

Research paper

Uncovering key themes in modular construction waste management and exploring their impact and centrality

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ABSTRACT

Modular construction, encompassing prefabrication and off-site construction, presents compelling benefits over conventional building techniques, notably in mitigating material waste, expediting project schedules, and reducing environmental footprint. The current study investigates 118 studies from 1,843 potential publications to identify the thematic evolution and knowledge gaps in modular construction waste management from 1996 to 2024 using combined text-mining techniques. Network mapping and node analysis using Biblioshiny and SciMat tools provide thematic development and centrality insights. Trend analysis demonstrates a significant increase in research activity post-2015, following the establishment of the United Nations Sustainable Development Goals. Co-occurrence analysis using VOSviewer identified key themes and their interrelations. Cluster analysis further delineated key themes, showing the dominance of topics such as "performance," "mechanical properties," and "recycled aggregate concrete (RAC)". We found that "Reuse" and "Recycling" themes exhibit lower occurrences and link strengths. Additionally, a Sankey Diagram visualizes interrelationships between key themes, references, and contributing countries, notably highlighting contributions from China (34 %) and Spain (21 %). Further findings reveal a sustained interest in recycling from 2014, particularly recycled concrete from 2018 to 2022, underscoring the adoption of off-site construction to mitigate waste and incorporate recycled materials. Impact-centrality analysis identifies "RAC" as a high-impact theme, following "Prefabrication" and "Sustainability." Network analysis highlights that the mechanical properties of RAC are of considerable interest and concern. The adopted text-mining approach provides a comprehensive view of thematic developments and identifies knowledge gaps, aiding researchers in addressing current waste challenges and developing evidence-based waste policies.

1. Introduction

The burgeoning volume of construction and demolition waste (C&DW), representing 35–50 % of global solid waste, is increasingly alarming, this poses significant threats to both national economies and sustainability efforts [1–3]. Given its practical importance, sustainable C&DW management research is increasingly popular [4–6]. Modular construction effectively tackles these concerns by significantly reducing waste production. According to Loizou et al. [7], modular construction significantly reduces waste weight by up to 83.2 % in the cases studied through efficient off-site production methods, leading to a 47.9 % cost reduction in waste for large structures. By prefabricating components off-site, the amount of waste generated during construction is significantly minimized, contributing to cost savings and environmental sustainability [7]. Manufacturing building modules in controlled factory

settings enhances the precision and quality of construction, leading to fewer errors and reduced material waste [8]. The preassembly of components leads to fewer on-site disruptions and faster project completion times, further bolstering the appeal of modular construction in modern building practices [8]. Tam et al. [9] also demonstrated that prefabrication can reduce concrete waste by 90 %, metal waste from rebar off-cuts by 92 %, and masonry waste by up to 100 %.

Lu et al., [10] analyzed 114 high-rise building projects in Hong Kong and found that using prefabricated components reduced onsite waste generation by an average of 770 kg/m². This significant reduction in construction waste contributes to various environmental benefits, including reduced landfill waste, lower greenhouse gas emissions, and decreased use of public vacant sites for illegal dumping [11–13]. Collectively, these studies underscore the profound impact of modular construction on waste management and environmental sustainability in the building sector.

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List of acronyms	
AU_CO	Author-country
CE	Circular Economy
CR	Cited Reference
C&DW	Construction and Demolition Waste
DE	Descriptor
L	Number of Links
LCA	Life Cycle Assessment
OCC	Occurrences
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RAC	Recycled Aggregate Concrete
SDG	Sustainable Development Goals
TLS	Total Link Strength
WoS	Web of Science

1.1. Literature review

In the last decade, there has been a significant increase in the development of software tools specifically designed for science mapping and bibliometric analysis in waste studies [14–16]. Table 1 presents notable research in the area, identifies knowledge gaps, and outlines the objectives of the current study.

Jin et al. [17] conducted a notable study identifying leading countries and authors in modular construction from 2008 to 2018. However, their research was primarily promotional, lacking a detailed thematic analysis. The present study aims to fill this gap by employing a text-mining approach to identify and trace the evolution of themes in modular construction waste management from 1996 to 2024. Unlike Jin et al. [17], who used VOSviewer without a thesaurus, leading to the inclusion of unrelated geographical terms, the present study incorporates a thesaurus document to exclude irrelevant terms, enhancing accuracy.

Ter Haar et al. [18] focused on off-site construction, particularly 3D concrete printing, identifying co-occurrences in this area. While their research provided valuable insights into 3D concrete printing, it did not address waste management within modular construction. The present study delves into this specific aspect, employing comprehensive text-mining methods using RStudio to analyze keyword trends from 1996 to 2024. This approach allows for the identification of key themes in waste management within the modular construction sector.

Jayawardana et al. [19] explored modular construction in various regions, including terms like "sustainability," "life cycle," and

"environmental impact." However, they did not focus on waste management, omitting keywords related to "waste," "recycle," and "reuse." The present study addresses this gap by incorporating an environmental perspective, using keywords such as "recycling," "waste," "reuse," and "circular economy (CE)." This approach enables a comprehensive analysis of modular construction waste management from an environmental standpoint.

Previous studies primarily highlighted leading countries and authors, whose prominence can vary. The present study diverges from this approach by conducting a co-occurrence analysis to identify influential themes and uncover knowledge gaps. By employing a combined text-mining analysis using VOSviewer, Bibliometrix, and SciMat tools alongside RStudio, the present study examines keyword trends over time, providing a more nuanced understanding of the field. Despite the significant advancements in modular construction research, there remains a lack of comprehensive text-mining analyses on modular construction waste management [20]. The present study addresses this gap by spanning from 1996 to 2024, using advanced text-mining techniques, cluster analysis, and network mapping to elucidate thematic pillars and keyword progression. This comprehensive approach aims to uncover areas that previous studies have not thoroughly explored, offering new insights and directions for future research. Recognizing key themes is crucial as it: (i) guides researchers towards pertinent issues, (ii) fosters interdisciplinary collaboration, (iii) informs policymakers and industry stakeholders about critical research areas, and (iv) highlights gaps and unexplored avenues for future research.

1.2. Objectives, novelties, and contributions

The study objectives are to [i] conduct a comprehensive text-mining analysis to uncover knowledge voids in the field of modular construction waste management from 1996 to 2024 and chart future avenues of inquiry, [ii] elucidate the thematic pillars shaping this domain through cluster analysis and network mapping techniques using VOSviewer, and [iii] investigate the progression and interrelation of keywords over time to evaluate the impact and centrality of themes and node analysis, employing integrated methodologies within the framework of RStudio and SciMat tool. This endeavor will employ combined text-mining tools and methods to ensure a meticulous and systematic exploration of the research landscape.

At the time of present study, no text-mining analysis specifically focused on waste management studies within modular construction has been conducted. The current research thus uniquely contributes by addressing several unexplored aspects in this domain, identifying key themes through co-occurrence analysis to highlight their focus areas and interconnections. Cluster network analysis categorizes themes based on impact and centrality, while node analysis explores collaborations

Table 1
Knowledge gaps in similar literature in modular construction waste management.

