et al., 2024; Minunno et al., 2018), disassembly (Akanbi et al., 2019; Balasubramanian et al., 2024), durability (Minunno et al., 2018; Saradara et al., 2024; She et al., 2024), and end-of-life planning (Ganiyu et al., 2020; Sadeghi et al., 2023; Zandee et al., 2024). Researchers have heavily emphasised the importance of incorporating these elements from the initial stages of any construction project, from bridges and roads to buildings and utilities. Maximising resource **efficiency** is a core principle of implementing circularity in construction (Balasubramanian et al., 2024; Saradara et al., 2024; Torgautov et al., 2021). Resource efficiency refers to achieving more output or function with fewer inputs (Waqar et al., 2023; Yevu et al., 2021). It advocates for precise targets in resource consumption and the optimisation of materials, energy, and water across all phases of infrastructure, effectively minimising waste, conserving resources, and reducing environmental impact throughout development, operation, and maintenance (Oke et al., 2024; Saradara et al., 2024).



Design
Design for disassembly, durability, adaptability, and end-of-life planning, to enable long-term value and material recovery.

Efficiency
Maximise resource efficiency by setting and meeting targets for energy, water, and materials to optimise consumption and minimise waste.

Reduce
Use of raw materials and waste generation throughout the building lifecycle to conserve resources and lower environmental impact.

Repair
Prioritise repair and maintenance to extend the life of construction components, reducing the need for replacements and supporting the sustainability goals.

Reuse
Salvage and repurpose construction components and materials for future projects, reducing the demand for new resources.

Recycle
Reclaim and reprocess waste materials to transform them into valuable resources that can be reused in construction, closing the loop on waste.

Recovery
Recover valuable resources from waste streams and building systems, repurposing them for new uses within the building or elsewhere.

Fig. 5. Circular economy principles for the construction industry.

Reduction emphasises minimising the volume and intensity of resource inputs and reducing all forms of waste generation across all types and phases of construction (Elghaish et al., 2022; Minunno et al., 2018). This principle aligns closely with design-stage interventions—strategies that are embedded during the planning and design phase to influence downstream construction practices. These include approaches such as Lean Construction, which eliminates non-value-adding activities and streamlines workflows; prefabrication, which shifts production to controlled environments to reduce material waste and inefficiencies; and modular design, which enables standardised components to be assembled with minimal waste and greater potential for reuse (Ganiyu et al., 2020; Minunno et al., 2018). Prioritising **repair** and maintenance has also been addressed as a key concept in different studies (Akomea-Frimpong et al., 2024; Sajid et al., 2024; Torgautov et al., 2021). Routine repair and maintenance delay degradation and prevent premature failure, allowing infrastructure to function efficiently over extended periods while conserving energy and materials embedded in replacement (Saradara et al., 2024).

Reuse involves direct or indirect salvaging of materials and components, or entire building systems for use in the same or new applications (Elghaish et al., 2022; Sajid et al., 2024; Xu et al., 2022). However, the environmental benefit of reuse is not guaranteed—it depends heavily on the energy, emissions, and transport involved in recovering, processing, and reapplying materials (Benachio et al., 2020; Ganiyu et al., 2020; Spisáková et al., 2022). Studies indicate that when reuse processes are inefficient or demand extensive reprocessing, they can generate greater environmental impacts than producing new materials (Minunno et al., 2018). Consequently, validating reuse strategies through robust Life Cycle Assessment (LCA) is essential to confirm that they deliver genuine net environmental benefits.

Recycling refers to the reprocessing of waste materials into raw materials for new products, aiming to reduce landfill use and close material loops (Qazi and Appolloni, 2022; Sajid et al., 2024; Xu et al., 2022). Similar to reuse, recycling must be carefully evaluated—particularly regarding energy use, emissions, and downcycling risks. LCA is commonly employed to compare recycling outcomes against virgin material use and disposal options, and to assess trade-offs such as energy intensity or transport emissions (Mesa et al., 2021; Zubair et al., 2024).

Recovery focuses on extracting valuable materials or energy from waste streams or end-of-life structures, enabling resources to re-enter the supply chain (Charef and Emmitt, 2021; Saradara et al., 2024). Charef and Emmitt (2021) and She et al. (2024) argue that recovery plays a crucial role in material circularity—particularly in urban mining and selective demolition—yet its sustainability outcomes must be measured through methods like LCA or Material Flow Analysis to guide decision-making and policy.

4.3. *Different phases of construction through a circular economy lens*

The transition from linear to CE models in the construction industry necessitates a comprehensive, lifecycle-focused approach that confronts traditional linear techniques and adopts cyclical strategies across various construction phases (Banihashemi et al., 2024). The construction lifecycle, when viewed through the lens of CE, encompasses a series of interconnected phases, each offering opportunities for circular practices. Despite growing research examining the circular economy and construction, existing literature lacks clarity on specific phases tailored to the CE principles. Researchers have classified construction phases in various ways: Hentges et al. (2022) identified phases such as design, planning, construction, use, and demolition; Charef (2024) outlined eight phases: programming, design, tendering, construction, handover, operation, refurbishment, and deconstruction; Hoeft et al. (2021) recognised design, construction, operation, and maintenance. The varied classification of construction phases illustrates distinct research viewpoints but presents difficulties in systematically implementing CE principles across projects. Therefore, a unified, yet flexible categorisation of construction phases is essential to ensure a consistent approach and accommodate the nuances of different project types, scales, and regional contexts while maintaining a core commitment to circular principles. This study established a unified framework (Fig. 6) by categorising construction into seven primary phases—planning, design, tendering, manufacturing, construction, operation, and end-of-life—to systematically incorporate CE principles and facilitate a cohesive, lifecycle approach to circularity across all construction projects.

The planning phase establishes the foundation for CE practices throughout the construction project (Al Rashid and Koç, 2023; Nilimaa, 2023). It involves identifying project-specific goals that align with CE principles such as minimising resource consumption, reducing environmental impact, and enhancing long-term asset value (Akanbi et al., 2019; She et al., 2024; Singh and Kumar, 2024). The design phase is closely linked to the CE principle of ‘design’, which focuses on creating adaptable, durable building systems designed for disassembly and made with low-impact materials (Allam and Nik-Bakht, 2024; Guerriero et al., 2024). This early-stage intervention is instrumental for embedding circularity into the project from inception. Tendering in CE-oriented construction expands the traditional procurement focus—beyond just cost and timeline—to incorporate sustainability credentials such as supplier commitment to material reuse, waste minimisation, and

