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Sustainable waste management in the construction industry

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The sustainability of the construction industry largely depends on effective waste management practices throughout both construction and demolition processes. Construction and demolition waste causes significant environmental degradation, resource depletion, and landfill overflow, making effective waste management an essential component of sustainable construction practices. As the construction industry is one of the biggest contributors of generated waste in today's world, achieving sustainability in this industry is essential for overall sustainable development. This study aims to examine the sustainable approach to construction and demolition waste and develop strategies for the industry. Based on the evaluation of various waste management techniques, this study used a standard approach in examining existing literature available in renowned research databases and key concepts to develop strategies for future construction and demolition waste management. This included identifying appropriate keywords or combining multiple keywords during the search process. Waste reduction and protecting the planet's precious natural resources have been the focus of this study. This research investigated strategies during the planning and design phases. Out of the three strategies tested; reduction at the source, recycling, and reuse, source reduction yields the best results. Selecting materials, optimizing designs, and improving processes are all essential techniques for source reduction. Additionally, it explores the role of policy interventions and regulatory frameworks in improving source reduction practices across the industry. However, as waste reduction may not always eliminate waste generation, especially during the demolition of buildings, it is important to supplement this with existing recycling and reuse approaches. With the use of alternative building materials, it is essential to reassess recycling and reuse options for innovative and sustainable construction materials. The findings illustrate that efficient waste reduction regulations, such as green building certifications and mandatory waste management plans, are critical to achieving sustainability. By incorporating source reduction measures in addition to recycling and reuse of waste management, the construction may drastically minimize its environmental effect while increasing cost efficiency and resource usage. This study emphasizes that source reduction should be mandatory for accomplishing sustainable construction and demolition waste management. Recycling and reuse should complement waste reduction efforts.

KEYWORDS

construction waste management, source reduction, sustainability, waste minimization, regulatory frameworks