Study	Topic	Dataset Formation	Objectives		
		Environmental Approach: Waste Management Keywords in Search String	Co-occurrence Keywords Analysis to Identify key themes in Modular Construction Waste Management	Evolution and Keywords Trend Analysis Over Time	Text-mining Impact/Centrality Analysis and Cluster's Network Analysis
[17]	Modular construction	NO	NO	NO	NO
[18]	Modular construction with 3D concrete printing	NO	NO	NO	NO
[19]	Modular construction in developed and developing regions	PARTIALLY, their search string did not encompass terms such as "recycle," "reuse," "waste," and similar keywords.	NO	NO	NO
Present Study	Modular construction waste management.	YES, present study focused on modular construction's waste and environmental impact. (Objective 1)	YES, Co-occurrence analysis was conducted using the VOSviewer tool in conjunction with a thesaurus file to enhance accuracy. (Objective 2)	YES, the trend of keywords was mapped using the RStudio and Bibliometrix Tool (Objective 3)	YES, Impact and Centrality of identified themes and network analysis were conducted using the RStudio, Bibliometrix, and SciMat tools (Objective 3)

among high-impact themes in sustainable modular construction. This approach provides a comprehensive view of thematic developments and identifies knowledge gaps from 1996 to 2024, aiding researchers in addressing current waste challenges and developing evidence-based waste policies [13,21,22].

2. Methodology

2.1. Methods

The PRISMA guidelines [23] were meticulously followed for the database search. Implementing the suggested search technique reduces the risk of bias, thereby significantly improving the study's reliability. In addition, the present study adheres to recent bibliometric guidelines [24] to perform a comprehensive analysis of modular construction waste management. VOSviewer was utilized to analyze the co-occurrence keywords, identifying key themes and their interconnections. Co-occurrence in VOSviewer refers to the frequency with which keywords appear together in the dataset [25]. This technique helps in visualizing and mapping the relationships and interactions between different research themes. The Bibliometrix package in RStudio offers a comprehensive set of tools for quantitative research in text-mining analysis. Developed in the R language, it is used to facilitate robust and comprehensive quantitative research [25]. High-impact themes were identified using the biblioshiny package in RStudio and the SciMat tool was subsequently employed for detailed node analysis [25,26]. In the context of co-occurrence analysis conducted via VOSviewer, the term "L" represents individual links between terms, "TLS" quantifies the cumulative strength of all connections associated with a specific term, and "OCC" denotes the frequency of occurrences of a particular term within the analyzed dataset.

2.2. Materials

An exhaustive literature search was conducted on the Web of Science (WoS) database to identify relevant scholarly resources on modular construction waste management from January 1996 to May 2024 (Fig. 1). WoS database is commonly adopted in bibliometric studies [27–29]. The selection of WoS was based on the compatibility of the export file format with the designated bibliometric tools, Bibliometrix, VOSviewer, and SciMat. Initially, preliminary trials were performed to test related keywords.

The keywords were categorized into three distinct segments: terms related to modular construction technology (e.g., "Modular*", "Pre-fabricat*"), terms associated with construction (e.g., "construction*"), and terms relevant to waste management (e.g., "waste*"). The complete search string is presented in Fig. 1. The initial search yielded 1843 potential resources indexed during the study period, marking the emergence of modular construction waste management as a critical research and practice area around 1996, with the earliest relevant studies appearing in the literature at that time. To refine the results, the selection was restricted to English sources and article types, reducing the dataset to 1232 articles.

Subsequent analysis involved abstract screening of the remaining articles to evaluate their relevance to modular construction waste management. This step excluded 1114 irrelevant papers, leaving a final corpus of 118 articles deemed suitable for further investigation. The initial large dataset and subsequent exclusion during the first screening can be attributed to the concept of modular construction being explored across various industries, such as material engineering, civil engineering, chemical engineering, environmental engineering, and other disciplines investigating this concept. However, present study aimed to focus specifically on environmental publications, necessitating the exclusion of others.

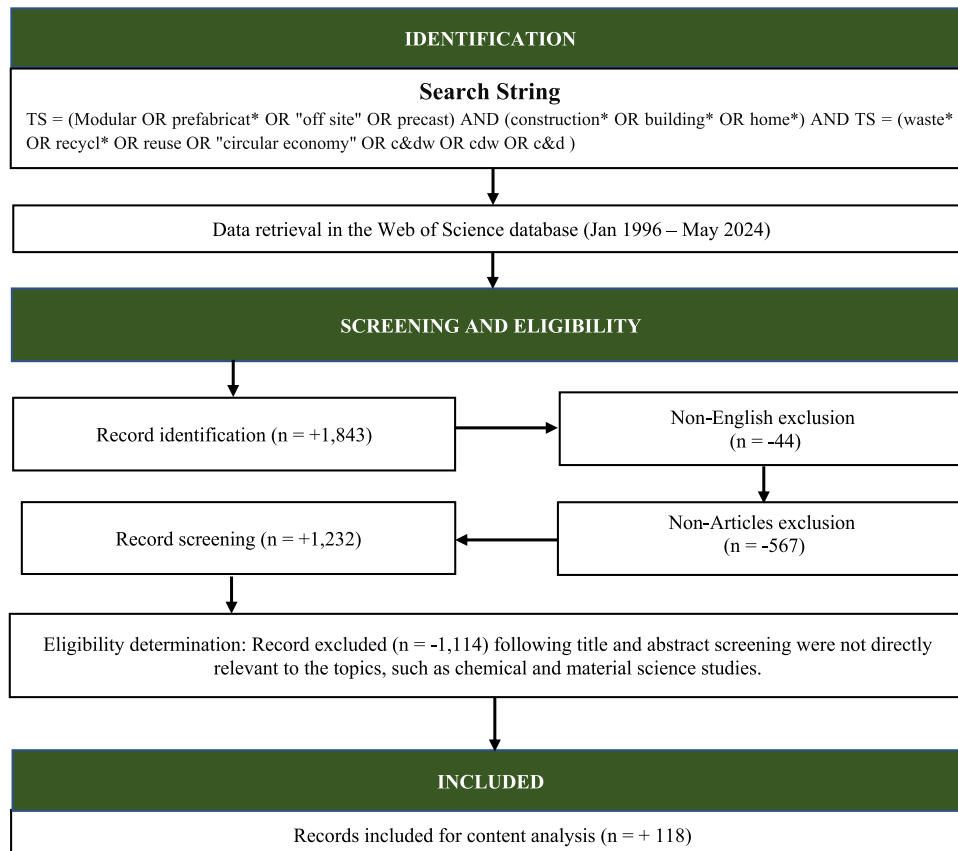


Fig. 1. Methodology flowchart of modular construction waste management following PRISMA Framework.

3. Result and discussion

3.1. Publication trends and citation analysis

The publication trend in Fig. 2 displays a gradual increase initially, followed by a pronounced upward trajectory starting around 2015, suggesting growing research interest and scholarly activity. The citation curve, depicted in blue, exhibits a lag phase with relatively low counts initially but a pivotal inflection point around 2015, when citations begin rising exponentially, culminating in a remarkable projected peak in 2023 (over 550 citations). The highest number of related WoS-indexed publications were also identified in 2023 ($n = 22$). This surge in modular construction waste management research beginning in 2015 may be attributed to the establishment of the United Nations Sustainable Development Goals (SDGs) in 2015 [30], which heightened the focus on environmental impact among researchers and countries.

