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Enhancing building material circularity: A systematic review on prerequisites, obstacles and the critical role of data traceability

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ABSTRACT

The construction industry significantly consumes natural resources and generates substantial waste due to linear supply chain practices. Circular economy strategies are essential for extending material lifespans and promoting regeneration. Material reclamation is a central strategy for implementing circularity, yet its practical application remains limited. The purpose of this research is to identify the factors hindering building material circularity and propose measures to overcome them. This paper aims to explore the prerequisites and obstacles to material reclamation in the construction industry to foster its transition into a circular economy. A systematic literature review of 74 papers was conducted using data from Scopus, Google Scholar, IEEE Xplore, and Web of Science, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses guidelines. The review identified eight key themes related to achieving material circularity, with design, informational, and technological factors receiving top priority in researchers' focus. Data availability emerged as a critical prerequisite, while the primary obstacle is the lack of data traceability throughout the building materials' lifecycle. This study concludes that digitalizing the material supply chain can address data unavailability and most of the identified obstacles. Ultimately, comprehensive material data will support the stakeholders in making solid circular decisions. This research provides guidance to construction industry stakeholders to overcome recognised obstacles and promote essential prerequisites of material circularity where no such information currently exists, to facilitate the transition to a circular construction industry.

1. Introduction

The construction sector stands as the world's largest consumer of raw materials, accounting for over 40 % of global reserves utilisation [2,3] concurrently generating approximately 40%–50 % of solid waste [4–6] and contributing to 30%–40 % of CO_2 emissions [7–10]. The construction industry consumes approximately 60 % of aggregates, such as sand and gravel, and 20 % of metals [11]. According to a report by the United Nations Environment Programme [12], "Building Materials and the Climate: Constructing a New Future", the built environment consumes 38 % of the world's wood products. Concrete is the most-used material in the building sector, and over the past 65 years, its use has increased tenfold, compared to a threefold increase in steel and near-stagnant growth in timber. Steel is the second most abundant material in buildings [12]. Additionally, according to that report, approximately 27 % of all aluminium products are used in buildings and construction. Despite this immense consumption, only 20–30 % of resources are reused

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or recycled during the demolition phase of the projects [13]. Consequently, over 90 % of construction waste originates from demolitions [2,14]. For instance, despite the demolition of approximately 2.5 billion bricks annually, only 5 % are reused, according to statistics in the United Kingdom [11]. Steel is typically reused only when it is more economical than selling it as scrap. Around 20 %–30 % of construction and demolition (C&D) waste is attributed from timber, with only 10 %–15 % of used timber undergoing recycling [15]. Similarly, most C&D waste, such as glass, metal, plastic, mechanical, electrical, and plumbing materials, are disposed of after their first use without any benefit from reclaiming.

Even though many building materials hold the potential for reuse or recycling, this potential often goes unrealised due to the prevailing linear supply chain practices in the construction sector [2]. The traditional linear economic model of "take, make, and dispose" frequently leads to the disposal of materials at the end of their life cycle, squandering their potential for reuse. This substantially threatens the environment, leading to natural resource depletion, waste proliferation, public health risks, biodiversity loss, and air and water pollution [16,17]. Hence, reconsidering conventional linear practices has become imperative for the construction industry to align with sustainability goals. In response, the Circular Economy (CE) has emerged as a novel economic paradigm for achieving better resource management [3]. The CE emphasises a circular supply chain by prioritising “3R’s principles”: reduction, reuse, and recycling, in that order [14,18,19]. The Ellen MacArthur Foundation (EMF) defined CE as a regenerative system striving to minimise new resource use, energy loss, and waste by effectively closing material and energy loops [20]. Implementing CE practices yields environmental benefits by reducing the consumption of energy and virgin materials, waste generation, and $CO2$ emissions. Additionally, it offers economic benefits by lowering raw material costs, waste management expenses, and environmental legislation compliance costs [14].

Reclaiming material is a central strategy within the CE framework for addressing environmental footprints [4,21,22]. Achieving this involves reusing, sharing, leasing, repairing, refurbishing, upcycling, and recycling building materials or components [23] through advanced design options [24], improved designs of building materials, extending the life of buildings or materials, and enhanced recycling capabilities [23]. Material reclamation can help to overcome waste generation challenges like ecological decline and limited resources [16], and reduce environmental and economic costs [25] by considering waste, by-products, and emissions as raw materials and nutrients for a new production cycle [26]. Material reclamation within the construction industry offers significant potential for minimising resource value loss and reducing raw material consumption. However, the decision to reclaim depends on several prerequisites [17]. When building materials fail to meet these prerequisites, disposal to landfills is often chosen at the end of life (EOL) [27].

Despite two decades of discussion on circularity, practical implementation of this concept in the construction sector remains minimal due to various obstacles. Although building materials have circular potential, the absence of codes and standards for reused materials in the construction industry poses a challenge, leaving designers uncertain about handling secondary materials in new constructions [11]. Additionally, the high costs associated with processing materials to create secondary materials [28] and the absence of stringent legislation hinders material circularity in numerous countries. Hence, it is acknowledged that numerous barriers exist to material reclamation despite the circular potential of building materials. Consequently, material reclamation is not currently practiced to a considerable extent. Several studies have investigated the drivers and barriers for implementing circularity in the construction sector within the broader context of the CE [29–33]. However, practical applications of circular strategies in the construction sector are very limited in most countries due to the lack of structured processes for using secondary materials in subsequent life cycles [2]. This highlights the existing need for research to develop standardised practices for reclaiming building materials that can be adopted by the construction industry. Furthermore, the unavailability, inaccessibility, and low quality of material data impede the development of standardised methods for material reclamation and hinder the understanding of future material reuse opportunities [34]. Therefore, this research aims to identify the obstacles and prerequisites for material circularity, providing a foundation for implementing circular practices in the construction sector with the goal of developing a structured method for reclaiming building materials.

Thus, this scholarly article embarks on a systematic literature review (SLR) to expose the prerequisites that drive circularity and the obstacles that hinder material circularity in the transition toward a CE paradigm. This paper aims to bridge this gap by identifying critical factors influencing the achievement of circularity in building materials and finding out the most applicable solution to overcome identified obstacles. The structure of this journal paper comprises six distinct sections: Section 2 outlines the SLR methodology, while Sections 3 and 4 present descriptive and content analysis results, respectively. Section 5 delves into a detailed discussion of the findings, and finally, Section 6 summarises the main findings and encapsulates the paper’s conclusion.

2. Research methodology

This section emphasises the current state of research on material circularity through a SLR. Xiao and Watson [35] explained that a literature review can enhance the existing knowledge and facilitate the development of new theories by identifying the boundaries and gaps in existing studies.

2.1. Systematic literature review

Providing a critical overview of previously published studies through a pre-planned or structured method by evaluating the studies quantitatively and qualitatively is a crucial feature of the SLR [36]. It is indeed a viable method for conducting a comprehensive search of scientific publications [18]. Furthermore, the SLR helps synthesise existing knowledge related to the formulated research questions, reduce bias, and identify directions for future research [35,37]. Tranfield et al. [38] outlined the process of conducting an SLR, which includes planning, executing, and reporting the review results.

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) is a guideline that facilitates the systematic review process [1]. This enables the generation of evidence-based outcomes through a rigorous and transparent literature evaluation. PRISMA is the commonly used data analysis method in SLR [36]. The use of PRISMA guidelines ensures transparency, reproducibility, and reduced bias [39]. Additionally, it facilitates the use of snowballing methods, enabling a more comprehensive review of existing research studies related to the formulated research questions [40]. Most cited articles in the domain of construction and CE, such as those authored by Benachio et al. [2], Chen et al. [18], have employed the PRISMA guideline to systematically review their research studies. Therefore, the same foundational guideline was employed to steer this research endeavour. Following the approach taken by Chen et al. [18], this study collects relevant articles related to the ongoing discussions on CE strategies, with a primary focus on building materials. These papers have been sourced from the Scopus, Google Scholar, IEEE Xplore, and Science Direct databases. Utilising different databases and various search engines can mitigate bias while granting access to articles from prominent research publishers [41]. The search criteria follow the principles of Boolean logic, which involves linking the chosen keywords using "AND" and "OR" connectors. The specific keywords designated for this research are detailed in Table 1.