1 Introduction

Infrastructure development is crucial for sustaining a country's economy. According to multiple studies (Akhtar and Sarmah, 2018), there is a significant relationship between the construction industry's growth rate of 3.6 percent (%) and the global economy's growth rate of 2.5–3% (Akhtar and Sarmah, 2018). The construction sector has been the subject of much research recently due to its significant energy consumption, environmental emissions, and waste generation (Singh et al., 2023; Yuan and Shen, 2011). The building materials sector plays a crucial role in large-scale resource exploitation, despite its positive contributions to urbanization worldwide. This aligns with the traditional linear "take-make-dispose" cycle (Zhang et al., 2020), where resources are extracted from the earth, processed into goods, and then discarded. Once materials have served their purpose, they are disposed of as waste (Islam et al., 2019). In 2015, the construction industry produced 548 million tons of waste, impacting the environment, according to the EPA's report. The construction industry heavily relies on natural resources like soil, grout, gasoline, bitumen, lumber, steel, and a host of other petroleum goods. The excessive use of these resources contributes to natural resource depletion. "Waste" refers to materials that have served their purpose but are now either broken or left behind after heavy usage. Through innovation, any unwanted substances can be turned into valuable byproducts, combined materials, or services. These encompass a diverse set of resources, which include building and remodeling debris, electronic waste, electrolysis waste, and municipal substantial refuse. Waste broken or unusable building components, and other garbage generated during a building's remodeling, demolition, repair, or construction process are collectively known as demolition and building waste. According to Nandal et al. (2022), the age and kind of construction of the towers being demolished or rebuilt affect the structure of the construction and demolition (C&D) debris. The phrase "C&D waste" is used to describe excess material resulting from various construction, restoration, and demolition tasks, including demolition of the site, land excavation, roadwork, and demolition (Shen et al., 2004). Anything that ends up in a landfill as a byproduct of building, remodeling, restoring, or destroying is considered C&D waste. Because of their size, weight, and density, these wastes are difficult to transport and store in standard trash cans. Both human and environmental health are negatively affected by the waste products of C&D operations. Worldwide, C&D waste accounts for 20–30% of solid waste, with 70–80% of that coming from concrete and masonry. For environmental sustainability, it is important to handle the massive amounts of C&D waste (Dean et al., 2016). Chen et al. (2018) examined managerial areas of C&D waste, highlighting key research trends and challenges. Also 40–50% of all carbon dioxide (CO_2) emissions come from the architecture, engineering, and construction (AEC) field (Dean et al., 2016; Fetting, 2020). Additionally, buildings consume 40 % of all energy consumed in the European Union (EU) (Fetting, 2020), with only 5–10% of that energy going into the production of building materials (Bundgaard et al., 2017). Major construction endeavors, commercial building construction, and housing development programs all contribute to the growing quantity of waste from construction (Begum et al., 2006). Additionally, 40–50% of the world's raw material extractions occur in the building industry (Saghafi and Teshnizi, 2011) or 60% in another study (Bribian et al., 2011). Worldwide, over 33% is comprised of C&D waste (Monier et al., 2011). Additionally, worldwide, C&D waste is often dumped in landfills without recycling (Duan and Li, 2016). As an outcome, C&D waste remains capable of being managed more efficiently. Despite the quantity of published studies on the subject, there is still more work to be done in quantifying the environmental benefits of C&D waste recovery. With the exception of developing nations in South Asia, previous studies on the ecological pros and cons of C&D waste recycling have focused on developed and expanding economies. Based on recent literature reviews, there is a complete lack of work on the attention of C&D recycling in Nepal (Bovea and Powell, 2016). Many scholars, including Esa et al. (2017a), Jimenez-Rivero and Garcia-Navarro (2017), Cabeza et al. (2014), Islam et al. (2015), and Ghisellini et al. (2018) have proposed frameworks for the execution of circular economy (CE) in C&D waste. Furthermore, CE has acquired political significance in the previous decade due to its widespread industrial applications (Kazancoglu et al., 2021). In comparison with the continuous economy's focus on the end-of-life scenario, the CE considers the entire lifecycle (Gedam et al., 2021). It is important to complete the intended management system of waste in order to attain a genuinely CE in buildings (Low et al., 2020), and these frameworks are criticized for not being able to accomplish their goal in developing economies lacking effective laws and regulations for managing waste from construction (Ferronato and Torretta, 2019). In emerging economies, there is almost no implementation of CE in construction, despite what appears to be a large amount of research supporting its adoption (Lockrey et al., 2016; Mahpour, 2018). The stakeholders are concerned about adopting circular practices due to a lack of advice and knowledge about efficient comprehension of C&D waste sorting, reuse, and recycling (Mahpour, 2018; Charef and Emmitt, 2021; Haselsteiner et al., 2021). Developing and urbanizing regions face the added problem of sustainable waste management. Doukari et al. (2023) explore the ways in which CE concepts could be applied to urban building information modeling (BIM) in order to improve sustainability and optimize treatment of demolition waste. Post-disaster debris management is another pressing issue, as highlighted by Esmaeilizadeh et al. (2017), who propose systematic approaches to handle earthquake-induced waste in the ancient City of Ray. Kabirifar et al. (2021) examine building and demolition waste in large-scale construction enterprises in Australia. They advocate for the use of the system for managing waste to encourage recycling and reduce trash. Problems with public knowledge and inadequate infrastructure are among the issues highlighted by Esmaeilizadeh et al. (2017) as they pertain to Iran's municipal garbage disposal. Similarly, the environmental and socioeconomic obstacles that Iran faces when trying to manage its solid waste. One potential answer is the waste-to-energy technology and efficient initiatives to recycle in Malaysia, which are evaluated by Esmaeilizadeh et al. (2017). Also, according to Esmaeilizadeh et al. (2017), developing nations should address their own unique waste management challenges by implementing individualized techniques. All things considered, these studies show how important it is to combine technological advancements, government regulations, and community involvement for sustainable garbage management on a worldwide scale. Rubber (Sukontasukkul and Chaikaew, 2006), slag from electromagnetic arc furnaces (Faleschini et al., 2015), and fly ash (Faleschini et al., 2015) are non-standard building materials, while C&D waste recycling is by far the most prevalent. It might lessen the strain on valuable urban space and natural resources while also augmenting the current mineral supply (Akhtar and Sarmah, 2018). However, the environmental benefits of C&D waste recycling are controversial and very conditional. According to research conducted by de Magalhaes et al. (2017), Brazil generated 45 million tons of construction waste (CW) in 2015, accounting for 57% of global waste material (Faleschini et al., 2015). It may supplement the current mineral supply and lessen the strain on precious urban space and natural resources (Akhtar and Sarmah, 2018). The ecological advantages of C&D waste reusing, however, are highly context-dependent and open to debate. Several countries have utilized life cycle methods to determine the pros and cons of recycling C&D waste. These countries include China (Ding T. et al., 2016), Brazil (Rosado et al., 2019), Hong Kong (Hossain et al., 2016), Spain (Ortiz et al., 2010), Serbia (Marinkovic et al., 2010), Italy (Blengini, 2009), Denmark (Butera et al., 2015), Finland (Dahlbo et al., 2015), and Africa (Vossberg et al., 2014). According to de Magalhaes et al. (2017), over 45 million tons of construction waste were created in Brazil in 2015, accounting for 57% of the country's total recyclable waste. Classifying source reduction is crucial for efficient handling construction and demolition waste. By minimizing the items to be handled, examined or discarded, there is a greater chance to limit waste formation at the point of generation. Modular building systems, for example, can reduce waste by using standard sizes and components to minimize offcuts. Additionally, good design planning can prevent over-ordering of resources. Incorporating green building practices, such as using resilient, recyclable, and environmentally conscious materials, can significantly reduce the need for future removal and reconstruction projects, leading to even less waste. Environmentally friendly construction projects can greatly benefit from decisions made during the design phase to control construction waste at its source (Ekanayake and Ofori, 2004; Esin and Cosgun, 2007; Esa et al., 2017b). Concepts from the CE could offer a long-term solution to the issue of C&D waste. Trash management is evolving with the help of new technologies like block-chain for material passports; and modular construction (Kazancoglu et al., 2021). For instance, the block-chain system promotes accountability by making it easy to track recycling of materials (Charef and Emmitt, 2021). Devaki and Shanmugapriya (2022) reviewed various life cycle assessment (LCA) approaches in C&D waste management, focusing on sustainability and efficiency. Rules and regulations play a significant role in environmentally friendly waste disposal methods. Laws like China's circular economy; Enhancement Law and the EU's Waste Guidelines Directive have established global standards. However, additional research is needed to address implementation issues and compliance discrepancies (Mahpour, 2018). In emerging countries like India and Brazil, C&D waste disposal poses unique challenges due to public ignorance and inadequate infrastructure. Innovative approaches, such as recycling programs organized by municipalities and waste management companies are highlighted in this research (de Magalhaes et al., 2017). Several worldwide legislative frameworks and directives help shape global construction and demolition (C&D) waste management regulations. The European Union Waste Framework Directive (2008/98/EC) establishes a 70% recycling objective for C&D waste, encouraging circular economy concepts throughout member states (Moschen-Schimek et al., 2023). Similarly, the United Nations Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities) and SDG 12 (Responsible Consumption and Production), prioritize sustainable waste management techniques to reduce landfill dependency and resource consumption (Li et al., 2022). In the United States, the Resource Conservation and Recovery Act (RCRA) and the Environmental Protection Agency's Sustainable Materials Management Program promote the reduction and reuse of construction waste, while enforcement varies by state. Meanwhile, China's Circular Economy Promotion Law (2008) and Technical Code for Building Waste Recycling (2019) have been enacted to increase recycling rates, while implementation is patchy (Duan et al., 2019). These global legislative guidelines jointly shape national waste laws, directing industry practices toward more sustainable building waste management.