3.2. Uncovering principal themes in modular construction waste management

A co-occurrence analysis generated by VOSviewer deciphers the intellectual structure and thematic concentrations within a specific field. The analysis uncovers the frequency at which certain terms co-occur within the literature, thereby revealing patterns of research focus and potential interdisciplinary linkages. The visualization (Fig. 3a) presents three distinct clusters (Blue, Red, and Green), each representing a different thematic concentration that has emerged from the analysis. Fig. 3a illustrates the collaborations between themes, while Fig. 3b depicts the occurrences and links of the identified themes.

As shown in Fig. 3a, the blue cluster highlights several key themes within the modular construction waste management research. The Blue Cluster is dominated by the theme "C&DW" (OCC:56, L:23, TLS:161), underscoring its centrality in the modular construction waste management discourse. Other significant themes include "Compressive strength" (OCC:12, L:18, TLS:40) and "Concrete" (OCC:11, L:18, TLS:34), highlighting the importance of material properties and structural integrity. The emphasis on "Sustainability" (OCC:10, L:13, TLS:23) aligns with the increasing global focus on sustainable construction practices. Additionally, themes like "Fly-ash" (OCC:6, L:17, TLS:27) and "Microstructure" (OCC:5, L:10, TLS:16) reflect specific material considerations

within the cluster.

The red cluster emphasizes themes related to construction components' material properties and performance (Fig. 3a). In the red cluster, Fig. 3b, "Performance" (OCC:23, L:22, TLS:80) and "Mechanical properties" (OCC:22, L:19, TLS:76) stand out, highlighting the critical evaluation of material behavior and properties. Themes such as "Aggregate concrete" (OCC:21, L:17, TLS:64) and "Recycled concrete" (OCC:13, L:18, TLS:54) align with anticipated focuses on the performance of recycled materials. Unexpectedly, themes like "Behavior" (OCC:13, L:18, TLS:43) and "Strength" (OCC:13, L:18, TLS:45) show robust link strengths despite moderate occurrences, suggesting a nuanced but important area of discourse.

The green cluster (Fig. 3a) highlights pivotal themes in modular construction waste management's implementation and operational aspects. As shown in Fig. 3b, the Green Cluster features "Prefabrication" (OCC:30, L:22, TLS:89) and "Design" (OCC:21, L:13, TLS:39), indicating a strong interest in the design and prefabrication aspects of modular construction. The prominence of "CE" (OCC:14, L:12, TLS:28) is noteworthy, reflecting a growing recognition of CE principles in construction waste management. However, the relatively lower occurrence of "Reuse" (OCC:7, L:13, TLS:21) and "Recycling" (OCC:5, L:11, TLS:15) is surprising, given their critical role in sustainable waste management and circularity.

A central observation from the analysis is the prominent role of "C&DW" and the substantial focus on "Performance" and "Mechanical properties" of materials, as expected. These themes are foundational to the field, emphasizing material performance and waste management. The attention to "Sustainability" and "CE" aligns with broader industry trends towards sustainable practices. Despite their importance, themes like "Reuse" and "Recycling" exhibit lower occurrences and link strengths. This suggests potential gaps or emerging areas in research that may require further exploration. Additionally, despite their moderate occurrences, the high link strength of themes such as "Behavior" and "Strength" in the Red Cluster highlights nuanced areas of interest that are integral to the structural performance in the field.

3.3. Keywords analysis

The Three-Field Plot (Sankey Diagram) visually represents the relationships between references, keywords, and countries within the