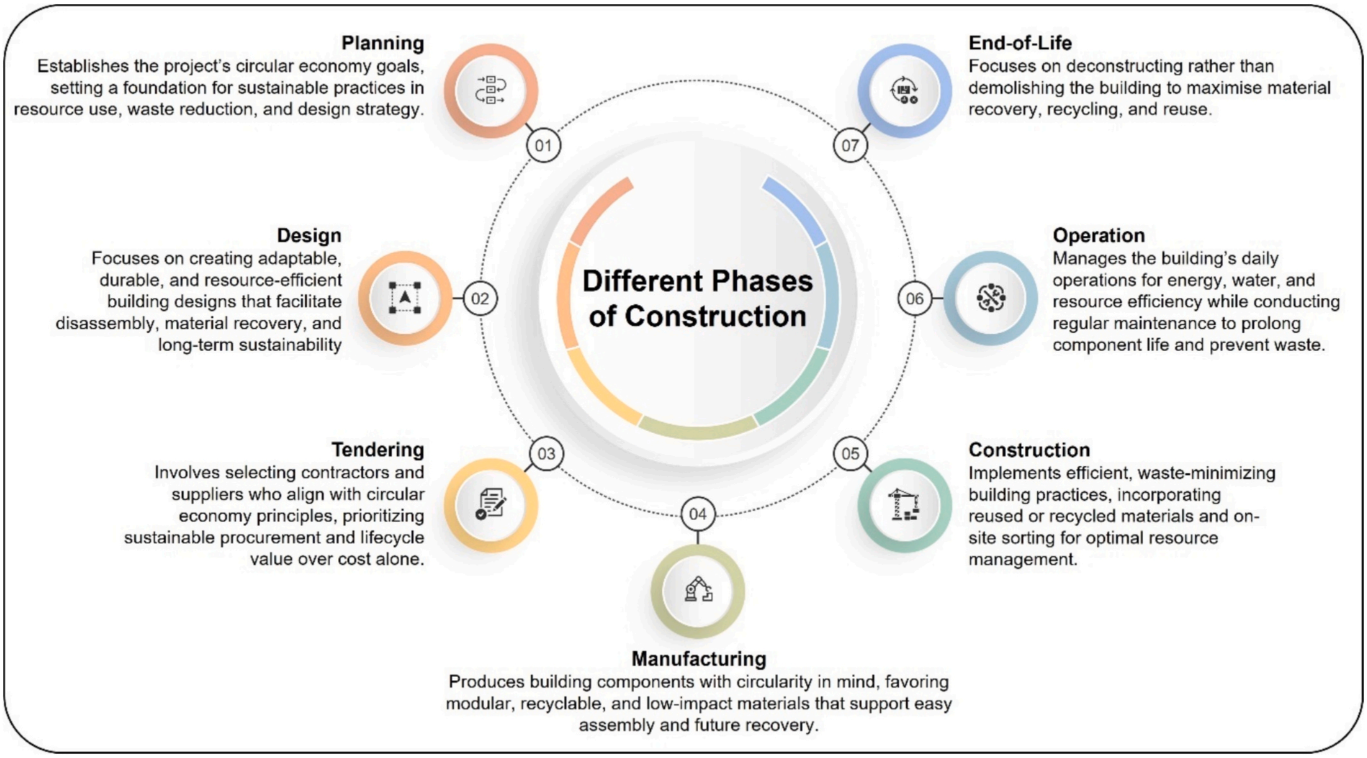


Fig. 6. Different phases of construction through the lens of the circular economy.

lifecycle considerations (Honic et al., 2021; Qazi and Appolloni, 2022; Yevu et al., 2021). The manufacturing phase plays a pivotal role in circularity by producing components that are recyclable, modular, and efficient in material use (Ganiyu et al., 2020; Rose et al., 2025). Off-site and prefabricated construction methods, often supported by digital tools, are increasingly promoted for their ability to reduce waste and improve quality control (Teisserenc and Sepasgozar, 2021; Hentges et al., 2022).

The construction phase is where CE strategies are executed on-site, using resource-efficient techniques, low-waste workflows, and real-time material tracking through digital tools (Moshood et al., 2024; Saradara et al., 2024; Talla and McIlwaine, 2024). Moshood et al. (2024) underscore the significance of digital technologies during the construction phase for monitoring materials and enhancing resource utilisation. The operation phase is concerned with efficient building performance, maintenance, and energy management—extending building lifespan and reducing operational impacts (Singh and Kumar, 2024; Zandee et al., 2024). Finally, the end-of-life phase emphasises deconstruction over demolition to optimise material recovery, with a focus on material recovery, selective disassembly, and closed-loop recycling (Banihashemi et al., 2024; Zandee et al., 2024). It is essential to acknowledge that although these phases appear in a seemingly linear order, they are interconnected and non-linear under CE principles. Feedback loops between phases—such as insights from operation guiding future design, or data from end-of-life informing material choices—are essential for continuous improvement. The interconnected nature of the construction lifecycle under CE requires integrated thinking and collaboration across all stages (Allam and Nik-Bakht, 2024; Ganiyu et al., 2020).

By viewing the construction lifecycle through a circular economy lens, we establish a foundation for targeted strategies. The next section builds on this outline by detailing phase-specific strategies that operationalise circular principles in practice.

4.4. Phase-specific strategies for circular economy

Existing studies have explored diverse strategies for implementing circular economy in construction; however, each study generally examines strategies from specific research perspectives, often concentrating on particular aspects such as material reuse (Allam and Nik-Bakht, 2024; Dervishaj and Gudmundsson, 2024; Guerriero et al., 2024), lifecycle thinking (Sajid et al., 2024; Yuan et al., 2024), modular construction (Langston and Zhang, 2021; Nilimaa, 2023; van der Heijden, 2023), or sustainable material selection (Masyhur et al., 2024; Shashi et al., 2023). Minunno et al. (2018) identified seven strategies: incorporating prefabricated structures, reusing by-products, reusing replacement parts and components, designing for adaptability and reusability, designing for disassembly, prioritising recyclability of materials, employing tracking technologies for subsequent use post-deconstruction, and utilising prefabrication to achieve material conservation and waste minimisation. She et al. (2024) proposed strategies to minimise the generation of construction and demolition waste, particularly within the Australian context. They emphasised strategies such as early stakeholder engagement and sustainability considerations, designing for adaptation, longevity, resilience, redundancy, disassembly, dematerialisation, deconstruction, and modularity, utilising technology for waste prediction and avoidance, onsite recycling methodologies, and the reuse of building materials, components, and products. Shi and Xu (2021) emphasised the digital cataloguing system, building material tracking systems such as Digital Product Passports (DPPs), and reverse logistics systems in their research concerning the end-of-life disposal of construction and demolition waste.

In addition, real-world projects have demonstrated how Construction 4.0 technologies are being applied to support circular economy strategies in practice. For example, Akanbi et al. (2018) applied BIM-integrated material passports to catalogue and visualise reusable components from existing buildings, enabling selective disassembly and reuse planning. Leising et al. (2018) conducted an in-depth examination of three Dutch case studies encompassing a new build, a renovation, and a demolition project. Collaborative digital platforms and shared material databases were used to improve lifecycle traceability and information transparency across stakeholders. In addition, the study highlighted the importance of extended supply chain responsibilities and innovative ownership models to enable material recovery, reuse, and long-term value retention throughout the project lifecycle.

Recent empirical studies have demonstrated the practical viability of circular economy principles across various construction contexts. For instance, Balletto et al. (2021) presented a strategic housing development in Sardinia, Italy, that emphasised modular construction, reuse of regional materials, and early-stage stakeholder collaboration to drive CE outcomes. In a comparative supply chain study, Nasir et al. (2017) analyzed the environmental implications of linear and circular supply chains within the insulation sector of the construction industry. Their life cycle assessment showed that recycled materials in circular supply chains significantly reduced carbon emissions, emphasizing the value of reverse logistics and secondary material flows. Kanagaraj et al. (2022) developed a roadmap for integrating CE in Indian infrastructure projects, identifying institutional, policy, and industry-level drivers needed to foster adoption. Together, these case studies complement the theoretical strategies outlined in this review and underscore the contextual, institutional, and technological factors necessary for successful CE implementation in the built environment.

Although these studies offer valuable insights into strategies for implementing the circular economy in construction from various perspectives, none have presented a comprehensive overview of all relevant circular economy strategies throughout the entire construction process, irrespective of construction type or scale. To address this gap, the current systematic review identified 37 strategies from existing literature and classified them based on the specific construction phases in which they are most effectively implemented, as shown in Fig. 7. Furthermore, this research extends beyond mere classification and compilation. In this paper, how these strategies contribute to the core principles of the

Fig. 7. Phase-specific circular economy strategies in construction and their contribution to core principles.

circular economy in construction has been identified, with clear links established between practical implementation strategies and overarching CE objectives. Through this approach, a more nuanced understanding is provided of how actions across various construction phases can collectively drive the transition towards a circular built environment.

To guide the classification of strategies presented in Fig. 7, this study draws on the R-imperatives framework proposed by Potting et al. (2017), which outlines a hierarchy of circular actions ranging from high-impact strategies like refuse, reduce, and reuse to those focused on material recovery, such as recycle and recover. These imperatives served as analytical criteria to assess how each strategy contributes to core CE principles across construction phases. Additionally, insights from the EMF (2015) ReSOLVE framework were consulted to ensure consistency with broader CE discourse. This dual referencing allowed for a comprehensive and robust mapping of strategies to circular objectives.

4.5. Construction 4.0 technologies

Construction 4.0 technologies not only address longstanding challenges in the industry, such as productivity gaps and safety concerns, but also open new avenues for adopting CE principles in construction phases. By enabling data-driven and efficient processes, these technologies significantly advance circular economy practices. Construction 4.0 offers an array of interconnected technologies, including data-driven platforms such as BIM and Geographic Information Systems (GIS), automation systems, and IoT devices, that collectively improve productivity, precision, and sustainability throughout every phase of construction (Balasubramanian et al., 2024; Deng et al., 2019). This review revealed a wide range of technologies that contribute to these goals, each with unique applications and benefits. The technologies were grouped according to their primary functions and applications, as shown in Table 2.