Artificial intelligence (AI)-powered predictive analytics and robotic sorting systems are revolutionizing the waste management sector (Li et al., 2022), allowing for more precise garbage sorting and improved recycling efficiency. Despite the importance of technologies like BIM and geographic information systems (GIS) in managing C&D waste efficiently, reducing waste at its source remains the most significant method (Li et al., 2022). Instead of only addressing the consequences, this strategy gets to the root of the waste. By integrating source reduction techniques into construction project planning and design, environmental effect can be minimized, cost savings can be achieved, resource efficiency can be improved, and more sustainable building practices can be promoted. To maximize the impact of C&D waste management techniques on long-term sustainability and waste reduction, decision-makers should prioritize eliminating waste at its source (Laurent et al., 2014). This study evaluates various waste management approaches, emphasizing the significant reduction in waste production during the design and planning phases to minimize environmental impact and promote resource conservation. The study also investigates policy interventions and emerging technologies that support waste minimization (Dahlbo et al., 2015). Furthermore, the report explores global trends and barriers to implementing sustainable waste management systems.

Despite increased global interest in C&D waste management, previous research has mostly concentrated on recycling and reuse options, with little attention paid to source reduction as a proactive approach. Furthermore, while bibliometric studies have examined trends in building waste research, few have combined these findings with a thematic analysis of policy efficacy, new technologies, and implementation challenges, particularly in developing and fast urbanizing locations. There is also a lack of comprehensive understanding of how digital tools like BIM and blockchain can be used to reduce C&D waste at the source. This study fills these gaps by combining rigorous mapping and review methods to assess not only publication trends, but also the legislative, technological, and operational obstacles that influence sustainable waste management.

Given the global issues connected with construction and demolition C&D waste, this study seeks to provide a complete assessment of existing management techniques and new solutions. Specifically, it aims to discover worldwide trends, thematic themes, and knowledge clusters relevant to C&D waste using bibliometric and literature analysis. The study also assesses the role of source reduction as a key approach for waste reduction, in comparison to more extensively used methods such as recycling and reuse. It also investigates the effectiveness of international regulatory frameworks and policy interventions in promoting sustainable practices in the building industry. The study also investigates the potential of emerging technologies such as Building Information Modeling (BIM), blockchain, and artificial intelligence (AI) to improve waste monitoring, material efficiency, and the implementation of circular economy concepts. Finally, it identifies crucial research gaps and makes recommendations for improving the implementation of sustainable C&D waste solutions, particularly in developing countries where enforcement and infrastructure are significant impediments. This study aims to evaluate sustainable building waste management and was carried out as a literature analysis at the American University of Sharjah in the United Arab Emirates (UAE) from 2024 to 2025. It utilizes academic articles, research papers, and regulatory documents to provide a comprehensive overview of current sustainable building and demolition waste management strategies and offers guidance toward achieving sustainability in the construction industry.

2 Materials and methods

This study adopts a dual approach by combining systematic mapping through bibliometric analysis with a systematic review of thematic content. While the mapping identifies publication trends, keyword clusters, and author networks, the review explores policy frameworks, regulatory gaps, and emerging technological interventions in C&D waste management.

2.1 Systematic mapping: bibliometric analysis

This study conducted a bibliometric analysis to examine research trends in construction waste management, emphasizing sustainability, circular economy, and source reduction. The Scopus database was selected for its extensive coverage of peer-reviewed literature, ensuring a comprehensive and structured dataset for analysis. The search strategy incorporated the following keywords: "Construction waste management" AND ("Demolition waste" OR "Source reduction" OR "Sustainability" OR "Waste Management" OR "Waste minimization" OR "circular economy" OR "Sustainability"), with the publication timeframe ranging from 2010 to 2025. This initial search resulted in the retrieval of 658 documents from the Scopus database. To refine the dataset, the language was restricted to English, and only final-stage publications were considered, reducing the dataset. Metadata extraction was performed on the selected articles, including titles, authors, publication years, journals, keywords, abstracts, and citation data. The extracted metadata was formatted for compatibility with VOSviewer, a specialized bibliometric analysis tool. The bibliometric analysis was conducted using VOSviewer to construct and visualize various bibliometric networks, such as co-authorship and keyword co-occurrence networks. Network visualization generated maps illustrating relationships and clusters, including keyword co-occurrence networks. Cluster analysis was used to identify major research areas, emerging trends, and influential keywords in construction waste management. The results of the bibliometric analysis were interpreted to highlight significant research keywords, influential sources, and major publications. The keywords were presented using VOSviewer-generated visualizations, supplemented by narrative explanations.