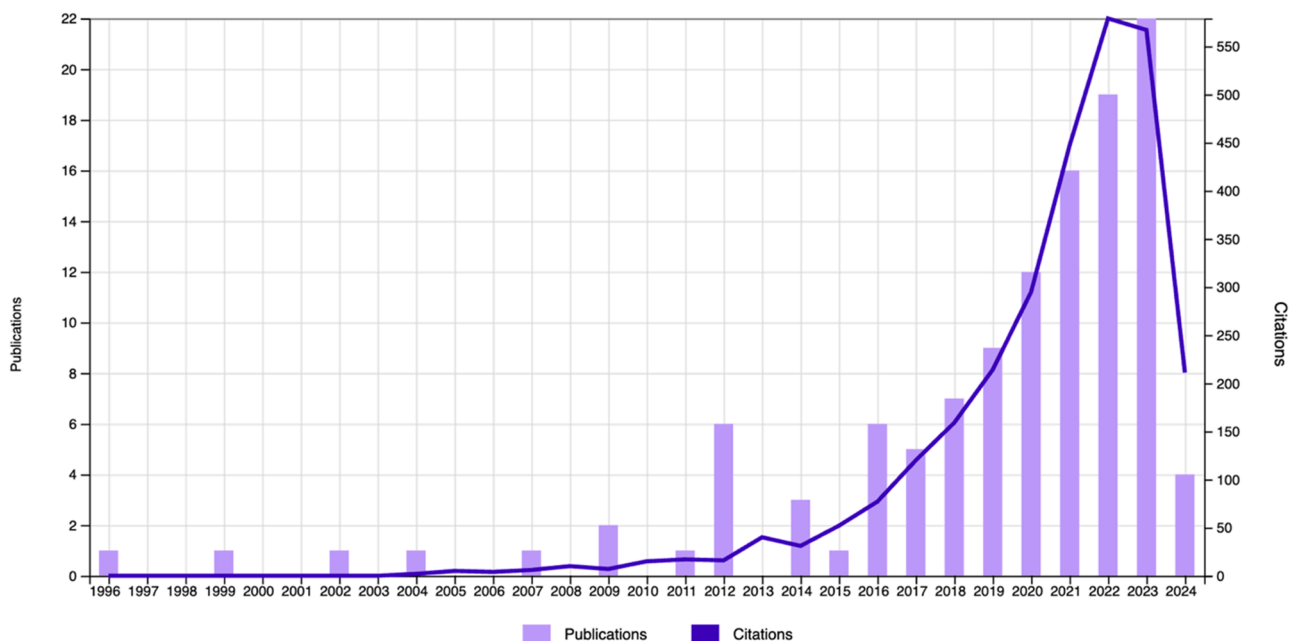
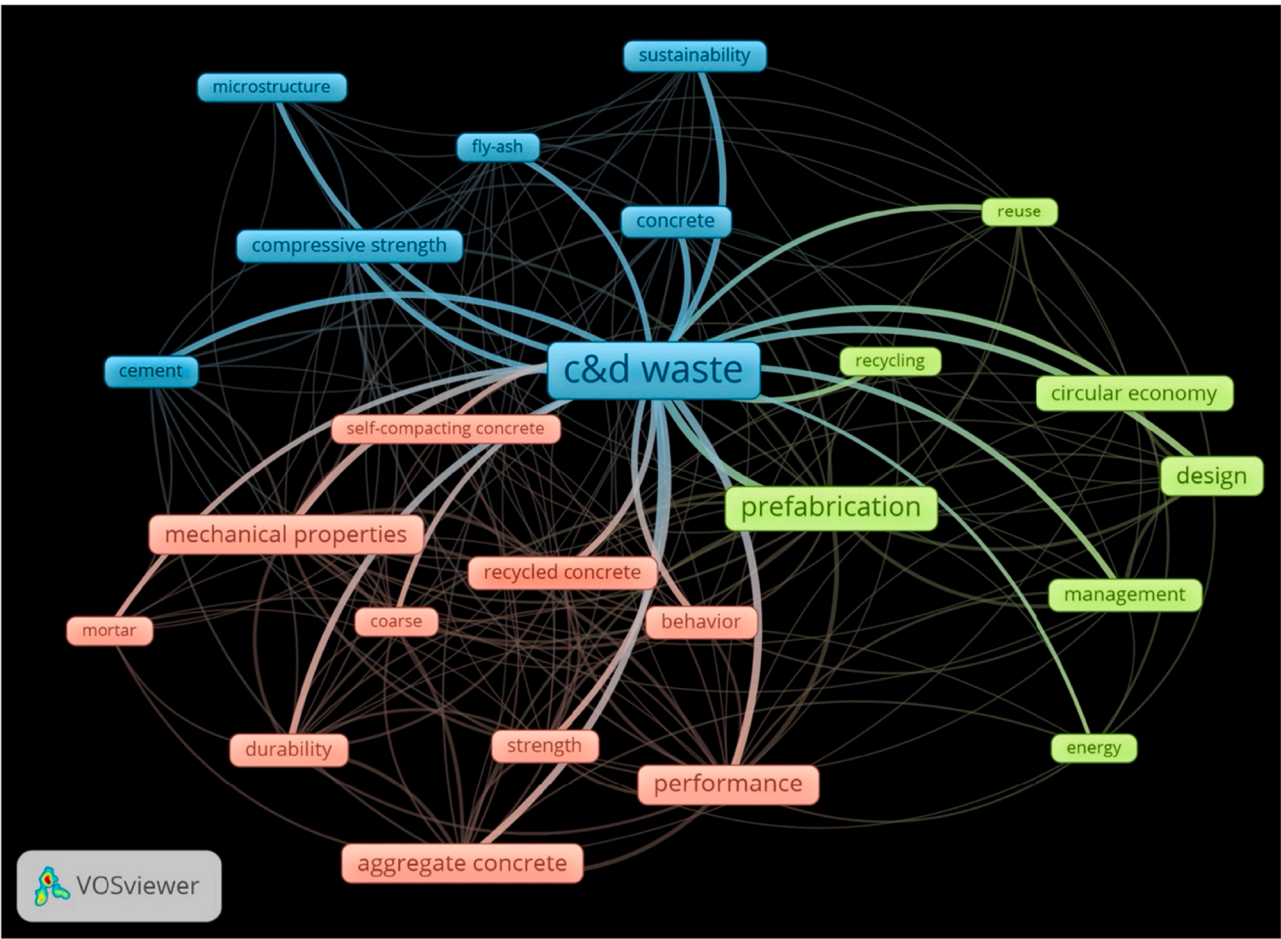
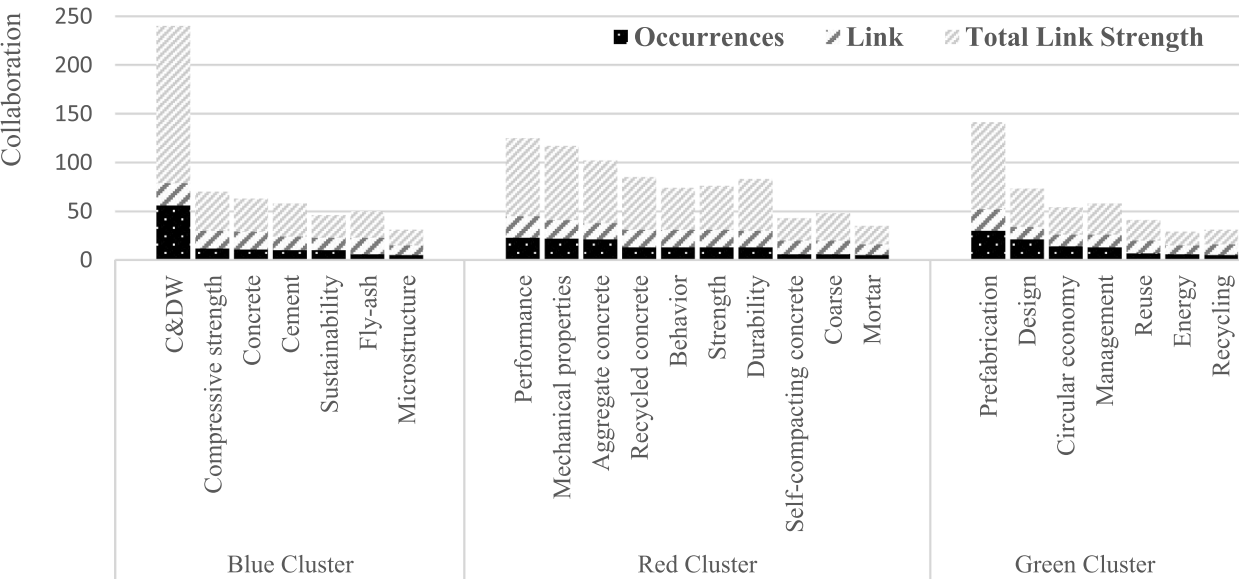


Fig. 2. Publication trends and citations in modular construction waste management.



a- Co-occurrence analysis and collaborationsto identify key themes



b- Occurrences and link of the identified themes

Fig. 3. Identified key themes in modular construction waste management using VOSviewer.

context of modular construction waste management (Fig. 4). This diagram offers valuable insights into this research area's prevalent themes, emerging concepts, and geographical contributions. While cited references (CR) represent the scholarly works referenced in modular

construction waste management research, descriptors (DE) act as keywords describing the identified key themes of these references. Additionally, author-country collaboration (AU_CO) helps to visualize connections between these references and the countries where the