4.6. Mapping the roles of construction 4.0 technologies across construction phases for circular economy integration

The role of Construction 4.0 technologies in advancing CE practices has gained attention; existing studies often focus narrowly on a single technology—most notably, BIM—and its potential to drive circularity in the construction industry (Rosayuru et al., 2022; Waqar et al., 2023). Although the significance of BIM is indisputable, this narrow focus has frequently resulted in the insufficient examination of other equally promising technologies and their potential roles in fostering circularity in construction. The focus on BIM in isolation limits opportunities to analyse and discuss the application of technology by onsite workers in construction, deconstruction and reuse, who are critical enablers of CE in the built environment. Furthermore, research frequently examines the influence of a singular technology on a specific aspect or principle of circularity, typically within a specific phase. For example, some research has explored the use of blockchain for enhancing supply chain transparency in the procurement phase (Singh et al., 2023), while others discuss the use of IoT for monitoring and managing resource use during the operational phase (Dosumu and Uwayo, 2023; Kazmi and Sodangi, 2022). This fragmented view overlooks the interconnected and synergistic nature of these technologies in enabling CE across the full construction lifecycle.

To address this gap, a novel integrative framework (Fig. 8) was developed, mapping 17 Construction 4.0 technologies across the construction lifecycle and linking them to specific circular economy (CE) principles. The framework aligns each technology with CE strategies—such as design for adaptability, efficient resource use, modular manufacturing, and material recovery—highlighting both strategic and operational pathways for circularity. Colour-coded CE principles provide a clear visual reference for practitioners and researchers to see how technologies directly support circular objectives in practice.

Table 2
Construction 4.0 technologies, derived from existing literature.

Group	Technology	References
Data Integration and Analytics Technologies	Building Information Modelling	(Abruzzini and Abrishami, 2022; Charef and Emmitt, 2021; Kamari et al., 2022; Shi and Xu, 2021; Sudarsan and Gavali, 2024; Waqar et al., 2023; Zubair et al., 2024)
	Geographic Information Systems	(Shashi et al., 2023; Yevu et al., 2021; Zubair et al., 2024)
	Digital Twins	(Dervishaj and Gudmundsson, 2024; Turk et al., 2022; Wang and Ma, 2024)
	Cloud Computing	(Charef, 2024; Kazmi and Sodangi, 2022; Masyhur et al., 2024; Ullah et al., 2024; Yevu et al., 2021)
	Big Data Analytics	(Huynh-Xuan et al., 2024; Kazmi and Sodangi, 2022; Siriwardhana and Moehler, 2023; Ullah et al., 2024; Xu et al., 2022)
Automation and Robotics Technologies	Robotics and Automation	(Balasubramanian et al., 2024; Hoeft et al., 2021; Huynh-Xuan et al., 2024; Maqbool et al., 2023; Oke et al., 2024; Sudarsan and Gavali, 2024)
	Robotic Deconstruction	(Allam and Nik-Bakht, 2024; Banihashemi et al., 2024; Elghaish et al., 2022; Sudarsan and Gavali, 2024)
	3D Printing (Additive Manufacturing)	(Batikha et al., 2022; do Carmo and Sotelino, 2022; Elghaish et al., 2022; Masyhur et al., 2024; Najjar et al., 2022)
Sensing and Monitoring Technologies	Internet of Things	(Abruzzini and Abrishami, 2022; Dosumu and Uwayo, 2023; Kazmi and Sodangi, 2022; Ullah et al., 2024; Yevu et al., 2021)
	Drones	(Balasubramanian et al., 2024; Dosumu and Uwayo, 2023; Huynh-Xuan et al., 2024; Moshood et al., 2024; Siriwardhana and Moehler, 2023)
	Wearable Technology	(Li et al., 2022; Oke et al., 2024; Ullah et al., 2024)
Visualisation and Simulation Technologies	Virtual Reality and Augmented Reality	(Allam and Nik-Bakht, 2024; Dosumu and Uwayo, 2023; Ganiyu et al., 2020; Liu et al., 2024; Maqbool et al., 2023; Oke et al., 2023; Yevu et al., 2021)
	Generative Design	(Dervishaj and Gudmundsson, 2024; do Carmo and Sotelino, 2022; Yevu et al., 2021)
Supply Chain and Lifecycle Management Technologies	Blockchain Technology	(Elghaish et al., 2022; Singh and Kumar, 2024; Singh et al., 2023; Voorter and Koolen, 2021)
	Digital Supply Chain Management	(Oke et al., 2024; Yevu et al., 2021)
	Smart Energy Grids	(Liu et al., 2024; Singh et al., 2023; Teisserenc and Sepasgozar, 2021)

The framework shows that BIM demonstrates versatility through its application across various construction phases, each facilitating distinct CE principles. During the planning phase, BIM is essential for lifecycle planning via simulation and modelling, enabling project teams to evaluate resource requirements, design alternatives, and environmental effects at an early stage (Charef and Emmitt, 2021; Oke et al., 2024). This capability significantly supports the Design and Reduce principles of the circular economy by fostering optimised design solutions that minimise material usage, energy consumption, and environmental impact from the outset. In the operational phase, BIM can be employed to assess building performance for maintenance requirements, thereby directly supporting the Efficiency and Repair principles of the circular economy

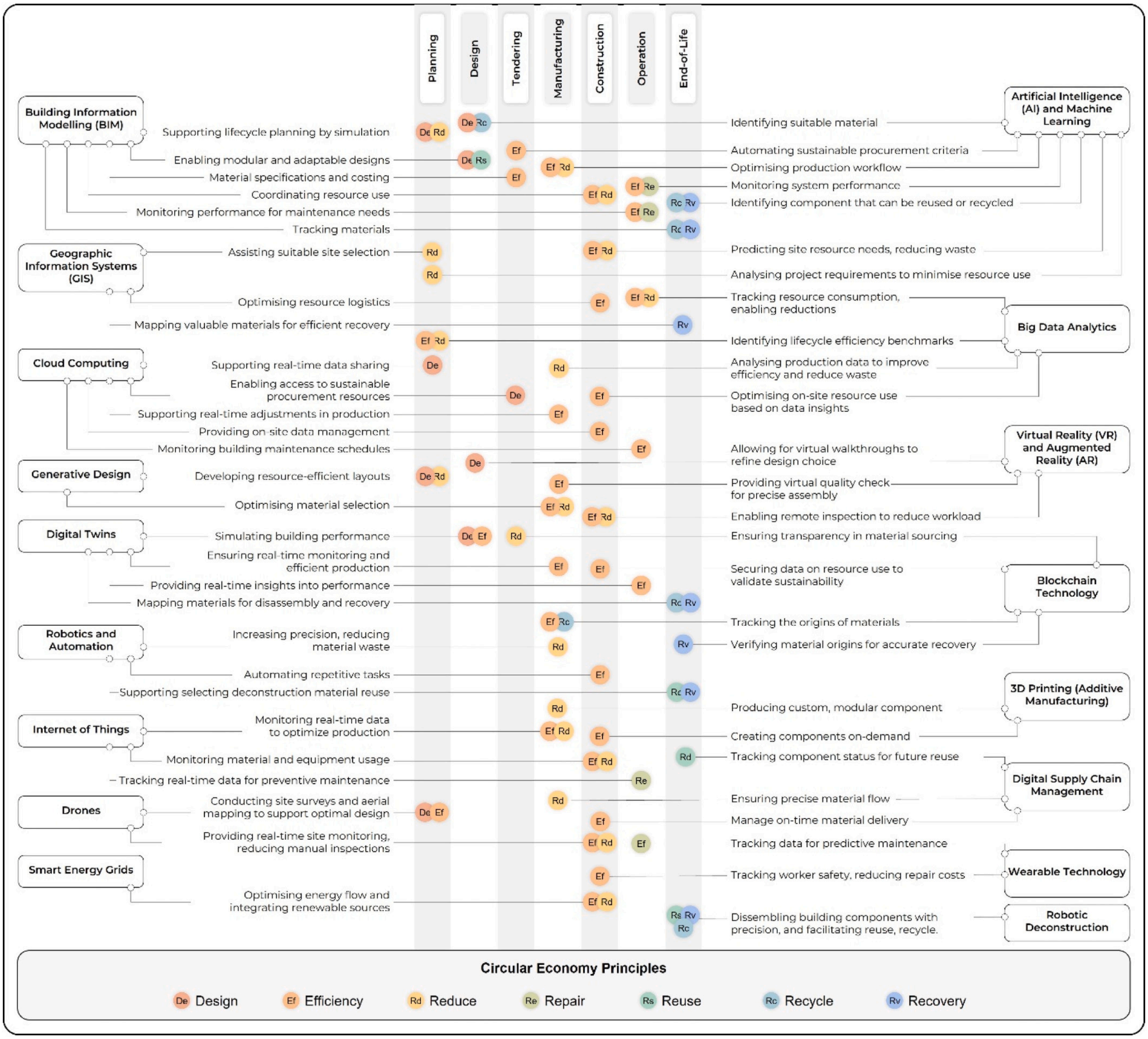


Fig. 8. Roles of Construction 4.0 technologies across construction phases and their alignment with CE principles.