A total of 439 publications related to construction waste management were identified in the Scopus database from 2010 to 2025, as illustrated in Figure 1. The publication trend shows a steady increase over the years, indicating growing academic interest in sustainable waste management practices within the construction sector. Between 2010 and 2015, the number of publications fluctuated, with a moderate rise from 4 publications in 2010 to a peak of 31 publications in 2016, followed by a slight decline in 2017 and 2018. However, from 2019 onward, a consistent upward trend is observed, with a notable increase in publications reaching 31 in 2019, 34 in 2020, and 39 in 2021. This upward trajectory aligns with the increasing emphasis on sustainability, circular economy practices, and stricter regulations on construction waste management during this period. The most significant rise in publications occurred between 2021 and 2024, with numbers increasing from 39 publications in 2021 to 54 in 2023, ultimately reaching a peak of 68 publications in 2024. The drop in publications for 2025 (7 publications) can be attributed to the partial data availability at the time of analysis, as ongoing research is yet to be fully indexed in Scopus. In addition to annual trends,

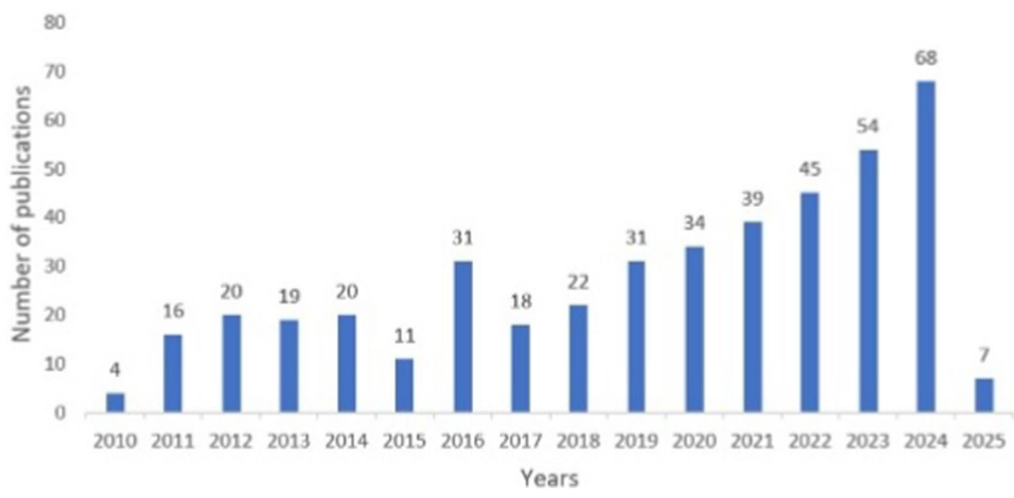

FIGURE 1
Annual publications and cumulative publications on the C&D waste management.

Figure 2 illustrates the distribution of the 439 selected documents by type, showing that the majority are journal articles, followed by conference papers, reviews, and a smaller number of book chapters and editorials. This distribution reflects the academic rigor of the dataset, as journal articles and reviews typically undergo more extensive peer review, enhancing the credibility of the findings. The presence of diverse document types also suggests that the topic of C&D waste management is attracting attention across both theoretical and practical domains.

A co-occurrence analysis was conducted using VOS viewer, which measures the relatedness of keywords based on how frequently they appear together in the same documents. Network Visualization of the co-occurrence of all keywords are shown in Figure 3. The authors' keywords dataset included 1,821 keywords, out of which 142 met the threshold of appearing at least five times. For these selected keywords, VOS viewer calculated the total strength of their co-occurrence links, which represents the frequency with which they co-exist within the literature.

Several key observations emerged from this analysis. The keyword "waste management" had the highest occurrence (188 times) with a total link strength of 1,436, reinforcing its central role in construction waste-related research. The term "construction industry" was also highly prevalent, with 105 occurrences and a total link strength of 867, highlighting the strong connection between industry practices and waste generation. "Construction waste management" (occurrences: 101, total link strength: 651) and "construction and demolition waste" (occurrences: 75, total link strength: 706) further underscore the increasing focus on waste reduction, recycling, and responsible material disposal. Additionally, "sustainable development" (occurrences: 55, total link strength: 462) indicates growing research interest in aligning construction waste management with global sustainability goals and circular economy principles. The high co-occurrence and strong link strengths of these keywords suggest that construction waste management research is closely interconnected with sustainability, industry practices, and resource efficiency. These findings emphasize the importance of integrating circular economy strategies, regulatory frameworks, and innovative technologies to enhance sustainable construction waste management.

A rigorous quality assessment using numerous criteria was carried out to assure the reliability and rigor of the selected 439 papers. First, only peer-reviewed journal articles and respectable conference proceedings were included to ensure academic authenticity. The methodological rigor of each study was assessed by looking at the research design, data collection methods, sample size (for empirical studies), and analytical procedures, with papers that lacked a defined research framework or methodological information being removed. Additionally, publications were evaluated for their direct relevance to construction and demolition (C&D) waste management, ensuring that those focusing on municipal solid waste or unrelated sustainability subjects were excluded. Citation impact was used to balance influential and emerging research, promoting highly cited studies while also considering newer research that introduced innovative ideas despite having fewer citations.