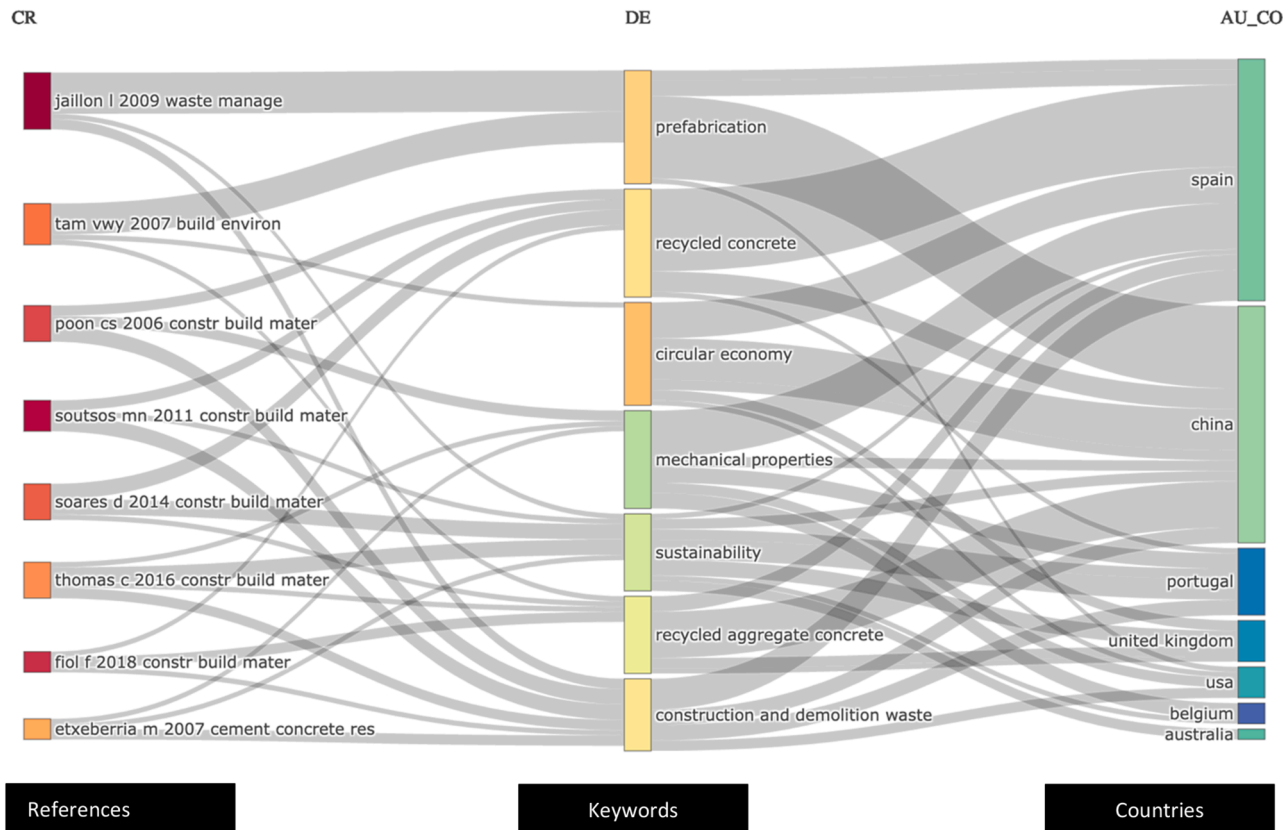


Fig. 4. Three-Field Plot (Sankey Diagram) in modular construction waste management during the study period.

authors are affiliated. The AU_CO analysis highlights multi-country collaborations, showcasing the research's international and cooperative nature. A recent bibliometric study on electronic waste management research reported that collaborative work is important in driving innovations and research productivity [31].

The left column (Fig. 4) displays the seminal studies that have significantly influenced the modular construction waste management domain, with the thickness of the lines emanating from these studies indicating the strength of their associations with the corresponding thematic keywords and countries. Notably, the study by Jaillon et al. [32] on waste management exhibits robust connections to the critical themes of prefabrication, sustainability, and C&DW.

The central column distills the core themes that have emerged as the focal points of investigation in modular construction waste management research. Prominently featured concepts include (i) prefabrication, (ii) recycled concrete, (iii) circular economy (CE), (iv) mechanical properties, (v) sustainability, and (vi) recycled aggregate concrete (RAC). The prevalence of these themes reflects the industry's heightened awareness of the imperative to adopt sustainable construction practices, mitigate waste generation, and explore innovative solutions that promote resource efficiency and environmental responsibility. Ultimately, this thematic mapping empowers researchers to position their work strategically, contribute to advancing knowledge, and drive the development of innovative solutions that can transform the construction industry's approach to waste management and sustainability.

The identified themes underscore critical insights for readers by offering a comprehensive overview of current focus areas in the field. Prefabrication techniques play a pivotal role in optimizing construction processes and minimizing material waste. Understanding these methods is crucial for identifying efficient practices that can be implemented across projects. As discussed in the next paragraph, over 34 % of these studies originated from China. In fact, prefabrication studies originated from three countries (China, Spain, and USA) only. Insights into recycled

concrete and RAC inform researchers about innovative ways to reuse construction materials, thereby reducing landfill use and conserving natural resources. Spain published 21 % of the studies, reflecting a significant contribution to the advancement of sustainable construction practices. The emphasis on CE highlights systemic approaches to enhancing resource efficiency and reducing waste. Knowledge of mechanical properties ensures that recycled and prefabricated materials meet stringent performance standards, ensuring safety and reliability in construction projects. Finally, the focus on sustainability underscores the imperative of adopting eco-friendly practices in the construction industry.

The third column on the right (Fig. 4) represents the countries associated with the research output in modular construction waste management. A thicker line represents a larger proportion of the WoS indexed studies from the author_country during the 27.4 year study period. China and Spain exhibit significant inflow contributions, as indicated by the thickness of the lines connecting these countries to the keywords and keyword-plus terms. Surprisingly, Spain dedicates a large portion of the dataset, contributing 21 %, while China contributed 34 %. This finding is unexpected, as in most bibliometric studies, China typically dominates due to its large volume of published documents [33–35]. The prominent presence of Spain in this research area, contributing over one-fifth of the dataset, suggests a strong interest and focus on modular construction and waste management practices within the country. Spain's strong focus on modular construction and waste management practices can be attributed to several factors. The country has implemented a waste management model, the Alcores model, which has been successful in quantifying and managing C&DW [36]. However, there are still challenges in on-site waste management, particularly in the segregation of plasterboard waste [37]. Despite these challenges, Spain is making efforts to address the environmental impacts of the construction sector, including waste generation [38]. The economic potential of C&DW is also being explored, with a focus on sustainable

waste management practices [39]. These efforts reflect Spain's commitment to environmental protection and sustainable development. Portugal, United Kingdom, and USA also contributed considerably to the literature (Fig. 4). "Sustainability" appears to be a key theme for studies originated from Portugal, whereas "Recycled aggregate concrete" appears to be a key theme from UK studies. Studies from the USA appears to be diversified, addressing various topics and keywords.

The trend topic analysis over time, as depicted in Fig. 5, presents a keyword trend related to modular construction waste spanning from 2012 to 2024. Each term is represented by horizontal lines and circles, where the position of the circles along the horizontal axis indicates the period the term was most frequently used, and the size of the circles represents the frequency of term usage. For example, CE peaks in 2022 with the highest frequency of 13, illustrating a recent surge in research interest. "Prefabrication" shows increased interest post-2020, peaking around 2021 with a frequency of 12, reflecting the growing emphasis on efficient construction methods. Both "Sustainability" and "RAC" reached frequencies of 9 in 2021, indicating a consistent focus on sustainable practices and material reuse. "Recycled Concrete" appears consistently throughout the timeline, peaking in 2021 with a frequency of 11, highlighting ongoing research in material recycling. "Construction and Demolition (C&D) Waste" has risen steadily since 2018, peaking at 10 in 2020, underscoring the importance of waste management in construction. "Durability" and "Recycling" maintain moderate frequencies, peaking at 5 in 2020 and 2019, respectively. "Mechanical Properties" and "Precast Concrete" show significant interest, peaking at 8 in 2019 and 2018, respectively, while "Precast" reaches a frequency of 7 in 2018. "Construction Waste" showed early interest around 2016 with a frequency of 6.