The preliminary exploration was conducted within the Scopus database, using its advanced search capabilities and diverse filtering options. The defined search parameters were focused on the fields of Engineering, Environmental Science, and Material Science, aligning seamlessly with the research's scope. Only research papers in English were considered to ensure coherence, establishing a unified foundational base for the study. For precision, the publication time frame was set to encompass the past 20 years, ensuring a concentrated focus on recent research endeavours. Notably, according to the Scopus database, all publications pertinent to the research subject fall within this designated timeframe, showing them up to date as of December 2023. The search was confined to peer-reviewed journal papers and conference papers to ensure the quality of the sources, deliberately excluding any relevant books and review papers. The relevance of the articles was assessed based on the research question, "What are the prevailing obstacles and prerequisites for material circularity to implement the CE in the construction sector?". Articles discussing building material circularity that were peer-reviewed or part of conference proceedings were selected as authentic data sources. Review papers were eliminated to avoid any probable bias, as their literature heavily depends on the findings of other research articles [41]. Additionally, review papers were omitted to prevent the repetition of themes that may arise from including secondary sources and to ensure that this SLR focuses on the primary research studies that provide first-hand findings. After applying the defined search string and relevant filtering process, 321 documents were yielded from the Scopus database. The identical procedure was replicated across the Science Direct database, Google Scholar, and IEEE Xplore, identifying a cumulative total of 411 articles during the initial search phase. These articles were subsequently subjected to a meticulous refinement process, as depicted in the flowchart in Fig. 1, in adherence to the PRISMA guidelines.

Among the 411 retrieved articles, 73 duplicates were eliminated. An initial screening was conducted to assess the relevance of the articles based on factors such as the titles, abstracts, and authors' keywords. After the initial screening, 254 articles were excluded due to their lack of alignment with the research topic. Papers unrelated to construction materials or waste, such as those centred on mining, agricultural, and quarry waste, and strategies for recycling or reusing non-construction materials were omitted from consideration. Additionally, papers primarily focused on technical properties and structural aspects within the domain of material science were excluded. Finally, unfiltered review papers from the automated filtering process were manually excluded. These review papers primarily focused on the circularity assessment methods, the relevance of the CE to the UN Sustainable Development Goals, technical analyses of circular product manufacturing, and the general challenges and opportunities for implementing circular strategies in the construction sector. As a result, six review papers were excluded due to the irrelevance of their findings to this study, as none of them specifically addressed material circularity or provided first-hand data. Upon the culmination of the initial screening process, 84 articles that presented challenges in terms of determination solely from their titles and abstracts were advanced for further evaluation by thoroughly reading the full texts to gauge their quality. During the quality assessment, 84 papers were thoroughly read to ascertain their relevance to the research topic. After a comprehensive review of selected papers from the initial set, 37 papers were excluded: 36 were unrelated, and 1 remained inaccessible. Later, the authors implemented an iterative snowball sampling process to identify additional relevant papers beyond the initial set of 411. Backward snowballing was employed to trace references of selected papers to proceed with the full-text analysis, while forward snowballing involved reviewing citations to uncover the most recent publications in the research area [42]. This process continued until no further relevant papers were identified. 27 supplementary papers were identified through the snowballing method and included in this evaluation. In conclusion, 74 papers were considered for content analysis in the SLR.

Table 1
Defined keywords for the search criteria.

Article Title/Abstract/Keywords						
"circular econom*" OR "circular design"	**AND**	"building material*" OR "building component*" OR "construction material*"	**AND**	prerequisite* OR driver* OR requirement* OR condition* OR precondition* OR requisite* OR strateg*	**OR**	obstacle* OR barrier* OR hinder* OR challeng*

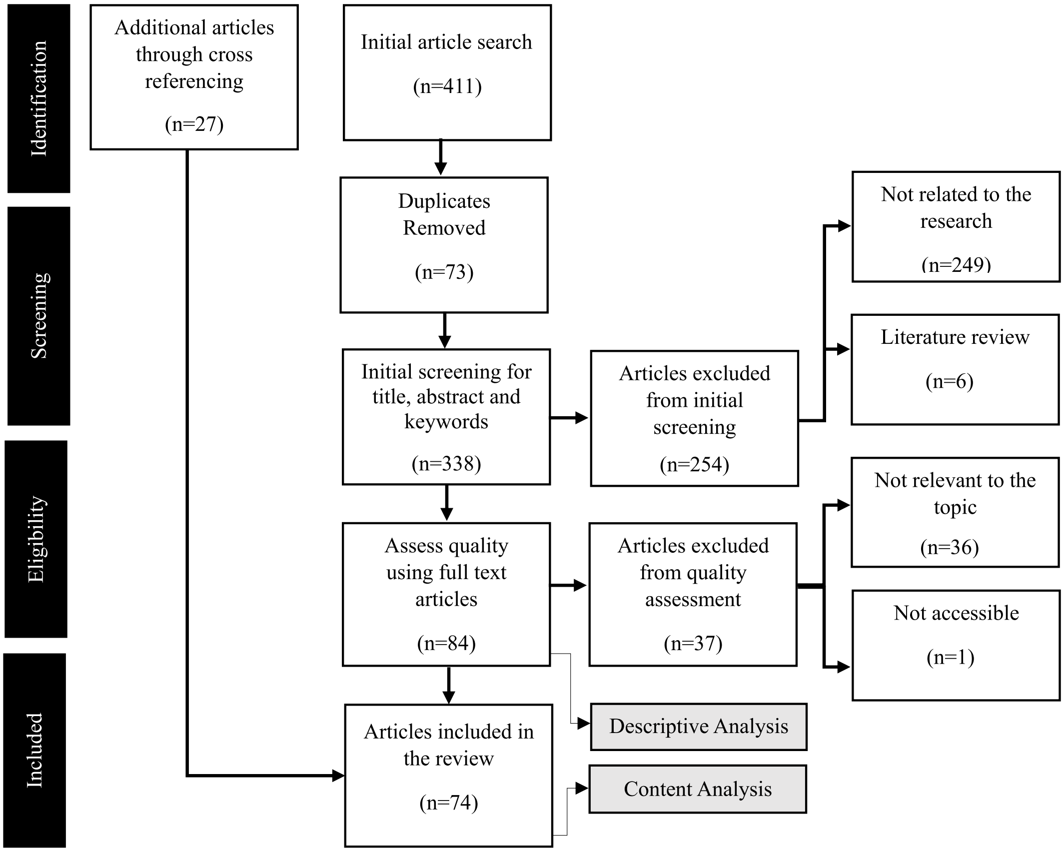

Fig. 1. Refinement Process based on PRISMA guideline (adapted from Moher et al. [1]).

2.2. Descriptive analysis

Serving as a rigid foundation for the SLR and as a substructure for the content analysis [as cited by 41], a descriptive analysis was carried out through bibliometric analysis. Within the descriptive analysis, the evolution of the term "building material circularity" was scrutinised across various dimensions, including publication year, authors' keywords, article source, and geographical distribution. The 84 articles filtered from the initial screening process were utilised for the quantitative analysis. The results of the descriptive analysis are presented in Section 3.

2.3. Content analysis

This research segment delves into a comprehensive content analysis of the data extracted from selected articles, which is a pivotal step in the systematic review. Following qualitative research principles, data analysis was conducted concurrently with data collection to refine the research direction and identify emerging themes [36]. Selected articles were reviewed in full text to identify factors impeding the reclamation of building materials for extended life cycles. Concurrently, prerequisites for building material reclamation were also identified. The extracted data were systematically coded using NVivo qualitative data analysis software under two major categories: obstacles and prerequisites of building material circularity. The identified factors within each category were then thoughtfully organised into relevant themes, including design, economic, quality, informational, social, technological, risk, and regulatory aspects. The selected articles were analysed in a transparent, repeatable, and consistent manner, identifying and coding additional factors into existing or new themes. The identified prerequisites and obstacles for attaining building material circularity have been elucidated in sections 4.1 and 4.2, respectively.