While bibliometric analysis can provide useful insights into research trends, keyword relationships, and citation networks, it does have some limits that should be addressed. One significant drawback is database limits, as this analysis depends heavily on Scopus, which, despite its broad coverage, may exclude important studies from alternative databases such as Web of Science or Google Scholar, thereby adding selection bias (Duan et al., 2019). Furthermore, citation bias can influence results, as highly cited publications appear more frequently in studies, even if they do not necessarily represent the most recent advances in the area (Li et al., 2022). Another issue is language bias, which occurs when non-English papers are underrepresented, reducing the comprehensiveness of the global research environment. Furthermore, bibliometric analysis does not

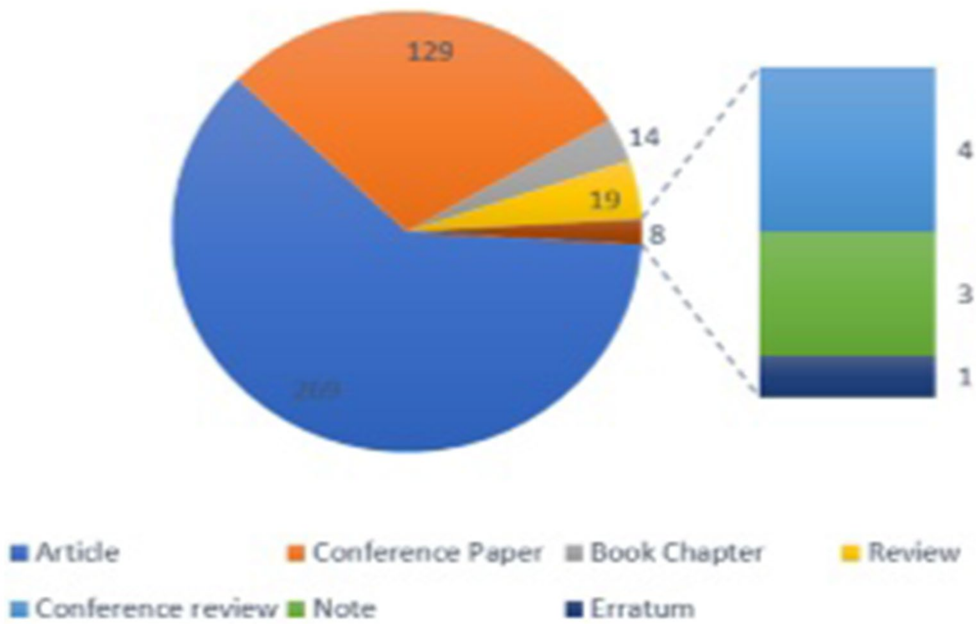

FIGURE 2
Publications on the C&D waste management sorted by document type.

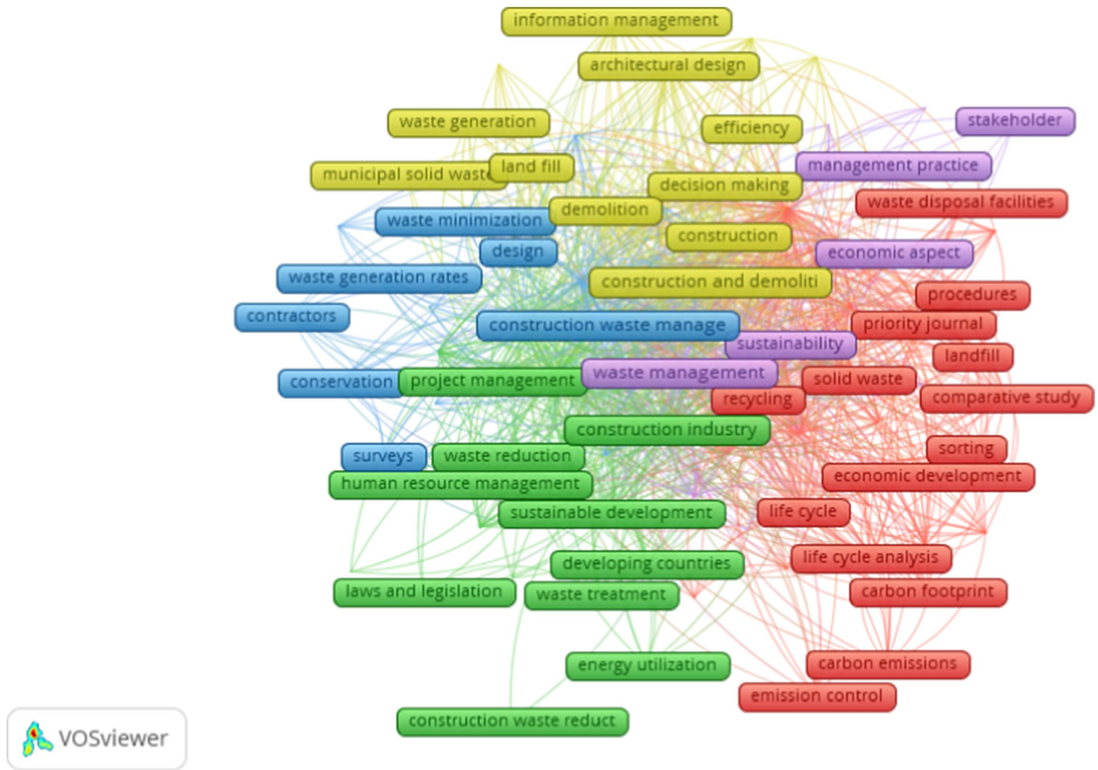

FIGURE 3
Network visualization of the co-occurrence of all keywords.

evaluate the quality or methodological rigor of the papers under consideration, necessitating further qualitative assessments to ensure a more comprehensive knowledge of research trends (Kazancoglu et al., 2021). Recognizing these limitations, future research should examine multi-database techniques, the inclusion of gray literature, and the incorporation of qualitative content analysis to reduce potential biases and strengthen bibliometric conclusions.