A significant finding depicted in Fig. 5 is the sustained interest in "Recycling" from 2014 to 2019, and specifically in "Recycled Concrete" from 2018 to 2022. Off-site construction not only mitigates waste and reduces construction costs but also incorporates the use of recycled materials in factory-made components. This approach has been increasingly adopted by the scientific community in recent years, indicating a shift in the industry's focus. Furthermore, Fig. 5 highlights the growing interest among researchers in recent years in CE, prefabrication, and sustainability. Understanding these trends is crucial as it enables researchers and practitioners to concentrate on high-impact areas, promoting innovation and efficiency in waste reduction strategies. Funding agencies are recommended to develop specific programs to better support research on these emerging topics. By mapping the frequency and timeline of key terms, this analysis provides valuable insights into the progression and current emphasis in the field, keeping the viewer well-informed and engaged.

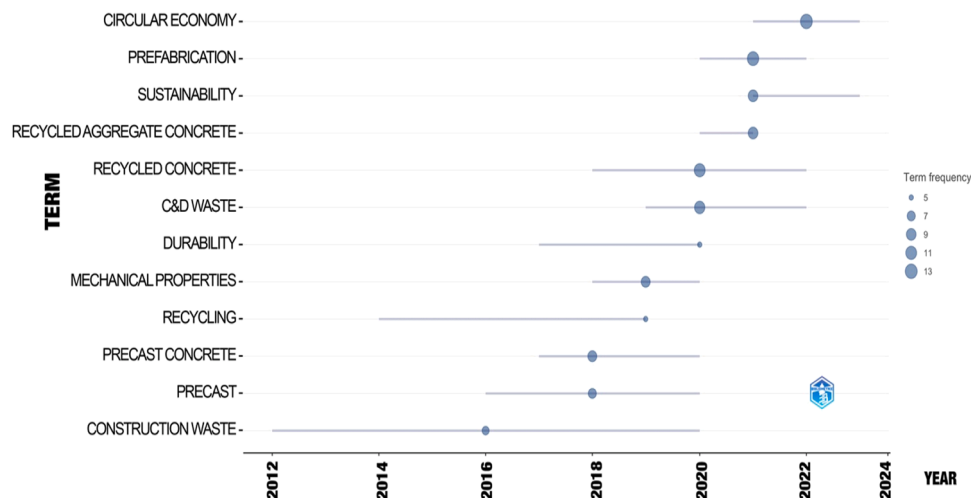


Fig. 5. Trend topics in modular construction waste management.

Fig. 6 illustrates the relative positioning of various themes based on their impact and centrality. The X-axis of Fig. 6 represents the impact of the themes, while the Y-axis represents their centrality within the research field. The "conf %" represents the confidence score, indicating how certain the clustering algorithm is about assigning each research theme (circle) to its specific position within the impact-centrality landscape. The analysis reveals that themes such as "CE" (impact: 2.271, centrality: 1.113, frequency: 18) and "prefabrication" (impact: 2.143, centrality: 1.169, frequency: 15) are not only highly impactful but also central to the discourse on modular construction waste management. These themes are critical as they integrate concepts of sustainability and efficiency, reflecting their importance in contemporary research and practice.

Interestingly, the theme "RAC" (impact: 1.876, centrality: 1.118, frequency: 10) also shows a high degree of both impact and centrality, indicating its significant role in addressing waste management through the reuse of construction materials. This is particularly noteworthy because, compared to "CE" and "prefabrication", "RAC" has been a traditional research topic with publications dating back to earlier years, highlighting its longstanding relevance in the field (Fig. 5). This long-term research focus contrasts with the recent popularity of "CE" and "prefabrication", which have gained prominence in later years.

As shown in Fig. 6, "CE" (impact: 2.271, centrality: 1.113, frequency: 18) and "prefabrication" (impact: 2.143, centrality: 1.169, frequency: 15) have emerged as significant themes only more recently. The enduring research interest in "RAC" emphasizes its foundational role in sustainable construction practices. This historical perspective adds depth to our understanding of how traditional methods continue to underpin modern advancements in waste management. The theme "Recycled concrete" (impact: 1.996, centrality: 1.117, frequency: 29) appears prominently, underscoring the importance of recycling practices in reducing construction waste. The strong centrality of these themes suggests that they are well-integrated within the broader research landscape, serving as pivotal points that connect various sub-disciplines and research areas. For example, steel is commonly recycled across the globe, and it appears most of the recent work has focused on recycling concrete structures. This emphasis on recycling is critical for advancing sustainable modular construction waste management practices. On the other hand, recycling of cross-laminated timber or bamboo received much less attention than steel and concrete.

One unexpected finding is the high impact of the "carbonation" theme (impact: 2.941, centrality: 1.087, frequency: 2). This indicates that while the topic is not frequently discussed, it has a substantial centrality in the field, suggesting emerging interest or breakthrough findings that could have significant implications for future research.

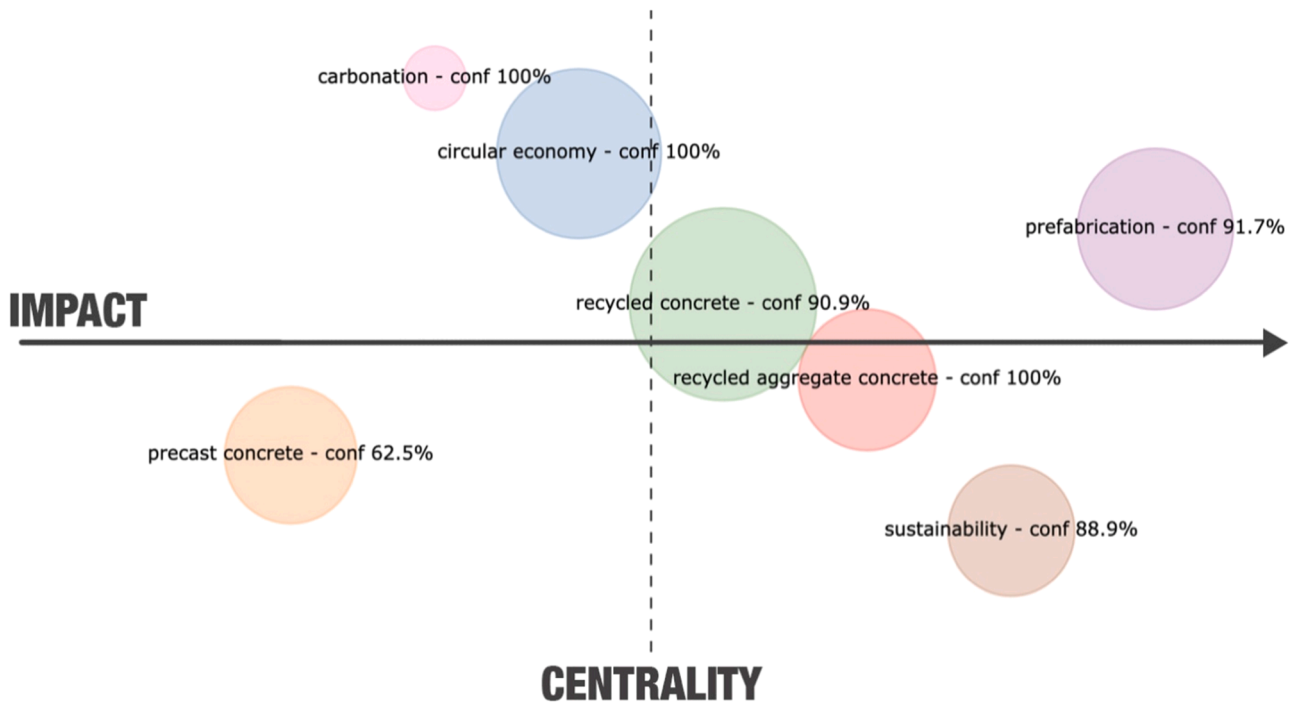


Fig. 6. Centrality and impact of the identified themes in modular construction waste management.