3. Results of descriptive analysis

3.1. Annual trend of publications

The tendency of reclaiming building materials was examined by analysing the number of publications per year within the selected articles. Articles included in the quantitative analysis are scattered from 2014 to 2023 (as of December 2023), showcasing a consistent rise in publications from 1 in 2014 to 24 in 2021. According to Fig. 2, up until 2019, the articles published per year were less than 10. However, with the advent of the 21st century, it surged to 12, 24, and 21 in the years 2020, 2021, and 2022, respectively. These data show that material circularity has become a prominent subject in construction and architecture. Scholars are actively researching new ideas to achieve circularity, which is evident from the shift from 15 % (13 out of 84) of publications before 2020 to 85 % (71 out of 84) afterward. Moreover, the cumulative total of 14 publications from 2023 until December further accentuates the sustained upward trajectory of research within the construction industry.

3.2 Research trend using co-occurrence of author's keywords.

The authors identified key research trends in the CE within the built environment by analysing the co-occurrence of authors' keywords. As shown in Fig. 3, the co-occurrence of authors' keywords from the 84 selected articles was visualised using VOS viewer software. The resulting keyword network illustrates how CE research is interconnected and organised [43]. To ensure clarity and focus on the most relevant terms, a minimum occurrence threshold of three was set. This analysis revealed five key research clusters related to the CE. The first cluster (blue) highlights the implementation of CE through waste management strategies, such as recycling, recovery, and reuse. The second cluster (red) focuses on applying CE principles in the construction industry, particularly in the building sector. Cluster three (yellow) emphasises the importance of life cycle costing and life cycle assessment in the context of CE. Cluster four (purple) underscores the strong relationship between CE and building materials. The fifth cluster (green) highlights C&D waste management strategies, such as design for disassembly, urban mining, and material reuse, as essentials for implementing CE. Additionally, Fig. 3 shows the most frequently occurring keywords within each cluster and the number of links between them and other keywords. The keyword analysis reveals a significant lack of research on material circularity or reclamation, highlighting a clear gap in this area due to its minimal occurrence and limited connections in the network.

3.2. Geographical distribution

According to the analysis, the Netherlands emerges as a leading contributor to the research concept of "building material circularity", boasting the publication of 14 relevant articles. Denmark, the United Kingdom, and Italy closely follow the suit, with 10,9 and 7 articles, respectively. Brazil and Australia occupy the fourth and sixth positions, contributing 6 and 5 articles on the subject matter (refer to Fig. 2). In summation, the geographical distribution of articles around the circularity concept in construction predominantly spans countries within the EU, while other nations are in nascent stages of exploration.

3.3. Prominent publishers

Publishers who display the most significant engagement in the research domain were identified through the journal titles in which the selected articles were published. Foremost among them is the Journal of Cleaner Production, which has published 10 articles in this area. Additionally, Sustainability and Resources, Conservation and Recycling contributed 9 and 8 articles, respectively, signifying their considerable interest in circularity. Buildings, Journal of Construction Engineering and Management, Waste Management, and Waste Management and Research have each contributed 3 articles on the subject. The analysis of prominent publishers reveals a clear trend: journals associated with energy, environmental science, and sustainability play a dominant role in contributing to research on circular construction.

4. Results of content analysis

4.1. Prerequisites for material circularity

The list of prerequisites driving the shift towards circular building materials which discerned through an extensive analysis of multiple studies, is expounded upon in this section. These requirements cover the entire spectrum of the building materials supply

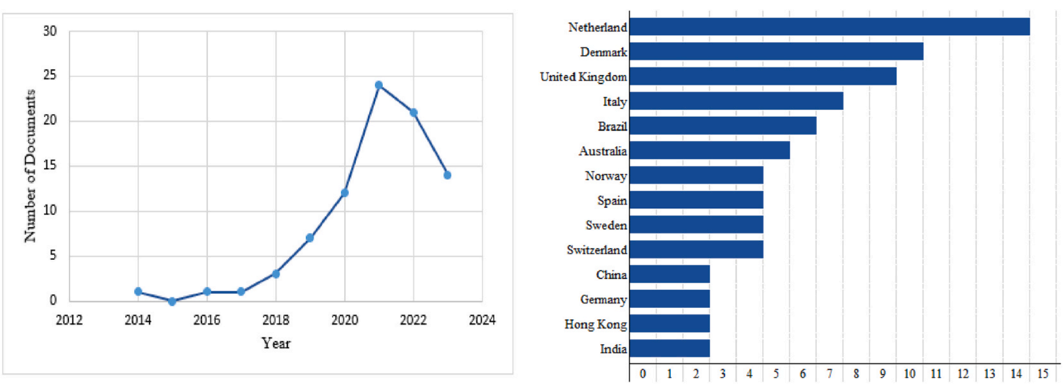

Fig. 2. Distribution of documents by year and geographical locations.

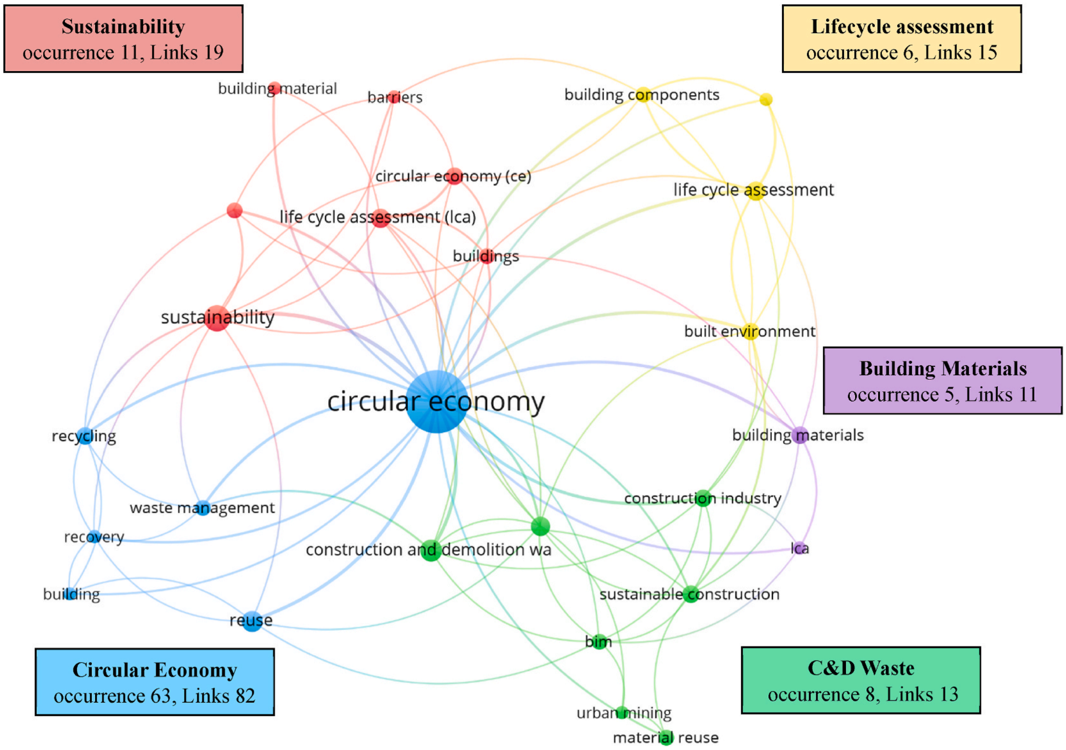

Fig. 3. Frequency of authors' keywords (Generated through VOS Viewer).

chain, from the initial production and design stages to the EOL. The identified prerequisites (*emphasised in bold*) are categorised into eight distinct themes: design, economical, quality and performance, information, social and behavioural, technological, risk and uncertainty, and regulatory.