2.2 Systematic review: thematic literature analysis

In parallel with the bibliometric mapping, a qualitative systematic review was conducted to examine the broader thematic context of sustainable construction and demolition waste management. This review involved synthesizing scholarly literature that explored policy frameworks, source reduction strategies, circular economy implementation, and technological innovations in various geographic and regulatory settings.

The reviewed literature included case studies from countries such as Sweden, Germany, China, and the UAE, focusing on best practices and challenges in C&D waste policy implementation. Attention was also given to emerging technologies such as BIM, AI-based sorting, blockchain material tracking, and modular construction systems. Furthermore, the review critically assessed global directives including the EU Waste Framework Directive, China's Circular Economy Promotion Law, and the U.S. EPA's Sustainable Materials Management Program, comparing their adoption and effectiveness in promoting sustainable practices. This thematic review allowed the study to go beyond publication trends and co-occurrence networks, providing a deeper understanding of the qualitative drivers and barriers shaping current and future approaches to sustainable construction waste management.

3 Results

3.1 Global trends in C&D waste generation

There is an urgent need for appropriate management of C&D waste due to the scarcity of disposal options, associated costs, contamination, and environmental impact. The practice of dumping C&D debris in cities leads to river pollution, clogged surface drains, halted traffic, and an unsightly urban landscape. It is beneficial for the environment and its resources to divert building and demolition waste from landfills and find new applications for it (Nandal et al., 2021). Recycling aggregates from building and demolition trash helps reduce mining's environmental impact, saves limited resources of high-quality virgin aggregates, and closes the production-to-consumption gap. Jain et al. (2020) state that in many nations, C&D debris is progressively supplanting natural aggregates. Inadequate management of open dumping puts both humans and the environment in danger (Khasreen et al., 2009). Recycling, together with garbage reduction and the construction of a single disposal and treatment facility, should be the main priorities for waste management to make it more efficient and ecologically beneficial. Figure 4 illustrates the primary sectors contributing to waste generation, including residential, institutional,

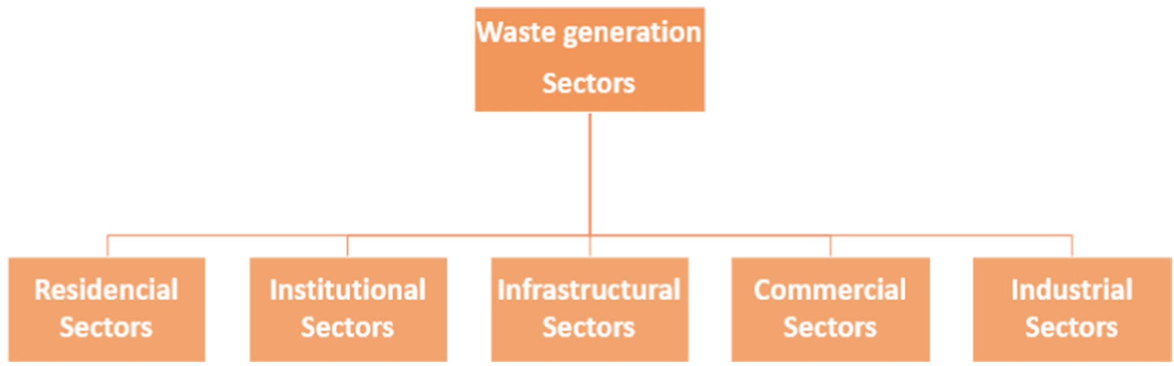

FIGURE 4
C&D waste generated in several fields.

infrastructural, commercial, and industrial sectors. Understanding these categories is crucial for implementing targeted waste reduction and management strategies. The residential sector contributes to C&D waste through house construction, restorations, and demolition, whereas the institutional sector, which includes schools, hospitals, and government buildings, produces waste through infrastructure expansion and refurbishment. The infrastructure sector generates enormous amounts of garbage from public works projects like roads, bridges, and utility networks. Similarly, the commercial sector, which includes office buildings, shopping malls, and corporate enterprises, generates trash owing to continuous restorations and rebuilding. Finally, the industrial sector produces C&D trash through plant expansions, warehouse development, and manufacturing-related infrastructure. This classification illustrates the numerous sources of C&D waste, emphasizing the importance of sector-specific waste management solutions to increase trash reduction, recycling, and long-term material recovery.