Additionally, the lower centrality and impact of "precast concrete" (impact: 1.283, centrality: 0.811, frequency: 9) compared to other themes like "sustainability" (impact: 1.263, centrality: 1.144, frequency: 8) might be surprising given the prevalent use of precast methods in modular construction. Salesa et al. [40] underscore the potential for waste minimization in precast concrete production, demonstrating that multi-recycled precast concrete can match or surpass the performance of control concrete. However, Bossio et al. [41] emphasize the necessity for further investigation into precast concrete recycling, particularly given its extensive average service life of 75 years. While precast concrete may initially promote waste minimization at the construction stage, the limited recycling studies of these structures at the end of their life cycle present a critical gap. With an anticipated surge in research efforts in the next decade, exploring precast recycling methods will become increasingly imperative.

Clustering by coupling analysis identifies key themes and reveals the underlying relationships and emerging trends shaping this field. Examining themes such as "CE" and "prefabrication" through the lenses of impact and centrality underscores their dual role in promoting sustainability and efficiency. Additionally, recognizing other significant C&DW materials like gypsum board, lumber, and steel alongside the prominence of "RAC" and "recycled concrete" emphasizes the critical importance of recycling in reducing waste and enhancing resource efficiency. The unexpectedly high impact of the "carbonation" theme, despite its low frequency, suggests it may be a burgeoning area of interest with the potential for significant breakthroughs, illustrating the evolving nature of research priorities.

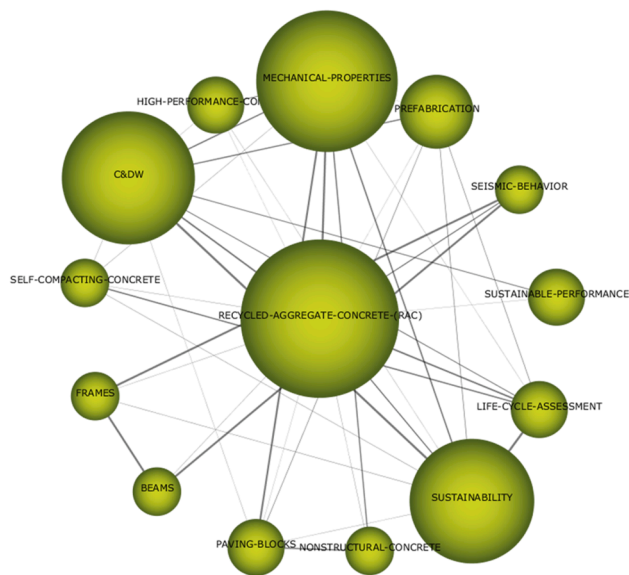
3.4. Cluster's network analysis

The text-mining analysis of modular construction waste management, as depicted through the node analysis in Figs. 7a–d, provides significant insights into the categorized themes presented in Fig. 6 and their interconnections within the domain. Based on Fig. 6, the three themes (RAC, Sustainability, and Prefabrication) were identified as high impact, while C&DW was also noted as a key theme, prompting their selection for detailed node analysis.

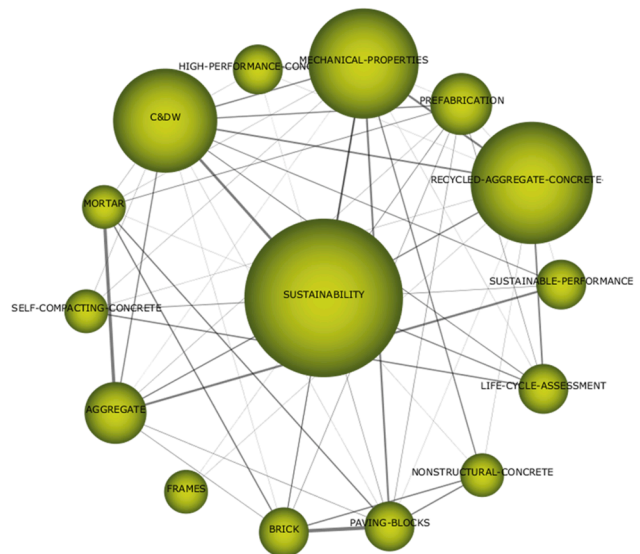
These figures, generated using the SciMat tool, offer a

comprehensive overview of the thematic clusters and the relationships between various topics in the field. Each theme is represented by a network of interconnected nodes, where the size of the nodes reflects the number of documents, and the links denote the relationships between them. In Fig. 7a, the RAC theme is prominently central, with strong links to nodes such as mechanical properties, prefabrication, and sustainability. This network suggests that the use of RAC is fundamentally linked to improving mechanical properties and enhancing sustainable construction practices. The interconnectedness with prefabrication indicates a growing trend toward integrating recycled materials in modular construction components, which aligns with sustainable development goals. Expectedly, the emphasis on mechanical properties and sustainability aligns with existing literature prioritizing structural integrity and environmental impact. Fig. 7b showcases the Sustainability theme, which dominates the network with extensive links to various nodes, including high-performance concrete, C&DW, and LCA. This network underscores the centrality of sustainability in modular construction waste management, highlighting its role as a unifying concept that intersects with numerous aspects of construction practice. A strong linkage to LCA is particularly expected, as it is a critical tool for evaluating the long-term environmental impacts of construction materials and methods. Interestingly, the notable connection to high-performance concrete suggests an unexpected finding: sustainability efforts are not only about recycling and waste reduction but also about advancing high-performance materials that contribute to longer-lasting and more efficient buildings.