4.1.1. Design

Circularity of the building materials should be initiated from the beginning of the design process through improved design strategies [24]. Adhering to the waste hierarchy, prioritising the reuse of building materials emerges as a pivotal principle [21]. Consequently, **reusability** is a prerequisite for achieving material circularity, enabling their incorporation into new construction projects with minimal alterations to their original form [27,44,45]. Building materials should be designed for durability and prolonged life cycle to allow for reuse across multiple cycles within a closed loop [23]. Thus, a material's durability and longevity directly correlate with its increased reusability, and a prolonged lifespan enables these materials to benefit multiple users [46,47]. A cornerstone strategy of the CE concept of "slowing" can be achieved by designing for an extended material life [48], which reduces waste generation by optimally using materials throughout their lifecycle [23,49].

Design for recycling is the next best alternative to non-reusability [50]. Designing for resource cycle closure can take two distinct paths: a biological cycle, where materials are designed for retention in the natural cycle using processes like biodegradation, and a technical cycle, where materials are maintained within a closed loop via technical methods like recycling [6,51]. Therefore, for materials to truly function within a circular framework, they should possess both **recyclability** [6,8,44–46,52] and biodegradability [6,21] characteristics. According to Knoth et al. [21], materials designed for biodegradability have safe and healthy features and can be used as compost at their EOL once they can no longer be utilised in construction [6]. Opting for materials with higher recyclability or biodegradability in construction promotes circularity at the project's EOL. Moreover, Antwi-Afari et al. [53] highlighted that materials with higher **recycled content** have higher circularity, which could be addressed at the material production phase.

In building design, toxic or environmentally unsafe materials should be avoided as part of a CE strategy [9]. By prioritising **non-toxic** construction materials, toxic waste at C&D phases can be eliminated [6,54]. According to Bertino et al. [50], where avoidance is impossible, such materials should be labelled and documented to facilitate easy traceability and ensure they are handled with utmost care at their EOL. **Maintainability** and durability are the foremost strategies in the CE concept to slow the resource loop [45,51]. Designing for effortless repair and maintenance significantly extends the lifespan of building materials, preventing their premature disposal due to minor damages or faults [9]. Numerous scholars advocate for the **adaptability and flexibility** of materials, components, and buildings as a CE strategy [2]. Adaptability transforms discarded materials or products for repurposing for alternative functions, thereby prolonging their lifespan [8]. Flexibility, on the other hand, entails seamless adjustment to new cycles with minimal alterations. Nian et al. [5] cited that the combined attributes of flexibility and adaptability of materials facilitate their reuse for different purposes, a term known as adaptive reuse.

Design for Disassembly (DfD) stands out as a prominently addressed CE strategy within the construction industry [6,55–58]. It aims to protract the life cycle of building materials through reuse and recycling [59]. A core feature of DfD involves the seamless separation of materials from the building at any stage and throughout its life cycle [60], allowing for future repair, reuse, adaptive reuse of the building, and incorporation of reclaimed materials into new construction projects [51]. **Ease of disassembly** offers numerous opportunities for building materials to have a second life, maintaining higher quality and minimising damages during the disassembly process [45,50,61,62]. As Talla and McIlwaine [23] highlighted, "**Design for Deconstruction**" streamlines disassembly and material recovery. Embracing this strategy ensures that building materials can be systematically dismantled, facilitating material circularity by enabling future reuse, repurposing, or recycling [9,50,63]. While reclaimed materials from building deconstruction and disassembly are readily accessible, stakeholders have pointed out potential challenges in incorporating these old materials into new construction due to size variations [46]. Therefore, adopting **modularity and standardisation** in manufacturing building materials and components [44,51,57], shaping them into standardised forms, facilitates the repeated utilisation of these materials [46,64]. Nian et al. [5] stated that modularisation creates a pathway for standardisation, promoting material circularity by reducing design constraints stemming from material variations and enabling repeated use of standardised materials [4,65].

Resource consumption can be limited by **improving manufacturing efficiency and the design** process [23], thereby enhancing the reusability of building components [60]. Mhatre et al. [9] concluded their research study by highlighting the material circularity potential through material management, such as **material substitution**. Material substitution involves replacing virgin materials with waste from other industries [7] or reusing secondary materials to produce building materials [55], as exemplified by using reclaimed glass in cement production. **Dematerialisation**, which entails designing with fewer resources [51], such as constructing buildings without unnecessary finishing materials to minimise the resource loop, and **product stewardship**, which shares responsibility for the environmental impact of a product among stakeholders throughout its lifecycle [5], are recognised as critical prerequisites for achieving circularity.

4.1.2. Economical

The economic viability of secondary materials and financial incentives are recognised as essential economic prerequisites for the transition to material circularity, as emphasised in various studies. Nuβholz et al. [66] proposed that a price alignment strategy between secondary and virgin materials can promote circularity in building materials. Li et al. [25] asserted that the profitability of recycling plays a pivotal role, and material circularity can be improved when the economic cost of secondary materials falls within a similar range as the cost of virgin materials [5,67]. Government **financial incentives or subsidies** within the supply chain can encourage material circularity. These incentives may include support for innovative manufacturers who embrace circular business models [21], reduced fees or lower loan interest rates for builders and buyers of zero-waste buildings [68], encouragement for demolition contractors engaged in deconstruction [27], rewards for firms involved in recycling material collection [69], subsidies for developing material recovery units, support for the development of secondary markets, and funding for research and technology advancement [9].

4.1.3. Quality and performance

Ensuring the quality and performance of reclaimed materials is paramount for eliminating consumer suspicions [25] and overcoming reluctance to buy secondary materials [21]. Thus, the availability of **standards and certification** for reclaimed materials is a prerequisite for achieving material circularity [48]. Hence, suppliers' capacity to furnish certifications and assurances, including test results and environmental certificates, can stimulate demand for secondary materials [7,70]. The **performance of the secondary material** plays a vital role in circularity [71] when it possess requisite use-value and quality to attract consumers [48]. Providing comprehensive information on quality [27,72] through guarantees, insurance, and certificates [48] can build the buyer's confidence in the product's usability [46].

4.1.4. Informational

Leising et al. [73] and Andersen et al. [74] stated that effective information management across the material lifecycle is pivotal for advancing the transition to a circular construction industry. **Collaboration** fosters communication among professionals and processes within projects, with the common goal of collectively achieving circularity [23]. **Information sharing** and collaboration can be enhanced using information-sharing technologies [72,75,76]. Through collaborative efforts and improved information exchange, circularity can be advanced by developing innovative approaches and technologies and leveraging available data [4,49]. Kovacic et al. [10] and Linares et al. [77] emphasised the role of LCA as a critical approach in the transition to a CE. LCA enables comprehensive analysis of material flows throughout the lifecycle, facilitating environmental impact evaluation and optimisation [as cited by 10, 57] and CE decision-making [59].

Material **data availability and traceability** are prime prerequisites for making circularity decisions at a product's EOL [34,75,78–81]. The importance of data traceability in construction research is underscored, and it is directly related to all the prerequisites discussed here. Talla and McIlwaine [23], Dräger et al. [82] cited that material information should be stored centrally, in a digital format with transparency and traceability. Data on existing material stock promotes circularity, aids successful disassembly and deconstruction [50], and fosters higher reuse and recycling rates [25,55]. Moreover, data availability reduces uncertainty, preventing environmentally damaging decisions like landfilling hazardous materials without processing [34]. Tracking building assets enhances supply chain transparency, reduces resource consumption in daily tasks, extends asset lifespan, and facilitates reuse and recycling [10,34]. Detailed data such as material origin, properties, and status drive demand for reclaimed materials [48]. Data traceability relies on material tracking technologies [51], and digital information management platforms [65] such as Building Information Modelling

(BIM), material passport, Internet of Things (IoT) and blockchain technology.