(Abruzzini and Abrishami, 2022). Researchers have examined the application of BIM during the tendering phase of construction, specifically concerning material specifications and cost estimation. The 5D capabilities of BIM, which integrate cost data into the model, yield more precise and comprehensive cost estimates, facilitating more informed decisions regarding material selection and procurement (Bynum et al., 2013; Sebastian, 2011).

AI and Machine Learning (ML) are powerful Construction 4.0 technologies capable of transforming circularity throughout all seven stages of construction (Omotayo et al., 2025; Banihashemi et al., 2024; Honic et al., 2021). During the Manufacturing phase, AI and ML can be utilised to enhance production workflows by analysing real-time data to detect bottlenecks, modify processes, and allocate resources effectively (Balasubramanian et al., 2024; Hoeft et al., 2021). This directly aligns with the Efficiency and Reduction principles of the circular economy by minimising resource waste, optimising energy consumption, and facilitating seamless, resource-efficient production. In the Operation phase, AI and ML can be employed to monitor system performance in infrastructure, analysing data from IoT devices to forecast maintenance requirements, optimise energy usage, and identify anomalies in infrastructures (Abruzzini and Abrishami, 2022). AI and ML facilitate predictive maintenance and performance optimisation, thereby enhancing the Efficiency and Repair principles of CE, prolonging the lifespan of building components and minimising resource consumption (Elghaish et al., 2022). During the End-of-life phase, AI and ML technologies can identify components suitable for reuse, recycling, or recovery, thereby effectively endorsing the principles of Reuse, Recycle, and Recovery within the circular economy (Akanbi et al., 2019; Charef and Emmitt, 2021). AI and ML also learn from past projects to improve decision-making—for example, identifying recyclable assemblies or selecting materials with lower embodied carbon (Omotayo et al., 2025).

Digital Twins provide adaptable applications throughout various phases, including the Design phase, where they simulate building performance under diverse scenarios, thereby enhancing both Design and Efficiency principles through resource-efficient planning (Moshood et al., 2024; Oke et al., 2024). In the End-of-Life phase, digital twins can map materials and systems to guide efficient disassembly and recovery, contributing to the Recycle and Recovery principles. Combining AI and Digital Twins will allow predictive, closed-loop systems that adapt building operation and material decisions in real-time to achieve net-zero material flows. Researchers have recognised the IoT as an essential Construction 4.0 technology that exhibits considerable potential in enhancing circularity throughout multiple construction phases (Ullah et al., 2024). During the Construction Phase, IoT can be employed to oversee material and equipment utilisation, ensuring optimal resource allocation and waste reduction (Balasubramanian et al., 2024). This directly promotes the principles of Efficiency and Reduction. During the Manufacturing phase, IoT's real-time data monitoring facilitates modifications to enhance production workflows, thereby further aligning with these principles (Yevu et al., 2021). Blockchain technology presents advantageous applications in the Manufacturing Phase for tracing material origins, thereby enhancing Efficiency and Recycling principles (Singh et al., 2023; Voorter and Koolen, 2021). During the End-of-Life Phase, blockchain can be utilised to authenticate the origins of materials for precise recovery, thereby directly supporting the Recovery principle (Oke et al., 2024; Siriwardhana and Moehler, 2023). This corresponds with the increasing interest in utilising blockchain to improve transparency and traceability in construction processes. Future applications may involve smart contracts for dynamic CE compliance or carbon credit tracking.

Other emerging technologies—including 3D printing, VR/AR, drones, and wearables—also contribute to circularity across multiple phases of construction. 3D printing enables localised, material-efficient production and the use of recycled inputs, advancing the CE principles of Reduce and Recycle. VR and AR enhance design precision and provide real-time on-site guidance, minimising errors and material waste, thereby supporting Design and Efficiency. Drones contribute significantly during the planning phase by conducting aerial site surveys to inform optimal design decisions (Design, Reduce), and in the construction phase by enabling real-time monitoring and reducing the need for resource-intensive manual inspections (Efficiency, Reduce). Also, wearables enhance worker safety and productivity, indirectly strengthening Efficiency by reducing downtime and improving workflow continuity.

The integration of these technologies across the construction lifecycle signifies a fundamental transformation in the industry's approach to sustainability and resource management. These technologies are frequently used together, producing integrated solutions that enhance their respective advantages (Balasubramanian et al., 2024; Huynh-Xuan et al., 2024; Zhang et al., 2024). For instance, combining BIM with IoT enables real-time monitoring and data-driven insights across all project phases (Elghaish et al., 2023; Elghaish et al., 2022). Similarly, digital twins and VR/AR enhance both design accuracy and on-site performance monitoring, ensuring optimal resource allocation and aligning closely with CE principles (Dervishaj and Gudmundsson, 2024; Teisserenc and Sepasgozar, 2021).

Several pioneering projects exemplify how these technologies are being combined in practice. For instance, Elghaish et al. (2022) documented how blockchain and BIM were integrated in a supply chain context to support material traceability and CE compliance. In a UK-based design optimisation case, AI-enabled BIM tools were used to forecast environmental performance and automate material selection, aligning with CE goals such as reduction and adaptability (Elghaish et al., 2023). Similarly, a pilot project in the Netherlands deployed IoT sensors on-site to monitor energy use and construction waste, enabling real-time adjustments and promoting resource efficiency (Yevu et al., 2021). These applied cases illustrate that Construction 4.0 is not merely a conceptual toolset but a practical ecosystem enabling the implementation of circular economy principles in real-world projects.

However, the implementation of Construction 4.0 may necessitate significant upfront financial expenditures and the engagement of qualified professionals (Balasubramanian et al., 2024; Huynh-Xuan et al., 2024). Nonetheless, continuing advantages regarding resource efficiency, waste minimisation, and enhanced lifecycle management are expected to surpass these initial expenditures (Balasubramanian et al., 2024; Elghaish et al., 2022). Moreover, realising the full potential of these technologies in supporting CE requires active involvement and collaboration from various stakeholders, including contractors, suppliers, designers, and policymakers (Abdelaal and Guo, 2022; Dongez et al., 2021; Honic et al., 2021; Sadeghi et al., 2023).

Beyond identifying current applications, the review of existing studies reveals several visionary pathways that represent fertile ground for innovation within Construction 4.0–enabled circular construction. A particularly promising area is the deeper integration of AI into BIM environments to support predictive design optimisation, scenario simulation, and lifecycle-based material selection (Ganiyu et al., 2020; Elghaish et al., 2022). AI-driven BIM supports the circular economy by integrating intelligent data management, automation, and predictive analytics into the building lifecycle (Omotayo et al., 2025). AI enhances BIM's ability to track materials, assess their condition, and optimise reuse or recycling at the end of a building's life (Akanbi et al., 2019; Talla and McIlwaine, 2024). This data-rich, model-based approach enables designers and contractors to choose materials with higher recyclability, plan for disassembly, and reduce waste during construction (Omotayo et al., 2025).

Another key direction lies in coupling digital twins with IoT-enabled real-time sensing to enable dynamic, closed-loop decision-making, especially during the operation and end-of-life phases (Teisserenc and Sepasgozar, 2021; Moshood et al., 2024). These digital ecosystems can support continuous monitoring of performance, degradation, and reuse potential, facilitating responsive circular strategies. Blockchain-based circular supply chains offer new opportunities for traceability, material provenance, and dynamic pricing mechanisms that incentivise recovery and reuse (Elghaish et al., 2022; Singh and Kumar, 2024). Integrating blockchain with procurement and inventory platforms could further ensure transparency and accountability in material flows (Ara et al., 2021; Kim and Kim, 2024).