Solid waste management is necessary throughout the entire lifecycle of different types of urban trash, from creation to disposal (Purohit et al., 2021). Medical waste, construction debris, and municipal solid waste all fall within this category. China produces the largest amount of C&D waste and Australia the least (Purohit et al., 2021). The building sector accounts for 39% of all energy-related CO_2 emissions (United Nations (UN), 2021) and 35% of all landfill waste (OECD, 2019). Therefore, the C&D sector is crucial in advancing material circularity and social sustainability on a global and European scale. C&D waste accounts for almost 30% of global material waste, with a significant portion of it being recyclable. Given that some of these materials contain toxic compounds that are harmful to people and the environment, it is critical to reduce C&D waste production and manage its long-term ecological effects (Khoo, 2009). Saudi Arabia faces significant challenges in managing C&D waste, as highlighted by Haider et al. (2022). Similarly, Australia has been grappling with the impacts of C&D waste on the environment and urban infrastructure (Zhao et al., 2022). In Denmark, issues related to construction waste have been extensively studied, emphasizing the need for sustainable management practices (Christensen et al., 2022). The European Union has also recognized the urgency of addressing C&D waste through updated policies and regulations (Moschen-Schimek et al., 2023). Furthermore, Norway is experiencing growing concerns over the environmental impact of C&D waste, necessitating improved recycling and reuse strategies (Svedmyr et al., 2024). Beyond these regions, Malaysia has also been identified as a country facing substantial C&D waste challenges (Hentges et al., 2022). Similarly, the UAE is dealing with increasing construction waste due to rapid urbanization and infrastructure expansion (Nie et al., 2024). In Egypt, the issue of C&D waste has been examined, with studies highlighting the need for more efficient waste reduction and recycling strategies (Daoud et al., 2023).

Mixed concrete and ceramic waste have been identified as the major types of C&D waste around the world. Table 1 shows the distribution of different waste categories in total construction and demolition (C&D) waste generation by country. Mixed concrete and ceramic waste is the most common type, with Spain (85%), Italy (84.3%), and Portugal (82.9%) having the highest quantities. The UK (27%) and Norway (14.58%) have significantly greater wood waste rates, showing regional disparities in construction materials and demolition techniques. The presence of metals, asphalt, plastics, and gypsum varies greatly, with countries such as the United States (14% asphalt), Portugal (4.5% metal), and the United Kingdom (10% gypsum) having greater numbers in specific categories. The data shows geographical variations in waste composition, which reflect changes in construction processes, material utilization, and trash management policies between countries. The basic components of the waste created by the C&D industry in the UAE include substances and nutritional waste, paper, packaging, brick, bitumen roofing, plastics as a wood substitute, road concrete, and asphalt, glass, drywall, and ceiling tile fragments. The predicted doubling of the global population by 2040 is expected to lead to an increase in the demand for housing and, consequently a doubling of waste production. An astonishing 92% of Greenhouse Gas (GHG) emissions stem from solid waste disposal in Abu Dhabi landfills, with 6.9% of these emissions from the waste industry overall, as reported by the Environment Agency of Abu Dhabi (EAD). In 2016, approximately 4.55 million cubic yards of non-hazardous waste were generated by the construction and demolition sector, accounting for roughly 50% of the total waste produced (Ouda et al., 2017). There was a significant increase of 62.92% from the previous year, with C&D activities producing 34% of the non-hazardous waste in 2015, of which 66% ended up in waste dumps, landfills, or other disposal facilities.

Waste management for C&D is a significant issue for major economies such as the US and China. According to Jin et al. (2017), the rapidly expanding construction sector and urbanization in China

TABLE 1 Distribution of waste categories in total C&D waste generation.

Country	Soil and Rocks	Mixed concrete and ceramic waste	Wood	Paper	Plastic	Gypsum	Metal	Asphalt	Other	Sources
Spain	–	85.00	11.20	–	0.20	–	1.80	–	1.80	Mercader-Moyano et al. (2022)
UK	–	33.00	27.00	18.00	–	10.00	3.00	–	11.00	Li et al. (2022)
Italy	–	84.30	–	–	–	–	0.08	6.90	8.80	Galderisi et al. (2022)
Norway	–	67.24	14.58	–	–	–	3.63	–	14.55	Svedmyr et al. (2024)
Portugal	–	82.90	–	1.20	0.16	6.40	4.50	4.20	–	Sharma et al. (2023)
United States	–	72.00	7.00	–	–	3.00	1.00	14.00	–	Vincent et al. (2022) and Sharma et al. (2023)
India	35.00	65.00	2.00	–	–	–	5.00	2.00	1.00	Sharma et al. (2023)
China	–	–	5	20	–	–	8		18	Sharma et al. (2023)

account for 30–40% of global C&D waste, while the US contributes 30–40% as well. In 2014, the US generated approximately 534 million tons (Mt) of C&D waste, while China produced over 1,130 Mt (Lu et al., 2017; Menegaki and Damigos, 2018). However, the amount of C&D waste increased in 2015, with US generating 548 Mt. and China producing 2,500 Mt (Duan et al., 2019). In contrast, according to Menegaki and Damigos (2018), China's average rate of recycling C&D debris was only 5% between 2014 and 2015. Table 2 shows the percentage of C&D waste disposed of in landfills across regions. Hong Kong (65%) and the United Kingdom (50%) have the highest landfill disposal rates, reflecting a strong reliance on landfilling due to poor recycling facilities or legal limits. In contrast, Australia (20–30%) and the United States (33%) have lower landfill rates, indicating improved waste diversion techniques, stronger restrictions, or more advanced recycling programs. The statistics show large geographical differences in landfill dependency, underlining the need for improved waste reduction efforts and circular economy techniques in areas with high landfill disposal rates (Kofoworola and Gheewala, 2009).

According to the most recent government figures from 2021, the UAE collected 35 million tons of garbage in 2016, with over 66% of that amount coming from building and demolition (Faridi and El-Sayegh, 2006). For new building work, the overall generation rate of building materials per built region was 0.22 tons per square meter (t/m^2), while for renovation work, it was 0.41 t/m^2. The unit weight of new building waste was found to be 0.98 tons per cubic meter (t/m^3), and for reconstruction work, it was 0.92 t/m^3, according to research conducted by Ferreira et al. (2014).