4.1.5. Social and behavioural

Although the concept of material circularity has been extensively addressed in the theoretical background, its application in the construction sector is hindered by prevailing **awareness gaps and entrenched traditional practices** [72]. Over recent years, several prominent international organisations, including the EMF, the European Green Building System, and the Building Research Establishment Environmental Assessment Method, have played significant roles in promoting CE [51]. Achieving circularity necessitates widespread education of all supply chain stakeholders through training programs, integrating CE into university curricula [51], educating designers on material replacement criteria [9], improving international cooperation for studying new systems [15], and conducting public awareness campaigns to shift behaviours and mindsets [25,48]. Market formation and demand are pivotal factors in driving material circularity [23,79,83], serving as fundamental prerequisites for effectively utilising reclaimed products [48]. When a thriving market and demand for secondary materials are in place, principles of CE, including efficient C&D waste management [as cited by 72], recycling initiatives [25], building deconstruction, and the production of more durable goods, can be significantly bolstered and advanced [60].

4.1.6. Technological

Established infrastructure, such as integrating advanced technologies into every facet of the supply chain infrastructure, is pivotal in fostering material circularity [7,8]. Researchers have identified several main prerequisites for achieving this goal, including product optimisation through automation technologies [46], setting up reuse infrastructure that enables easy access to and ordering secondary materials [21], enhancing the production process [66], and developing technologies to facilitate material recirculation [9]. Adopting these technologies not only ensures higher quality by reducing defects in production and construction [7], but also leads to an increased recycling rate and the creation of innovative materials that promote greater circularity [84].

In addition to technological advancements, **innovative approaches to reusing and recycling**, such as "pay-per-use" and "product-as-a-service" models, where material ownership remains with the supplier [46], "take-back" programmes facilitated by manufacturers for remanufacturing or reusing while retaining ownership and maintenance responsibility [51] and "rent to buy" options that allow consumers to rent products for a specified period and return them for reusing or recycling [85], are instrumental in elevating material circularity through extending the life of materials within a closed-loop system. Moreover, they recognised that the **pilot projects** benefit the stakeholders by familiarising them with circular driven reuse practices and processes.

Many scholars recognised the pivotal role of **digitalisation** in expediting the transition towards circular construction materials and waste recycling [23,62,76,81,86,87]. They have highlighted how digital technology can revolutionise various facets of the construction process by enhancing stakeholder communication and collaboration. Digitalisation of the construction industry will enable database management for both existing and new buildings for establishing comprehensive material inventories that promote circularity. It will also facilitate a digital marketplace for secondary materials [21], predict and optimise future waste generation [10], foster information sharing on material resources and their life cycle data through digital tracking platforms [8] and enhance data traceability [34] in the construction sector.

4.1.7. Risk and uncertainty

Implementing a new concept like material circularity into the conventional construction industry can introduce a range of risks associated with cost, time, technology, regulation, and design. Consequently, there is a notable reluctance among crucial stakeholders, especially designers, manufacturers, builders, and consumers, to fully embrace CE principles [16]. Reusing building materials remains entangled with substantial risks such as financial perspectives, documentation issues, material availability, and sourcing [21]. Thus, risk sharing among all stakeholders will minimise the **risk and uncertainty** in driving circular construction.

4.1.8. Regulatory and legal

Torgautov et al. [46] and Dervishaj et al. [76] stated that a country's **regulatory and legal** framework has significant potential to push its economy and social behaviour to facilitate material circularity. Specifically, the construction sector can attain material circularity by embracing regulations that promote circular practices. The government should consider providing tax incentives for circularity-focused projects, establishing development manuals and guidelines for CE-oriented construction, implementing comprehensive C&D waste management plans that prioritise reuse and recycling, imposing higher taxes on landfills, integrating CE principles into building codes, and encouraging companies to adopt digital tools such as BIM [7, as cited by 21, 51, 57, 69, 72, 83, 88]. Notably, the primary regulatory and legal prerequisites for achieving greater material circularity include raising taxes on virgin materials, increasing taxes for new construction while lowering taxes on adaptive reuse, promoting construction regulations that facilitate material reuse, providing tax relief for companies that promote reusing and recycling, setting ambitious recycling targets, and establishing regulations for maintaining a registry and sharing information on secondary materials [9,10,27,51,72].

4.2. Obstacles for materials circularity

In the second phase of content analysis, obstacles hindering the achievement of material circularity were identified. Themes derived for prerequisites of material circularity are utilised for this section and identified obstacles (*emphasised in bold*) within the context of each theme, resulting in a comprehensive and in-depth analysis.

4.2.1. Design

According to Cruz Rios et al. [51] the traditional mindset prevents the separation of materials because buildings and products are made to be strong enough and are intended to last a lifetime. As per Torgautov et al. [46], adhesive or "wet" joints pose a serious obstacle to material circularity, making reuse unfeasible and complicating the deconstruction process. Important design barriers for building material circularity include complex product composition, composite materials, irreversible joints, intricate designs that thwart simple disassembly, and traditional welded connections [16,27,89]. The complexity of disassembly demands additional techniques and time, incurring extra costs that stakeholders may be reluctant to bear [27]. Consequently, the **complexity of disassembly** may lead to a preference for demolition over deconstruction, ultimately limiting opportunities for material reuse or recycling.

Conventional demolition practices are often perceived as unproductive, as materials at the project's EOL are not efficiently reclaimed. Although selective demolition enables efficient material recovery [72], according to Pun et al. [90], its adoption is hindered by concerns related to increased labour demands, time consumption, and associated costs. Consequently, stakeholders involved in the EOL stage frequently opt for unproductive demolition practices, often overlooking the potential long-term economic and environmental benefits that can result from embracing material circularity principles [as cited by 91].

Numerous research studies have demonstrated the significant impact of inadequately planned designs on resource and energy consumption and waste generation within the construction sector [86]. Scholars identified several key design-related challenges that hinder the advancement of material circularity, including the inability to integrate reuse principles into the design process [46], conflicting objectives between pre-engineered structures and future reuse [51], limited incorporation of circular design strategies such as adaptability, disassembly, and deconstruction [20], and a tendency to prioritise constructability over future reuse [27]. Knoth et al. [21] emphasised that insufficient involvement of reuse experts in the design stage contributes significantly to these design-related obstacles. Furthermore, Torgautov et al. [46] discovered a significant challenge in the utilisation of circular materials such as organic, refurbished, recyclable, and environmentally friendly materials due to their higher cost and labour intensity in installation compared to traditional materials. Additionally, consumer preference for materials designed for short-term lifespans, higher initial investment associated with circular materials, and the reluctance to commit to long-term building ownership pose considerable obstacles to the adoption of material circularity [51].

4.2.2. Economical

Higher costs associated with adopting circular design strategies have been identified by several scholars [51,86]. Various cost-related aspects associated with circular supply chain activities include: higher design fees to incorporate circular principles [51], higher implementation costs for digitalisation in supply chain management [23], increased labour costs for disassembly and deconstruction [6], additional costs for integration of new technologies to improve efficiency throughout the supply chain [46], transportation and storage costs of reused materials [21], and costs associated with waste sorting [as cited by 4]. Consequently, the consensus among researchers is that high costs stand as a prominent impediment to the widespread adoption of material circularity within the construction sector [25,27,91].

As highlighted by Mahpour [16], the lack of incentives for reclaiming building materials has discouraged stakeholders from engaging in circular practices, leading them to resort to detrimental actions like off-site waste sorting and direct landfill disposal. Additionally, the pricing of secondary materials directly influences consumers' decisions regarding the utilisation of reclaimed materials [27,92]. Scholars noted that when the cost of recycling exceeds the value of reclaimed material, recycling yields a negative value, resulting in futile material circularity [16,19]. Furthermore, certain research studies indicated that recycling and scrapping steel can be financially more appealing than reusing it [27], leading stakeholders to opt for the most cost-effective solution. However, life cycle cost analysis reveals that high rates of steel reuse are more economical than scrapping [5].