Advanced robotics, particularly in combination with AI, can automate complex CE tasks such as selective deconstruction, on-site material sorting, and recovery in urban mining contexts—areas where manual intervention is currently resource-intensive and inefficient (Elghaish et al., 2022; Rodrigo et al., 2023). Emerging robotic workflows for construction and demolition (waste selective deconstruction and sorting) indicate potential to raise recovery rates and quality while improving safety (Lee and Brell-Cokcan, 2023). Early case-based demonstrations further showcase mobile robotic systems for earth-based additive manufacturing and on-site sorting, which align with CE objectives when integrated with digital material inventories and passports (Kokkalis et al., 2025).

5. Future research directions

Drawing on insights from the reviewed literature that has begun to articulate visionary pathways for integrating Construction 4.0 and CE principles, this section delineates key avenues for future research aimed at deepening and operationalising this integration. Future research should explore novel and interdisciplinary domains that can advance circularity in construction beyond current approaches. Emerging interdisciplinary areas present promising avenues for advancing CE practices throughout the construction lifecycle. For instance, AI-driven generative design tools, already discussed in relation to resource-efficient layouts, hold potential for the automated development of disassemble and low-impact buildings. Similarly, blockchain-based logistics systems—examined here in the context of supply chain traceability—can support closed-loop material flows and enhance accountability. There is also considerable scope to explore how digital twins might be leveraged for real-time collaboration among project stakeholders, enabling more responsive and integrated circular decision-making. Collectively, these developments signal a shift from conceptual models towards more dynamic, data-informed CE practices.

In this context, AI-driven BIM emerges as a particularly urgent research frontier. Although applications are beginning to appear, they remain scarce and limited in scope, creating a critical gap that must be addressed as a strategic priority. Building on this, future research should also explore how combinations of Construction 4.0 technologies—particularly AI-driven BIM, IoT-enhanced digital twins, and blockchain-enabled supply chain platforms—can work in synergy to accelerate the transition towards circularity. Addressing practical challenges, such as interoperability, data governance, and lifecycle integration, will be critical to unlocking their transformative potential. Seamless communication across platforms, devices, and stakeholders is essential to achieving system-wide circularity. These integrations mark a shift from isolated technological applications to systemic, interoperable solutions that holistically advance circularity in the built environment. Moreover, the role of specific technologies, such as robotics and digital twins, in less-explored phases like manufacturing and end-of-life, warrants further investigation.

To advance each identified research area, future studies should go beyond conceptual discussions and focus on practical implementation pathways. For example, research on Construction 4.0 technologies could explore integrated platforms (such as combining AI, BIM, and IoT) to optimise material flows and enable predictive maintenance. Likewise, the circular economy strategies introduced in this study can be strengthened through empirical validation in real-world projects across different regions and construction types.

Furthermore, future research should build on the introduced framework by examining how Construction 4.0 technologies can enhance stakeholder collaboration and address the industry's persistent fragmentation. Embedding stakeholders within construction and CE phases alongside digital tools would create a more comprehensive framework for identifying both opportunities and barriers to circular practices. A major research priority is understanding how these technologies can help shift the industry from a linear to a circular model, which will require not only individual adoption but also coordinated uptake across the network of stakeholders. CE will ultimately require a fragmented industry to function in an ongoing cyclical fashion, which will require a deep understanding of technology adoption by, and importantly between, various stakeholders.

6. Conclusions

This systematic literature review developed a novel technology–phase framework explaining how Construction 4.0 technologies can operationalise Circular Economy (CE) principles across the construction lifecycle. Drawing on thematic and co-occurrence analyses of 58 peer-reviewed studies, the research identified how digital innovation supports circular practices across seven key phases—Planning, Design, Tendering, Manufacturing, Construction, Operation, and End-of-Life.

The synthesis demonstrates that digitalisation is reshaping the construction industry's pathway towards circularity. Technologies such as BIM, IoT, digital twins, AI, robotics, and blockchain collectively enhance resource efficiency, traceability, and lifecycle performance, helping to close material and information loops. However, the analysis also reveals uneven technological maturity, fragmented collaboration, high upfront financial costs, and institutional barriers that limit widespread adoption.

Building on these insights, several key takeaways emerge from the synthesis, highlighting both the current state of knowledge and the pathways for advancing circularity through digital transformation:

- Early integration of digital tools during the planning and design stages yields stronger downstream circular outcomes.
- BIM and IoT remain the most established technologies, offering real-time visibility, material tracking, and lifecycle optimisation.
- AI and digital twins enable predictive circularity through forecasting, maintenance, and end-of-life resource recovery.
- Robotics and blockchain are still in the early stages of application within the construction industry. Yet, they hold substantial potential to advance circularity by improving automation, traceability, and material flow transparency across project phases.
- Collaboration across disciplines and governance mechanisms is critical for translating digital potential into measurable circular outcomes.
- Persistent policy and capacity gaps continue to restrict the uptake of Construction 4.0, particularly in developing economies.

While this review provides a significant synthesis, it is limited by its focus on English-language publications, which may omit insights from non-English studies. Future research should therefore expand the linguistic and geographical scope while validating and operationalising the proposed framework to guide the global transition towards circular and digitally enabled construction.

CRediT authorship contribution statement

Sara Rashidian: Writing – original draft, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **SK Tahsin Hossain:** Writing – original draft, Methodology, Data curation, Conceptualization. **Kirsty Volz:** Writing – review & editing, Writing – original draft, Supervision, Methodology, Data curation. **Melissa Teo:** Writing – review & editing, Supervision, Conceptualization.

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.

Acknowledgements

This research was supported by the Publication Support Funding from the School of Architecture and Built Environment at Queensland University of Technology (QUT).

References

Abdelaal, F., Guo, B.H.W., 2022. Stakeholders' perspectives on BIM and LCA for green buildings. J. Build. Eng. 48, 103931. https://doi.org/10.1016/j.jobe.2021.103931.

Abruzzini, A., Abrishami, S., 2022. Integration of BIM and advanced digital technologies to the end of life decision-making process: a paradigm of future opportunities. Journal of Engineering, Design and Technology 20 (2), 388–413. https://doi.org/10.1108/JEDT-12-2020-0524.

Akanbi, L.A., Oyedele, L.O., Akinade, O.O., Ajayi, A.O., Davila Delgado, M., Bilal, M., Bello, S.A., 2018. Salvaging building materials in a circular economy: A BIM-based whole-life performance estimator. Resour. Conserv. Recycl. 129, 175–186. https://doi.org/10.1016/j.resconrec.2017.10.026.

Akanbi, L.A., Oyedele, L.O., Omoteso, K., Bilal, M., Akinade, O.O., Ajayi, A.O., Davila Delgado, J.M., Owolabi, H.A., 2019. Disassembly and deconstruction analytics system (D-DAS) for construction in a circular economy. J. Clean. Prod. 223, 386–396. https://doi.org/10.1016/j.jclepro.2019.03.172.

Akomea-Frimpong, I., Jin, X., Osei Kyei, R., Tetteh, P.A., Tumpa, R.J., Ofori, J.N.A., Pariafsai, F., 2024. A review of circular economy models and success factors on public-private partnership infrastructure development. Built Environment Project and Asset Management 14 (1), 109–126. https://doi.org/10.1108/BEPAM-01-2023-0014.

Al Rashid, A., Koç, M., 2023. Additive manufacturing for sustainability and circular economy: needs, challenges, and opportunities for 3D printing of recycled polymeric waste. Mater Today Sustain 24, 100529. https://doi.org/10.1016/j.mtsust.2023.100529.

Alcalde-Calonge, A., Sáez-Martínez, F.J., Ruiz-Palomino, P., 2022. Evolution of research on circular economy and related trends and topics. A thirteen-year review. Ecol. Informatics 70, 101716. https://doi.org/10.1016/j.ecoinf.2022.101716.

Allam, A.S., Nik-Bakht, M., 2024. Supporting circularity in construction with performance-based deconstruction. Sustainable Production and Consumption 45, 1–14. https://doi.org/10.1016/j.spc.2023.12.021.