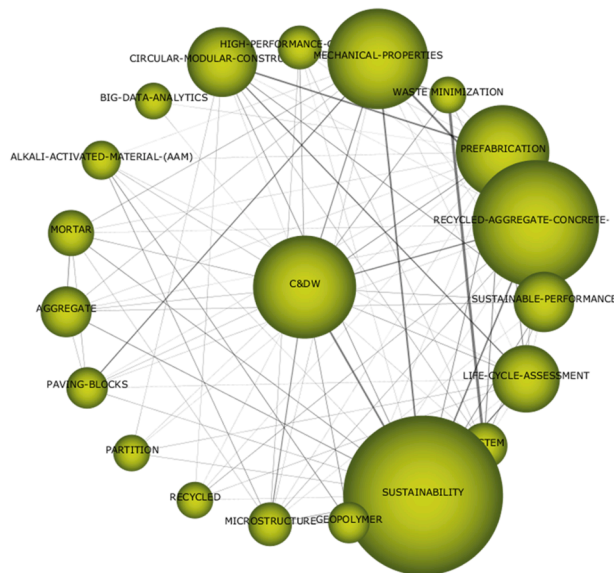
In Fig. 7c, the C&DW theme presents a network emphasizing its relationships with sustainability, circular modular construction, and mechanical properties. This cluster reflects the crucial role of managing C&DW in achieving sustainable construction practices. The strong link to circular modular construction is an expected finding, as the concept of a CE is integral to minimizing waste and maximizing resource efficiency. The network also reveals an unexpected prominence of alkali-activated materials, suggesting a growing interest in innovative waste utilization methods, which indicates a shift towards more advanced material science applications in waste management. Fig. 7d highlights the Prefabrication theme, with a network showing significant connections to C&DW, sustainability, and RAC. Prefabrication's link to these nodes



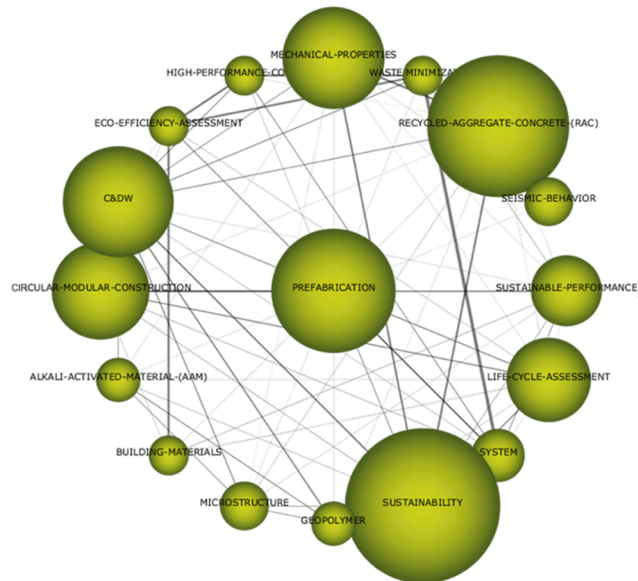
a- RAC Theme



b- Sustainability Theme



c – C&DW Theme



d- Prefabrication Theme

Fig. 7. Cluster's network in the four identified high-impact themes in modular construction waste.

underscores its importance in modern construction practices, where off-site construction methods can significantly reduce waste and improve efficiency. The strong ties to RAC and sustainability reflect expected findings, as prefabrication inherently supports waste reduction and resource efficiency. However, an unexpected finding is a prominent connection to eco-efficiency, suggesting a heightened focus on optimizing the entire construction process to minimize environmental impact, which goes beyond traditional waste disposal strategies.

The expected findings, such as the centrality of sustainability and the integration of recycled materials, align well with current research

trends. Unexpected findings, such as the emphasis on high-performance materials and eco-efficiency, indicate emerging areas of interest and potential future directions for research. The interconnected nature of the themes highlights the complexity of the field and the necessity of a holistic approach to waste management in modular construction. The comparative analysis of Figs. 7–d highlights the centrality of sustainability across all thematic clusters in modular construction waste management, with common connections to mechanical properties and life cycle assessment (LCA), underscoring their importance in structural integrity and environmental impact. Divergences are evident in each

theme's focus: RAC emphasizes mechanical properties and prefabrication, C&DW concentrates on circular modular construction and innovative materials like alkali-activated substances, while Prefabrication underscores eco-efficiency. Unexpectedly, a significant focus on high-performance materials emerges, indicating a shift towards integrating advanced material science with sustainability efforts. This surprising trend suggests future research potential in developing innovative, durable, and efficient construction materials, advocating for a holistic approach to revolutionize waste management and resource utilization in the construction industry. It also highlights the importance of sustainable waste management in all building and construction projects.

4. Limitations

The study relied solely on the WoS database due to its compatible output file formats for the bibliometric analysis tools employed, such as VOSviewer, Bibliometrix, and SciMAT, potentially excluding relevant resources indexed in other databases. Gray literature, conference papers, and other non-journal sources were not included in the analysis, which may have led to the omission of some emerging contributions to the field of modular construction waste management. As the search was restricted to English-language publications indexed in WoS, authors from developing countries who prefer to publish in local, non-English journals may be underrepresented in the dataset analyzed. Authors with multiple affiliations were not explicitly considered in this bibliometric study. This missing piece of information may be important to fully understand how multi-country collaborations have led to innovations or advancements in the field of modular construction waste management.

5. Conclusion

The current study presents a comprehensive text-mining analysis to uncover knowledge gaps and chart future research directions in modular construction waste management from 1996 to 2024. The findings elucidate thematic pillars through cluster analysis and network mapping techniques employing VOSviewer and R language's bibliometrix. The methodology adheres to the PRISMA framework and illustrates the systematic screening process that yielded a final dataset of 118 relevant articles for analysis.

Publication and citation trends reveal a significant surge in research interest and scholarly activity in modular construction waste management starting around 2015, potentially driven by the establishment of the United Nations SDGs. Co-occurrence analysis unveils three distinct thematic clusters, which collectively shape the intellectual landscape. The "C&DW" theme has highest occurrences of 56, with the total link strength of 161. The thematic evolution analysis demonstrated the evolving focus areas, with the Sankey diagram visualizing the collaboration of key themes such as "RAC", "Mechanical Properties", and others with influential studies and countries. Topic trend analysis tracks the evolution of research themes over time, revealing the emergence of sustainability-focused keywords such as "CE" after 2021 with the highest frequency of 13, reflecting the growing emphasis on environmental concerns. Further findings reveal a sustained interest in recycling from 2014, particularly recycled concrete from 2018 to 2022, underscoring the adoption of off-site construction to mitigate waste, reduce costs, and incorporate recycled materials. The clustering by coupling analysis highlights the impact (1.876) and centrality (1.118) of the identified "RAC" as a high-impact theme, following "Prefabrication" and "Sustainability" in the domain of modular construction waste management, underscoring their pivotal role in shaping the field. The cluster's network analysis highlighted the strong link between "RAC", "mechanical properties", "C&DW", and "sustainability", which are of considerable interest and concern. The present study comprehensively and systematically examines the thematic pillars and knowledge gaps in modular construction waste management, providing insights crucial for guiding

future research efforts and fostering sustainable construction practices.

The use of modular construction to minimize C&DW is a relatively new research topic. Many emerging construction practices and trends are predominantly published in trade magazines and conference proceedings. Gray literature can be included in future bibliometric studies. The use of multiple databases in different languages is also recommended to fully capture the recent research trends in this field. It is recommended funding agencies to provide specific funding programs for the identified emerging themes such as circular economy and prefabrication, helping us to improve environmental sustainability in C&DW management.

CRediT authorship contribution statement

Farzin Naghibalsadati: Writing – original draft, Software, Methodology, Conceptualization. **Arash Gitifar:** Writing – review & editing, Validation, Formal analysis. **Amy Richter:** Writing – review & editing, Formal analysis. **Anica Tasnim:** Writing – review & editing. **Kelvin Tsun Wai Ng:** Writing – review & editing, Supervision, Formal analysis.

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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Data availability

Data will be made available on request.

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