4.2.3. Quality and performance

Companies exhibit a preference for employing reclaimed materials only when they can ascertain the materials' properties and compare them with new materials [46]. Thus, **quality and performance** attributes of reclaimed materials emerge as pivotal factors in enabling material circularity. The lack of formal criteria for quality assurance of reclaimed materials [19,93], absence of standardisation in the selection of reusable materials [6], labelling CE-friendly materials as low quality [46], suboptimal quality of salvaged materials, inadequacy of performance evaluation tools [51,62,94], limited workability of reused materials [65], down-cycling practices [91], and scarcity of testing [27] directly affect consumers' perception of quality and their uncertainty regarding secondary materials. These issues collectively contribute to the prevailing perception of secondary products as having lower quality and performance, thereby impeding progress toward material circularity [21,48]. Furthermore, the lack of design standards with a specific focus on waste reduction [19], coupled with the scarcity of new standards addressing construction methods aligned with CE strategies, the persistence of outdated construction standards [46], building code non-compliance [91], and lack of specifications, codes, and standards for reclaimed materials [5,25,70,95], are identified as significant impediments to the advancement of material circularity.

4.2.4. Informational

The adoption of CE strategies within the construction sector remains limited, primarily due to a **scarcity of data and an absence of robust data traceability** throughout the supply chain [8,87,94–97]. Talla and McIlwaine [23] noted that the unavailability of material data at the product's EOL presents a substantial barrier to achieving material circularity in two ways: (1) difficulty in decision-making on material reclaim [23] and (2) the inability to incorporate reclaimed materials into new designs [46]. The absence of data on material properties, reuse potential, origin, environmental data, and cost makes the circularity of materials more challenging [70].

Maintaining data in an unstructured format and the unavailability of digital data-sharing methods in the construction sector lead to the unavailability or low-quality data at the EOL [10]. A deficiency of fundamental data on C&D waste impedes waste sorting, ultimately leading to landfill disposal due to unawareness of the material's history [16]. The effort to enhance data traceability throughout the supply chain is considered an ideal solution. However, challenges persist in obtaining comprehensive, high-quality data throughout the entire life cycle, given the fragmented nature of the construction's supply chain [49]. Another significant barrier to material circularity is the **transfer of material ownership** [16]. When material ownership is retained by the manufacturer or supplier through innovative concepts such as "pay by use," "product as a service," or "rent to buy," all material-related data is centralised with a single owner, allowing for more circular decisions [as cited by 4].

4.2.5. Social and behavioural

Lack of awareness and education among construction stakeholders regarding CE strategies, prevalent misunderstandings regarding the distinctions between reused and recycled materials [98], and beliefs on CE design [51] were also emphasised as hindrances to material circularity. Moreover, sociocultural factors, including perception, status, behaviour, and traditional thinking, have impacted material reuse [99]. Numerous authors underscored **consumer preferences** as a formidable barrier for adopting reclaimed materials [83]. Torgautov et al. [46] stated that well-established construction organisations have expressed concerns that incorporating reused materials could damage their companies' reputations and it is not demanded by clients due to their desires and cultural barriers [8]. Thus, consumers' preference and **resistance to change** from traditional materials hinder the advancement of material circularity [25].

The undeveloped market for secondary raw materials presents significant impediments to the transition towards material circularity [8,51]. The **absence of mature and functional markets** for secondary construction materials creates substantial challenges in sourcing reclaimed materials for integration into new projects [11,21,94]. Furthermore, the **lack of collaboration and coordination** among stakeholders hinders the effective implementation of CE strategies [27].

4.2.6. Technological

Technological barriers such as the non-existence of infrastructure for material recycling and refurbishment [100], lack of technological support for waste collection and sorting, insufficient tools for identifying and classifying salvaged materials [72], and limited visualisation technologies to evaluate circular design [51] were identified as obstacles to building material circularity [87]. Furthermore, the existing inertia of construction industry infrastructure, inadequate spaces for waste collection and segregation, and the absence of dedicated storage facilities for recovered materials until their use in a new life cycle hinder the circular process [21,27,45,72].

4.2.7. Risk and uncertainty

Limited availability and accessibility of reuse materials pose significant challenges in the circular construction industry [5,21,86]. The demand for reused materials across an entire project often cannot be met [23] due to the absence of a mature reuse material market, and materials salvaged from existing buildings are not typically designed for reuse [21]. Consequently, the scarcity of reusable materials introduces uncertainty and risks into circular design projects [27,65], as integrating old and new materials within the same project becomes difficult. Cruz Rios et al. [51] stated that matching the sizes and quality of old and new materials within the same building can be challenging when reclaimed materials are insufficient for the entire project. As researchers pointed out, the limited availability of reclaimed materials presents a barrier to material circularity, and this can be mitigated by mapping existing buildings and maintaining comprehensive data on material inventories [21].

Perceived risks and uncertainties surrounding material circularity, such as uncertainty about material quality at the end of a project due to its long lifespan [51], risks associated with finance and documentation, challenges in sourcing reused materials [21], and liability concerns related to the use of recovered products [91], collectively hamper material reclamation. Moreover, stakeholders' reluctance to take risks in using circular materials and the lack of risk-sharing lead the construction sector towards an unsustainable future [21]. Further, reclaiming materials from existing buildings entails time-consuming processes such as sorting, identifying reusable materials, and removing materials through disassembly or deconstruction [6,17,70]. Additionally, as per Densley Tingley et al. [27], the **construction sector's inertia** and resistance to deviating from traditional business concepts were identified as barriers to material circularity.

4.2.8. Regulatory and legal

As CE concepts are still in their infancy, many countries lack policies and standards for material circularity, with notable exceptions being the EU and China [101]. The absence of regulations and standards has been consistently recognised in research as a significant hindrance to material reuse and recycling. For instance, Kazakhstan's stringent legislative norms restrict the use of reused, refurbished, and secondary materials [46]. From the analysis, it is evident that issues such as cumulative taxes during the processing of reclaimed materials [7], inadequate waste management policies [8], charges and taxes related to material transportation, existing regulations and codes, lack of rigorous regulations [51], and the absence of well-defined national targets [16] collectively impede material circularity.

5. Discussion and future research directions

Descriptive analysis reveals a distinguished distribution of CE strategies, particularly emphasising building material reclaim. Fig. 2

illustrates a continuous increase in annual publications, underscoring the growing significance accorded to this field by researchers. Nevertheless, despite the daily advancement of theoretical research, the practical adoption of material reclaim remains predominantly concentrated only in the EU and China, as supported by content analysis. Commonly used keywords in the research have predominantly focused on CE, lifecycle assessment, sustainability, building material, and C&D waste (see Fig. 3). However, discussions related to the circularity or reclamation of building materials have been infrequent, indicating a recent surge in publications.

The construction industry's higher natural resource depletion, energy consumption, greenhouse gas emissions, and waste generation can be substantially offset by reclaiming building materials [17,102]. Researchers emphasised that material reclaim reduces the demand for virgin resources and diminishes the energy and resource consumption associated with manufacturing new materials [17,103,104]. However, to fully exploit these advantages, building materials must be designed with circular principles, facilitating their reclamation and utilisation through multiple life cycles [26]. Even though materials are designed with circular potentials, the practical application of material reclamation strategies is limited by several obstacles. Thus, this SLR conducts an in-depth analysis of the prerequisites and obstacles of material circularity to identify where the practical gaps remain.

The selected articles for this systematic review examined the prerequisites and obstacles to material circularity from various perspectives. Accordingly, the 74 articles were categorised into key themes: design, economic, quality and performance, informational, social and behavioural, technological, risk and uncertainty, and regulatory and legal, based on the primary focus of each study. Table 2 shows the focus of the obtained literature for this review.

According to the analysis, design aspects received the most attention, with 33 out of 74 articles focusing on building material circularity. This is unsurprising, as designing building materials or products with reclamation features is a fundamental requirement for achieving circularity potential. Designing for circularity in building materials following new production processes, techniques, and novel architectural strategies is recognised as a prerequisite for transitioning to a circular built environment [108]. This involves designing materials with crucial properties such as reusability, recyclability, durability, biodegradability, increased recycled content, maintainability, adaptability, and flexibility [26,30,78,105,107,111]. By doing so, materials can be effectively reclaimed at their EOL through reuse, recycling, refurbishment, or natural decay. Moreover, integrating CE strategies into component and building designs, such as DfD or deconstruction, ease of disassembly, modularity and standardisation, material substitution, dematerialisation, and product stewardship is discussed as fundamental prerequisites for achieving material circularity [26,30,78,103,111]. Utilising these design principles would allow for the easy removal of materials during demolition, preventing damage and enabling future reuse. Furthermore, it is recognised that designing building materials with circular potential has received equal attention in both academia and practical applications.