Ara, R.A., Paardenkooper, K., van Duin, R., 2021. A new blockchain system design to improve the supply chain of engineering, procurement and construction (EPC) companies – a case study in the oil and gas sector. Journal of Engineering, Design and Technology 20 (4), 887–913. https://doi.org/10.1108/JEDT-01-2021-0047.

Balasubramanian, S., Shukla, V., Islam, N., Manghat, S., 2024. Construction industry 4.0 and sustainability: an enabling framework. IEEE Trans. Eng. Manag. 71, 1–19. https://doi.org/10.1109/TEM.2021.3110427.

Balletto, G., Borruso, G., Mei, G., Milesi, A., 2021. Strategic circular economy in construction: case study in Sardinia, Italy. J. Urban Plann. Dev. 147 (4), 05021034. https://doi.org/10.1061/(ASCE)UP.1943-5444.0000715.

Banihashemi, S., Meskin, S., Sheikhkhoshkar, M., Mohandes, S.R., Hajirasouli, A., Lenguyen, K., 2024. Circular economy in construction: the digital transformation perspective. Clean. Eng. Technol. 18, 100715. https://doi.org/10.1016/j.clet.2023.100715.

Batikha, M., Jotangia, R., Baaj, M.Y., Mousleh, I., 2022. 3D concrete printing for sustainable and economical construction: a comparative study. Autom. Constr. 134, 104087. https://doi.org/10.1016/j.autcon.2021.104087.

Benachio, G.L.F., Freitas, M.D.C.D., Tavares, S.F., 2020. Circular economy in the construction industry: a systematic literature review. J. Clean. Prod. 260, 121046. https://doi.org/10.1016/j.jclepro.2020.121046.

Bynum, P., Issa, R.R.A., Olbina, S., 2013. Building information modeling in support of sustainable design and construction. J. Constr. Eng. Manag. 139 (1), 24–34. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000560.

Charef, R., 2024. A digital framework for the implementation of the circular economy in the construction sector: expert opinions. Sustainability 16 (14). https://doi.org/10.3390/su16145849. Article 5849.

Charef, R., Emmitt, S., 2021. Uses of building information modelling for overcoming barriers to a circular economy. J. Clean. Prod. 285, 124854. https://doi.org/10.1016/j.jclepro.2020.124854.

Chen, Q., Feng, H., Garcia de Soto, B., 2022. Revamping construction supply chain processes with circular economy strategies: a systematic literature review. J. Clean. Prod. 335, 130240. https://doi.org/10.1016/j.jclepro.2021.130240.

David, A., Yigitcanlar, T., Li, R.Y.M., Corchado, J.M., Cheong, P.H., Mossberger, K., Mehmood, R., 2023. Understanding local government digital technology adoption strategies: a PRISMA review. Sustainability 15 (12), 9645. https://www.mdpi.com/2071-1050/15/12/9645.

Deng, Y., Gan, V.J.L., Das, M., Cheng, J.C.P., Anumba, C., 2019. Integrating 4D BIM and GIS for construction supply chain management. J. Constr. Eng. Manag. 145 (4), 04019016. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001633.

Dervishaj, A., Gudmundsson, K., 2024. From LCA to circular design: a comparative study of digital tools for the built environment. Resour. Conserv. Recycl. 200, 107291. https://doi.org/10.1016/j.resconrec.2023.107291.

do Carmo, C.S.T., Sotelino, E.D., 2022. A framework for architecture and structural engineering collaboration in BIM projects through structural optimization. J. Inf. Technol. Constr. 27, 223–239. https://doi.org/10.36680/j.itcon.2022.011.

Dongez, N., Manisa, K., Basdogan, S., 2021. Tendency to circular economy: reuse of architectural elements. Enquiry 18 (2), 73–93. https://doi.org/10.17831/enqarcc.v18i2.1089.

Dosumu, O.S., Uwayo, S.M., 2023. Modelling the adoption of internet of things (IoT) for sustainable construction in a developing economy. Built Environment Project and Asset Management 13 (3), 394–411. https://doi.org/10.1108/bepam-08-2022-0123.

Elghaish, F., Matarneh, S.T., Edwards, D.J., Rahimian, F.P., El-Gohary, H., Ejohwomu, O., 2022. Applications of industry 4.0 digital technologies towards a construction circular economy: gap analysis and conceptual framework. Construction Innovation-England 22 (3), 647–670. https://doi.org/10.1108/ci-03-2022-0062.

Elghaish, F., Hosseini, M.R., Kocaturk, T., Arashpour, M., Bararzadeh Ledari, M., 2023. Digitalised circular construction supply chain: an integrated BIM-blockchain solution. Autom. Constr. 148, 104746. https://doi.org/10.1016/j.autcon.2023.104746.

EMF, 2015. Towards a Circular Economy: Business Rationale for an Accelerated Transition. Ellen MacArthur Foundation. Retrieved 11 November 2024 from. https://www.ellenmacarthurfoundation.org/towards-a-circular-economy-business-rationale-for-an-accelerated-transition.

Ferdosi, H., Abbasianjahromi, H., Banihashemi, S., Ravanshadnia, M., 2023. BIM applications in sustainable construction: scientometric and state-of-the-art review. Int. J. Constr. Manag. 23 (12), 1969–1981. https://doi.org/10.1080/15623599.2022.2029679.

Ganiyu, S.A., Oyedele, L.O., Akinade, O., Owolabi, H., Akanbi, L., Gbadamosi, A., 2020. BIM competencies for delivering waste-efficient building projects in a circular economy. Dev. Built Environ. 4, 100036. https://doi.org/10.1016/j.dibe.2020.100036.

Guerriero, A., Busio, F., Saidani, M., Boje, C., Mack, N., 2024. Combining building information model and life cycle assessment for defining circular economy strategies. Sustainability 16 (11), 4561. https://doi.org/10.3390/su16114561.

Hentges, T.I., Machado da Motta, E.A., de Lima, Valentin, Fantin, T., Moraes, D., Fretta, M.A., Pinto, M.F., Spiering Böes, J., 2022. Circular economy in Brazilian construction industry: current scenario, challenges and opportunities. Waste Manage. Res. 40 (6), 642–653. https://doi.org/10.1177/0734242X211045014.

Hoeft, M., Pieper, M., Eriksson, K., Bargstädt, H.J., 2021. Toward life cycle sustainability in infrastructure: the role of automation and robotics in PPP projects. Sustainability (Switzerland) 13 (7), 3779. https://doi.org/10.3390/su13073779.

Honic, M., Kovacic, I., Aschenbrenner, P., Ragossnig, A., 2021. Material passports for the end-of-life stage of buildings: challenges and potentials. J. Clean. Prod. 319, 128702. https://doi.org/10.1016/j.jclepro.2021.128702.

Hossain, S.T., Yigitcanlar, T., Nguyen, K., Xu, Y., 2024. Local government cybersecurity landscape: a systematic review and conceptual framework. Appl. Sci. 14 (13), 5501. https://doi.org/10.3390/app14135501.

Hosseini, Z., Laratte, B., Blanchet, P., 2023. Implementing circular economy in the construction sector: evaluating CE strategies by developing a framework. BioResources 18 (3), 4699–4722. https://doi.org/10.15376/biores.18.3.4699-4722.

Huynh-Xuan, T., Bui, N., Ngo-Thanh, T., Nguyen, D.T., Thi Binh, A.D., Le Thi Cam, H., 2024. Adopting construction 4.0 to promote sustainability in the Mekong Delta of Vietnam: a fuzzy delphi study. J. Ind. Prod. Eng. 41 (4), 380–396. https://doi.org/10.1080/21681015.2024.2315942.

Illankoon, C., Vithanage, S.C., 2023. Closing the loop in the construction industry: a systematic literature review on the development of circular economy. J. Build. Eng. 76, 107362. https://doi.org/10.1016/j.jobe.2023.107362.

Kamari, A., Kotula, B.M., Schultz, C.P.L., 2022. A BIM-based LCA tool for sustainable building design during the early design stage. Smart and Sustainable Built Environment 11 (2), 217–244. https://doi.org/10.1108/SASBE-09-2021-0157.