The economic viability of secondary materials and financial incentives were identified as key prerequisites [17] for achieving material circularity. However, only four of the selected articles (5 %) focused on the economic aspects related to building material circularity. To pave the way for these prerequisites, the government should incentivise stakeholders who implement the material circularity concept in their projects. This approach will indirectly reduce the cost of secondary materials compared to new materials. The social and regulatory impacts on building material circularity have received equal attention, with four articles dedicated to each theme, matching the focus on economic aspects. Having robust international standards for secondary materials will enhance their use by eliminating doubts regarding their performance and quality. Comprehensive material data, including the material's history, is essential for achieving material circularity, as it supports informed decision-making at the end of its lifecycle. Furthermore, the availability of material data related to its life cycle would facilitate the establishment of standards for secondary materials, the imposition of legal frameworks on material circularity, the assessment of performance and quality of secondary materials, the identification of reusability or recyclability, understanding deconstruction or disassembly methods, and fulfilling most of the other prerequisites for material circularity.

Data traceability can be achieved through the digitalisation of the construction sector [91] and technological advancements [111], both of which are identified as prerequisites for material reclamation. The significance of informational and technological factors in transitioning toward material circularity is evidenced by their ranking as the second (17 articles) and third (7 articles) most researched areas, respectively. Social awareness and education about material circularity should be promoted nationally, providing basic knowledge to everyone, from school students to the public. This will help people to understand the fundamental principles of CE and implement these principles from the ground up, starting in homes and schools and extending to the industrial level. Risk sharing among stakeholders and a circular-friendly legal framework foster greater interest and compel construction stakeholders to implement material circularity strategies within the sector. Integrating these prerequisites into the material cycle is essential to foster a circular construction industry.

While there is an increasing demand for circular construction practices, several significant obstacles remain along the supply chain, impeding material circularity [27]. Design-related barriers include design for complex disassembly, design for unproductive demolition, inadequate design for material recovery, and material design focusing on short-term lifespans [26,107,109,111]. These design practices hinder the deconstruction or disassembly of buildings at the end of their life cycle, often leading to demolition and direct disposal in landfills. Direct landfill disposal limits the availability of sufficient secondary materials for new projects, posing a significant obstacle for implementing material circularity in the construction industry. In the absence of government financial support for material circulation, stakeholders must fund circular strategies themselves. This raises the cost of secondary materials compared to new products, rendering material reclamation unfeasible. Thus, the lack of incentives and high secondary material prices [17,26] were identified as key economic obstacles. The unavailability of material data and standards for secondary building materials hinders the optimised utilisation of these materials. Furthermore, the absence of such standards makes end users hesitant about the performance and quality of secondary materials. Consequently, the lack of standards reduces customer preference for secondary materials and limits the establishment of a well-structured market. Moreover, low government involvement in funding and establishing relevant legal

Table 2
Table showing themes focused by researchers on CE in building materials.

Article	Circular Economy Themes for Building Materials							
	Design	Economical	Quality	Informational	Social	Technological	Risk	Regulatory
Ahkola et al. [54]	X							
Alberto López Ruiz et al. [88]		X						
Alhawamdeh et al. [56]	X							
Andersen et al. [74]				X				
Antwi-Afari et al. [53]				X				
Barbhuiya and Das [49]				X				
Benachio et al. [55]	X							
Bertino et al. [50]	X							
Bitar et al. [61]	X							
Bourke and Kyle [71]	X							
Cruz Rios et al. [51]	X							
Cruz-Rios and Grau [58]	X							
Dabaieh et al. [6]	X							
Densley Tingley et al. [27]				X				
Dervishaj et al. [76]				X				
Dräger et al. [82]				X				
Eberhardt et al. [59]	X							
Elshaboury and AlMetwaly [75]				X				
Geldermans et al. [105]	X							
Giovanardi et al. [34]						X		
Gordon and De Wolf [95]			X					
Górecki and Núñez-Cacho [106]	X							
Hentges et al. [7]								X
Hopkinson et al. [11]	X							
Huang [57]	X							
Jayawardana et al. [64]	X							
Jones and Urbano Gutiérrez [96]				X				
Joustra et al. [89]	X							
Kanters [30]	X							
Kanyilmaz et al. [86]							X	
Kempton et al. [79]				X				
Knoth et al. [21]				X				
Kovacic et al. [10]						X		
Kozminska [45]	X							
Lanau and Liu [97]				X				
Li et al. [25]					X			
Linares et al. [77]				X				
Lotz et al. [80]				X				
Mahpour [16]					X			
Malabi Eberhardt et al. [107]				X				
Meglin et al. [104]		X						
Mhatre et al. [9]	X							
Milios and Dalhammar [92]		X						
Moalem et al. [48]	X							
Mollaei et al. [83]					X			
Morganti et al. [87]						X		
Nian et al. [5]	X							
Niu et al. [93]			X					
Nuβholz et al. [52]								X
O'Grady et al. [60]	X							
Oliveira et al. [72]								X
Ottosen et al. [22]						X		
Parece et al. [108]	X							
Petrović et al. [8]	X							
Piccardo and Hughes [109]	X							
Raghu et al. [102]				X				
Ramos et al. [63]					X			
Rauf et al. [47]	X							
Sigrid Nordby [94]								X
Singh and Kumar [81]						X		
Sudarsan and Gavali [69]						X		
Talla and McIlwaine [23]						X		
Tleuken et al. [110]	X							
Tomczak et al. [62]			X					
Torgautov et al. [46]		X						
van den Berg et al. [17]				X				

(*continued on next page*)

Table 2 (*continued*)

Article	Circular Economy Themes for Building Materials							
	Design	Economical	Quality	Informational	Social	Technological	Risk	Regulatory
van den Berg et al. [17]							X	
van Stijn et al. [26]	X							
Viscuso [65]	X							
Xing et al. [78]				X				
Yang et al. [44]	X							
Zaman et al. [103]	X							
Zhuang et al. [4]	X							
Zywietz et al. [111]	X							
Total Number of Articles	**33**	**4**	**3**	**17**	**4**	**7**	**2**	**4**
Percentage from 74 selected Articles (~)	45 %	5 %	4 %	23 %	5 %	10 %	3 %	5 %

frameworks results in insufficient infrastructure for material reclamation, pushing the construction industry towards non-circular practices. The lack of necessary awareness and education programmes creates social and behavioural challenges.

Most researchers agreed that having comprehensive data on materials, including origin, properties, environmental data, design details, maintenance and operation data, circular potential, expected lifespan, and recycling or demolition procedures, is crucial for making informed circular-based decisions at EOL [30,102,106]. Furthermore, this data can help overcome several listed obstacles to material reclamation. The importance of building material data documentation, sharing, and tracing is highlighted by the fact that 23 % of the selected articles focused on informational aspects. However, sharing and storing information can be difficult due to supply chain fragmentation and the long lifespan of construction projects. Thus, building material data has not received the same level of attention in practice as it has in academic research. To address this, digitalisation in the construction sector emerges as a prominent solution to tackle data unavailability and traceability issues [22,78]. Utilising cyber-physical data to trace material data, track material status, inspect, and share reusable elements can improve their lifespan management and promote circularity [78,102]. Consequently, scholars have studied digital tools such as BIM, material passports, IoT, digital twins, artificial intelligence, and blockchain technology to support the transition to CE in the built environment [78,102,106]. However, Xing et al. [78] argue that existing digital data platforms are incapable of identifying reclaimable building materials by analysing real-time data on their location, condition,

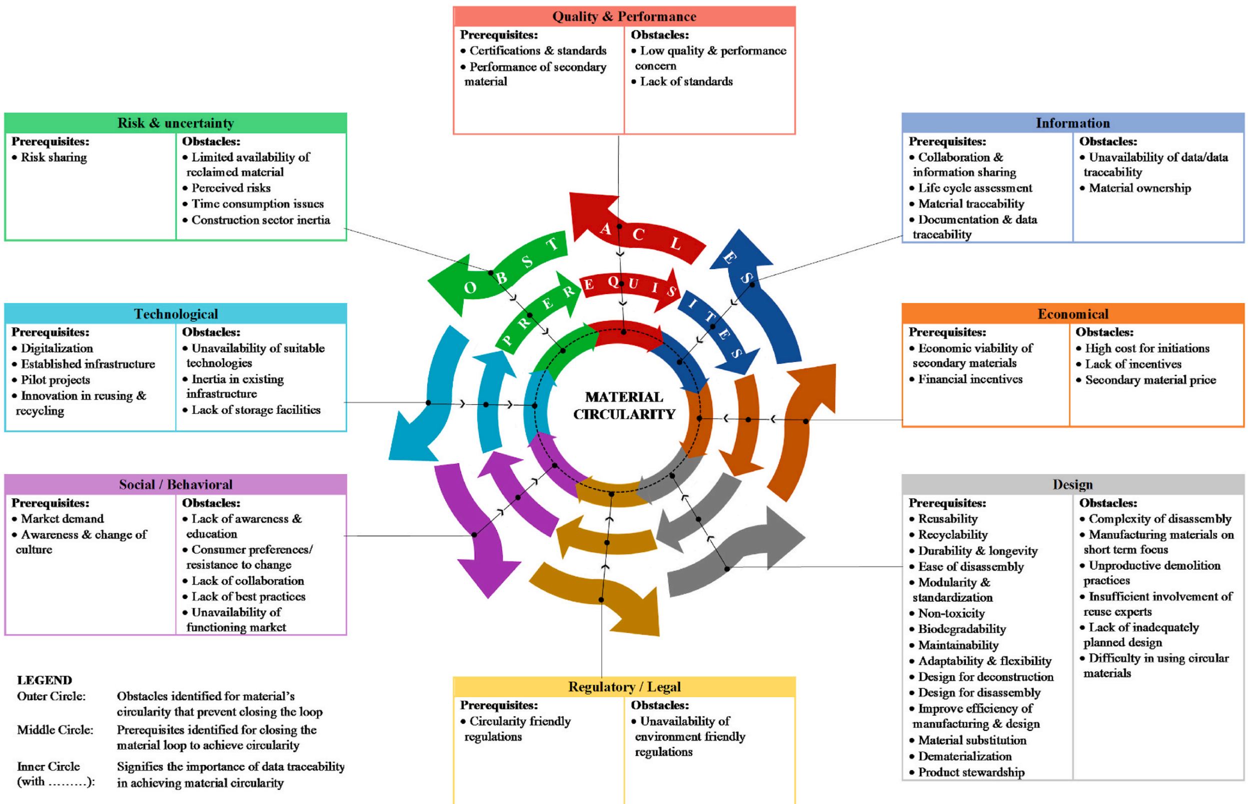

Fig. 4. Conceptualization of obstacles and prerequisites of material circularity.

performance, suitability, and availability. Hence, identifying an optimal digital tool capable of enabling data sharing and maintenance while ensuring transparency, security, accuracy, trust, immutability, and collaboration among stakeholders would be invaluable to implement material circularity. Therefore, one of the key prerequisites for implementing building material circularity in practice is leveraging digital technologies to trace building material data throughout its life cycle. This approach will facilitate overcoming numerous existing obstacles and pave the way for developing essential standards, legal frameworks, innovative solutions, and circular decision-making guidelines necessary for material circularity in the built environment.

Fig. 4 summarises the research findings and underscores the need utilise digital technologies to trace building material data. Notably, as depicted by the outer circle, obstacles identified within the material's life cycle disrupt its seamless circular progression. The arrows pointing in reverse represent the identified obstacles across eight key themes, with the arrowheads facing outward to indicate how these obstacles prevent closing the loop. Materials resume their thorough circular journey only when all prerequisites are satisfied, as depicted by the central circle. The adjacent arrows in the central circle indicate the impact of the prerequisites required to close the loop for full material circularity. Nevertheless, the gap between the arrows signifies the information flow inconsistency, posing challenges for effective end-of-life circular decision-making. Therefore, the inner circle underscores the vital role of data traceability in facilitating the successful implementation of material circularity. Additionally, the connection between the circles and the path to material circularity can be explained as follows: The second circle represents the stage of meeting prerequisites. This stage is achieved by overcoming obstacles through the implementation of circular strategies. Once these prerequisites are met, the inner circle, which symbolises the goal of material circularity, can be reached by applying data traceability from the prerequisites stage. This conceptualisation has been crafted based on the outcomes of the SLR, serving as the cornerstone for a research series committed to developing a digital tool that facilitates material circularity in the construction sector. The identified obstacles and prerequisites were gathered from literature sources, and all factors, along with their corresponding sources, are outlined in Appendix A, B, and C.

6. Conclusion

Reclaiming materials at the end of a project's life cycle has been identified as an optimal solution for reducing the environmental impact of the construction industry by facilitating the transition from a linear to a CE. However, the industry lacks a structured method for reclaiming building materials, particularly in terms of secondary material codes and standards, ensuring quality and performance, accessibility to available secondary materials, financial support, and regulations and policies. This systematic review aims to identify the prevailing obstacles to material circularity in the construction industry and propose solutions where comprehensive studies are currently lacking. Following the PRISMA guideline, a SLR was conducted using 411 articles from the Scopus, Google Scholar, IEEE Xplore, and Science Direct databases as of December 2023. The review was conducted in two sections: descriptive analysis through bibliometric analysis and in-depth qualitative analysis through content analysis using NVivo software.

6.1. Key findings

- Descriptive analysis shows that CE strategies have been increasingly discussed recently, with many papers published between 2019 and 2023. Geographically, the Netherlands emerged as the primary contributor to material circularity research.
- Reclaiming construction materials from existing buildings depends on the materials' circular viability. Consequently, prioritising the design of building materials with circular properties is the foremost prerequisite for ensuring their extended use across multiple life cycles. Even when materials are designed for reusability or recyclability, a significant amount still ends up in landfills due to numerous obstacles to material reclamation. Therefore, the existing obstacles and prerequisites for material circularity have been identified and categorised into eight themes: design, economic, quality, technological, informational, social, risk, and regulatory, as shown in Fig. 4.
- According to the analysis of selected papers, design aspects were the most frequently discussed, with 33 out of 74 articles emphasising the importance of design features in implementing material circularity. Informational and technological factors followed, with 17 and 7 articles, respectively, highlighting their significance. While design features already play a crucial role in practice, supported by increasing interest in digital technologies, the practical application of informational factors remains limited despite their higher focus on academic research.

6.2. Recommendations

- Recent studies have highlighted that the unavailability of comprehensive material data hinders circular decision-making for building materials and their potential future use. Creating robust data accessibility and traceability throughout the supply chain is crucial for overcoming these obstacles.
- Comprehensive material data supports the development of standards for secondary materials, establishes legal frameworks, aligns building designs with available material specifications, develops a structured secondary market, enhances consumer preferences for reclaimed materials, and fosters innovation in manufacturing new materials. Therefore, it is recommended to utilise relevant digital technologies in the construction industry to enable material data traceability, ultimately driving the industry towards circularity.

CRediT authorship contribution statement

Navoda Ranasinghe: Writing – original draft, Visualization, Resources, Methodology, Formal analysis, Data curation, Conceptualization. **Niluka Domingo:** Writing – review & editing, Supervision, Conceptualization. **Ravindu Kahandawa:** Writing – review & editing, Supervision.

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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.

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Appendix A. Supplementary data

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Data availability

No data was used for the research described in the article.

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