Kanagaraj, S., Thiyagarajan, H., Vasudevan, A., Moghul, M., 2022. Road map for implementing circular construction practices in India: an overview. Proc. Inst. Civ. Eng. Manag. Procure. Law 176 (4), 166–175. https://doi.org/10.1680/jmapl.22.00013.

Kazmi, Z.A., Sodangi, M., 2022. Modeling the constraints to the utilization of the internet of things in managing supply chains of off-site construction: an approach toward sustainable construction. Buildings 12 (3), 388. https://doi.org/10.3390/buildings12030388.

Khan, A., Sepasgozar, S., Liu, T., Yu, R., 2021. Integration of BIM and immersive technologies for AEC: a scientometric-SWOT analysis and critical content review. Buildings 11 (3), 126. https://doi.org/10.3390/buildings11030126.

Kim, M., Kim, Y.-W., 2024. Applications of blockchain for construction project procurement. Autom. Constr. 165, 105550. https://doi.org/10.1016/j.autcon.2024.105550.

Kokkalis, K., Konstantinidis, F.K., Koskinopoulou, M., Tsimiklis, G., Amditis, A., Frangos, P., 2025. RaapWaste: robot- and application-agnostic planning for efficient construction and demolition waste sorting. Sustainability 17 (16), 7293. https://doi.org/10.3390/su17167293.

Langston, C., Zhang, W., 2021. DfMA: towards an integrated strategy for a more productive and sustainable construction industry in Australia. Sustainability (Switzerland) 13 (16). https://doi.org/10.3390/su13169219. Article 9219.

Lee, H.J., Brell-Cokcan, S., 2023. Towards controlled semi-autonomous deconstruction. Constr. Robot. 7 (3), 253–263. https://doi.org/10.1007/s41693-023-00111-9.

Leising, E., Quist, J., Bocken, N., 2018. Circular economy in the building sector: three cases and a collaboration tool. J. Clean. Prod. 176, 976–989. https://doi.org/10.1016/j.jclepro.2017.12.010.

Li, Y., Sun, H., Li, D., Song, J., Ding, R., 2022. Effects of digital technology adoption on sustainability performance in construction projects: the mediating role of stakeholder collaboration. J. Manag. Eng. 38 (3), 04022016. https://doi.org/10.1061/(ASCE)ME.1943-5479.0001040.

Liu, Z., Liu, Y., Osmani, M., 2024. Integration of smart cities and building information modeling (BIM) for a sustainability oriented business model to address sustainable development goals. Buildings 14 (5), 1458. https://doi.org/10.3390/buildings14051458.

Maqbool, R., Saiba, M.R., Ashfaq, S., 2023. Emerging industry 4.0 and internet of things (IoT) technologies in the Ghanaian construction industry: sustainability, implementation challenges, and benefits. Environ. Sci. Pollut. Res. 30 (13), 37076–37091. https://doi.org/10.1007/s11356-022-24764-1.

Masyhur, R.T., Alias, A.H., Haron, N.A., Zulkafli, Z., 2024. A systematic review on green practices in the Malaysian construction industry: status, challenges, key motivations, rating systems and technology evolution. Energy Build. 320, 114550. https://doi.org/10.1016/j.enbuild.2024.114550.

Mesa, J.A., Fúquene, C.E., Maury-Ramírez, A., 2021. Life cycle assessment on construction and demolition waste: a systematic literature review. Sustainability (Switzerland) 13 (14), 7676. https://doi.org/10.3390/su13147676.

Minunno, R., O'Grady, T., Morrison, G.M., Gruner, R.L., Colling, M., 2018. Strategies for applying the circular economy to prefabricated buildings. Buildings 8 (9). https://doi.org/10.3390/buildings8090125. Article 125.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G., 2009. Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. PLoS Med. 6 (7), e1000097. https://doi.org/10.1371/journal.pmed.1000097.

Moshood, T.D., Rotimi, J.O., Shahzad, W., Bamgbade, J.A., 2024. Infrastructure digital twin technology: a new paradigm for future construction industry. Technol. Soc. 77, 102519. https://doi.org/10.1016/j.techsoc.2024.102519.

Najjar, M.K., Figueiredo, K., Evangelista, A.C.J., Hammad, A.W.A., Tam, V.W.Y., Haddad, A., 2022. Life cycle assessment methodology integrated with BIM as a decision-making tool at early-stages of building design. Int. J. Constr. Manag. 22 (4), 541–555. https://doi.org/10.1080/15623599.2019.1637098.

Nascimento, D.L.M., Alencastro, V., Quelhas, O.L.G., Caiado, R.G.G., Garza-Reyes, J.A., Rocha-Lona, L., Tortorella, G., 2019. Exploring industry 4.0 technologies to enable circular economy practices in a manufacturing context. J. Manuf. Technol. Manag. 30 (3), 607–627. https://doi.org/10.1108/JMTM-03-2018-0071.

Nasir, M.H.A., Genovese, A., Acquaye, A.A., Koh, S.C.L., Yamoah, F., 2017. Comparing linear and circular supply chains: A case study from the construction industry. Int. J. Prod. Econ. 183, 443–457. https://doi.org/10.1016/j.ijpe.2016.06.008.

Nilimaa, J., 2023. Smart materials and technologies for sustainable concrete construction. Dev. Built Environ. 15, 100177. https://doi.org/10.1016/j.dibe.2023.100177.

Oke, A.E., Aliu, J., Jamir Singh, P.S., Onajite, S.A., Kineber, A.F., Samsurijan, M.S., 2023. Application of digital technologies tools for social and sustainable construction in a developing economy. Sustainability 15 (23), 16378. https://doi.org/10.3390/su152316378.

Oke, A.E., Aliu, J., Onajite, S., Simeon, M., 2024. Success factors of digital technologies (DT) tools adoption for sustainable construction in a developing economy. Constr. Innov. 24 (4), 950–964. https://doi.org/10.1108/CI-08-2022-0207.

Omotayo, T., Tanyer, A.M., Deng, J., Kaima, A., Akponeware, A., Pekericli, M.K., Shikder, S., Ogunnusi, M., 2025. Advancing AI-powered BIM for circularity in construction in the UK and Turkiye: state-of-the-art review and capability maturity modelling. Buildings 15 (8), 1224. https://doi.org/10.3390/buildings15081224.

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A., 2017. Circular Economy: Measuring Innovation in the Product Chain. P. N. E. A, Agency.

Qazi, A.A., Appolloni, A., 2022. A systematic review on barriers and enablers toward circular procurement management. Sustainable Production and Consumption 33, 343–359. https://doi.org/10.1016/j.spc.2022.07.013.

Ramakrishna, S., Ngowi, A., Awuzie, B.O., 2020. Guest editorial. Built Environment Project and Asset Management 10 (4), 485–489. https://doi.org/10.1108/BEPAM-09-2020-164.

Rashidian, S., Drogemuller, R., Omrani, S., Banakar, F., 2023. A review of the interrelationships and characteristics of building information modeling, integrated project delivery and lean construction maturity models. Smart Sustain. Built Environ. 13 (3), 584–608. https://doi.org/10.1108/SASBE-10-2022-0236.

Regona, M., Yigitcanlar, T., Xia, B., Li, R.Y.M., 2022. Opportunities and adoption challenges of AI in the construction industry: a PRISMA review. J. Open Innov.: Technol. Mark. Complex. 8 (1), 45. https://doi.org/10.3390/joitmc8010045.

Rodrigo, N., Omrany, H., Chang, R., Zuo, J., 2023. Leveraging digital technologies for circular economy in construction industry: a way forward. Smart and Sustainable Built Environment 13 (1), 85–116. https://doi.org/10.1108/SASBE-05-2023-0111.

Rosayuru, H.D.R.R., Waidyasekara, K.G.A.S., Wijewickrama, M.K.C.S., 2022. Sustainable BIM based integrated project delivery system for construction industry in Sri Lanka. Int. J. Constr. Manag. 22 (5), 769–783. https://doi.org/10.1080/15623599.2019.1645263.

Rose, T., Makasi, T., Kajewski, S., Rashidian, S., 2025. Improving supply chain efficiency through traceability technology adoption in residential construction: a waste process approach. CIB Conferences 1, 104. https://doi.org/10.7771/3067-4883.2037.

Sadeghi, M., Mahmoudi, A., Deng, X., Luo, X., 2023. Prioritizing requirements for implementing blockchain technology in construction supply chain based on circular economy: fuzzy ordinal priority approach. Int. J. Environ. Sci. Technol. 20 (5), 4991–5012. https://doi.org/10.1007/s13762-022-04298-2.

Sajid, Z.W., Aftab, U., Ullah, F., 2024. Barriers to adopting circular procurement in the construction industry: the way forward. Sustain. Futures 8, 100244. https://doi.org/10.1016/j.sftr.2024.100244.

Saradara, S.M., Khalfan, M.M.A., Jaya, S.V., Swarnakar, V., Rauf, A., El Fadel, M., 2024. Advancing building construction: a novel conceptual framework integrating circularity with modified lean project delivery systems. Developments in the Built Environment 20, 100531. https://doi.org/10.1016/j.dibe.2024.100531.

Sebastian, R., 2011. Changing roles of the clients, architects and contractors through BIM. Eng. Constr. Archit. Manag. 18 (2), 176–187. https://doi.org/10.1108/09699981111111148.

Shashi, Centobelli, P., Cerchione, R., Ertz, M., Oropallo, E., 2023. What we learn is what we earn from sustainable and circular construction. J. Clean. Prod. 382, 135183. https://doi.org/10.1016/j.jclepro.2022.135183.

She, Y., Udawatta, N., Liu, C., Tokede, O., 2024. Circular economy-related strategies to minimise construction and demolition waste generation in Australian construction projects. Buildings 14 (8), 2487. https://doi.org/10.3390/buildings14082487.

Shi, Y., Xu, J., 2021. BIM-based information system for econo-enviro-friendly end-of-life disposal of construction and demolition waste. Autom. Constr. 125, 103611. https://doi.org/10.1016/j.autcon.2021.103611.

Shojaei, A., Ketabi, R., Razkenari, M., Hakim, H., Wang, J., 2021. Enabling a circular economy in the built environment sector through blockchain technology. J. Clean. Prod. 294, 126352. https://doi.org/10.1016/j.jclepro.2021.126352.

Shooshtarian, S., Maqsood, T., Caldera, S., Ryley, T., 2022. Transformation towards a circular economy in the Australian construction and demolition waste management system. Sustainable Production and Consumption 30, 89–106. https://doi.org/10.1016/j.spc.2021.11.032.

Singh, A.K., Kumar, V.R.P., 2024. Integrating blockchain technology success factors in the supply chain of circular economy-driven construction materials: an environmentally sustainable paradigm. J. Clean. Prod. 460, 142577. https://doi.org/10.1016/j.jclepro.2024.142577.

Singh, A.K., Kumar, V.R.P., Dehdasht, G., Mohandes, S.R., Manu, P., Pour Rahimian, F., 2023. Investigating the barriers to the adoption of blockchain technology in sustainable construction projects. J. Clean. Prod. 403, 136840. https://doi.org/10.1016/j.jclepro.2023.136840.

Siriwardhana, S., Moehler, R.C., 2023. Enabling productivity goals through construction 4.0 skills: theories, debates, definitions. J. Clean. Prod. 425, 139011. https://doi.org/10.1016/j.jclepro.2023.139011.

Spisáková, M., Mandicák, T., Mésáros, P., Spak, M., 2022. Waste management in a sustainable circular economy as a part of design of construction. Appl. Sci.-Basel 12 (9), 19. Article 4553. https://doi.org/10.3390/app12094553.

Sudarsan, J.S., Gavali, H., 2024. Application of BIM in conjunction with circular economy principles for sustainable construction. Environ. Dev. Sustain. 26 (3), 7455–7468. https://doi.org/10.1007/s10668-023-03015-4.

Talla, A., McIlwaine, S., 2024. Industry 4.0 and the circular economy: using design-stage digital technology to reduce construction waste. Smart Sustain. Built Environ. 13 (1), 179–198. https://doi.org/10.1108/sasbe-03-2022-0050.

Teisserenc, B., Sepasgozar, S., 2021. Project data categorization, adoption factors, and non-functional requirements for blockchain based digital twins in the construction industry 4.0. Buildings 11 (12), 626. https://doi.org/10.3390/buildings11120626.

Torgautov, B., Zhanabayev, A., Tleuken, A., Turkyilmaz, A., Mustafa, M., Karaca, F., 2021. Circular economy: challenges and opportunities in the construction sector of Kazakhstan. Buildings 11 (11). https://doi.org/10.3390/buildings11110501. Article 501.

Turk, Ž., García de Soto, B., Mantha, B.R.K., Maciel, A., Georgescu, A., 2022. A systemic framework for addressing cybersecurity in construction. Autom. Constr. 133, 103988. https://doi.org/10.1016/j.autcon.2021.103988.

Ullah, F., Olatunji, O., Qayyum, S., 2024. A scoping review of green internet of things in construction and smart cities: current applications, adoption strategies and future directions. Smart and Sustainable Built Environment. https://doi.org/10.1108/sasbe-11-2023-0349.

van der Heijden, J., 2023. Construction 4.0 in a narrow and broad sense: a systematic and comprehensive literature review. Build. Environ. 244, 110788. https://doi.org/10.1016/j.buildenv.2023.110788.

Voorter, J., Koolen, C., 2021. The traceability of construction and demolition waste in Flanders via blockchain technology: a match made in heaven? Journal for European Environmental & Planning Law 18 (4), 347–369. https://doi.org/10.1163/18760104-18040003.

Wang, X., Ma, D., 2024. Smart city landscape architecture for sustainable urbanization in digital twin: practical sustainable and reliable renewable based smart cities energy hub development. Sustain Energy Technol Assess 65, 103785. https://doi.org/10.1016/j.seta.2024.103785.

Waqar, A., Othman, I., Hayat, S., Radu, D., Khan, M.B., Galatanu, T.F., Almujibah, H.R., Hadzima-Nyarko, M., Benjeddou, O., 2023. Building information modeling—empowering construction projects with end-to-end life cycle management. Buildings 13 (8). https://doi.org/10.3390/buildings13082041. Article 2041.

Xu, L., Jia, F., Yan, F., Chen, L., 2022. Circular procurement: A systematic literature review. J. Clean. Prod. 365, 132845. https://doi.org/10.1016/j.jclepro.2022.132845.

Yevu, S.K., Yu, A.T.W., Darko, A., 2021. Digitalization of construction supply chain and procurement in the built environment: emerging technologies and opportunities for sustainable processes. J. Clean. Prod. 322, 129093. https://doi.org/10.1016/j.jclepro.2021.129093.

Yu, Y., Yazan, D.M., Junjan, V., Iacob, M.-E., 2022. Circular economy in the construction industry: a review of decision support tools based on Information & Communication Technologies. J. Clean. Prod. 349, 131335. https://doi.org/10.1016/j.jclepro.2022.131335.

Yuan, H., Du, W., Zuo, J., Ma, X., 2024. Paving a traceable green pathway towards sustainable construction: a fuzzy ISM-DEMATEL analysis of blockchain technology adoption barriers in construction waste management. Ain Shams Eng. J. 15 (4), 102627. https://doi.org/10.1016/j.asej.2024.102627.

Zandee, D., Zutshi, A., Creed, A., Nijhof, A., 2024. Aiming for Bullseye: a novel gameplan for circular economy in the construction industry. Eng. Constr. Archit. Manag. 31 (2), 593–617. https://doi.org/10.1108/ECAM-03-2022-0288.

Zhang, Q., Liu, C., Zhu, W.H., Mei, S.Q., 2024. Demystifying the influencing factors of construction 4.0 technology implementation from a sustainability starting point: current trends and future research roadmap. Buildings 14 (2), 26. Article 552. https://doi.org/10.3390/buildings14020552.

Zoleykani, M.J., Abbasianjahromi, H., Banihashemi, S., Tabadkani, S.A., Hajirasouli, A., 2024. Extended reality (XR) technologies in the construction safety: systematic review and analysis. Constr. Innov. 24 (4), 1137–1164. https://doi.org/10.1108/CI-05-2022-0131.

Zubair, M.U., Ali, M., Khan, M.A., Khan, A., Hassan, M.U., Tanoli, W.A., 2024. BIM- and GIS-based life-cycle-assessment framework for enhancing eco efficiency and sustainability in the construction sector. Buildings 14 (2), 360. https://doi.org/10.3390/buildings14020360.