3.2 Factors affecting C&D waste generation

The UAE generates a significant amount of C&D waste due to poor design standards, low-quality materials, and lack of stakeholder awareness. Frequent revisions to building plans, excessive off-cuts, and disposal of temporary structures further contribute to waste accumulation (Bialko, 2023). In Turkey, design-related inefficiencies, such as multiple revisions, construction errors, and poor project planning, result in excessive waste (Esin and Cosgun, 2007). Additionally, ineffective site management and supervision, including improper material handling and uneconomical cutting methods, increase waste generation (Borghi et al., 2018; Gumusburun and Anaç, 2024). In Jordan, frequent client-driven design changes, contract misinterpretations, and poor materials storage lead to waste (Bekr, 2014). Lack of skilled labor, inadequate waste minimization measures, and difficult site conditions further hinder waste management. Other contributing factors include transportation damage, theft, vandalism, and inaccurate quantity estimations, leading to excessive material use. Sustainable waste management improves financial performance, cost savings, and profitability by minimizing material waste, reducing disposal costs, and enhancing resource efficiency (Ajayi et al., 2017). Financial models like life cycle costing and CE principles demonstrate long-term cost benefits of waste reduction investments (Kazancoglu et al., 2021). Different construction sectors require unique waste management approaches. Residential projects benefit from on-site material sorting, modular building, and prefabrication (Ajayi et al., 2017). Commercial buildings leverage green certifications, demolition planning, and BIM integration to enhance resource efficiency (Charef and Emmitt, 2021). Industrial construction prioritizes waste-to-energy projects, material recovery, and closed-loop recycling (Duan et al., 2019). Large-scale infrastructure and historic renovations rely on adaptive reuse, selective demolition, and recovered material integration (Kazancoglu et al., 2021). Additionally, academic institutions, training programs, and sustainability awareness initiatives are essential for advancing waste management techniques, driving research, and fostering industry collaboration to improve long-term sustainability.

TABLE 2 Disposal potential of construction waste (Yeheyis et al., 2013).

C&D waste	Biodegradable potential	Potential for landfilling	Potential for incineration
Concrete	No	Yes	No
Steel	No	No	No
Brick and block	No	Yes	No
Insulation	No	No	Yes
Glass	No	Yes	No
Ceramic	No	Yes	No
Aluminium	No	No	No
Plastic	Some are biodegradable	No	Yes
Paint	Some are biodegradable	No	Yes
Wood	Yes	Yes	Yes
Gypsum board	Yes	No	No
Cardboard	Yes	Yes	Yes
Asbestos	No	If sealed properly	No

Public-private partnerships (PPPs) are crucial to the successful implementation of construction and demolition (C&D) waste management policies, especially in terms of infrastructure development, recycling facility finance, and regulatory compliance. Given that governments frequently lack the financial and technical capacity to effectively enforce waste regulations, collaborating with private sector stakeholders enables increased investment in waste processing plants, digital tracking systems, and sustainable construction materials (Moschen-Schimek et al., 2023; Charef and Emmitt, 2021). In Germany and Sweden, PPPs have encouraged the creation of advanced recycling factories in which construction firms are incentivized to separate and process trash, resulting in much higher material recovery rates (80–90%). In China, government collaboration with private construction enterprises has resulted in greater use of prefabrication techniques, reducing material waste by up to 50% (Duan et al., 2019). Similarly, in the UAE, PPPs have played an important role in the Dubai Integrated trash Management Master Plan, which combines public and private sector efforts to encourage circular economy techniques such as on-site trash segregation, material reuse, and digital waste tracking. However, issues persist in underdeveloped economies, where PPP frameworks are frequently inadequate due to inconsistent regulations, a lack of transparency, and insufficient financial incentives for private investors (Ferronato and Torretta, 2019; Ajayi et al., 2017). In m any cases, private firms are reluctant to participate in recycling infrastructure due to unclear profits, and governments lack regulatory measures to assure compliance among industries (Tam and Shen, 2018; Low et al., 2020). Clear legal frameworks, financial incentives like as tax breaks and subsidies for sustainable construction techniques, and digital platforms like blockchain for accurate waste reporting are all necessary for successful PPP models (Li et al., 2022). PPPs can drive sustainable waste management activities, encourage technical innovation, and increase compliance with circular economy principles by strengthening collaboration among governments, industry players, and NGOs (Kazancoglu et al., 2021). Thus, including PPP-driven policies into building waste management programs is critical for long-term sustainability and economic feasibility.

Collaboration between governments, corporate sector partners, and non-governmental organizations (NGOs) is critical for improving waste reduction projects and ensuring their successful implementation. Governments can create legal frameworks, financial incentives, and policy guidelines, while the private sector drives innovation, investment, and operational efficiency in sustainable waste management (Moschen-Schimek et al., 2023). NGOs play an important role in lobbying, education, and capacity building by bridging the gap between policy creation and on-the-ground implementation (Ferronato and Torretta, 2019). Public-private partnerships, industry-wide waste management pledges, and cross-sector cooperation can help to speed the implementation of CE ideas in construction (Kazancoglu et al., 2021). Educational campaigns, incentive programs, and waste reduction training workshops are examples of tactics that can be used to raise public awareness and community participation (Ajayi et al., 2017). Mandatory waste audits, school-wide awareness campaigns, and digital platforms for tracking and reporting waste management progress can engage stakeholders at all levels. Furthermore, trash disposal guidelines, material reuse incentives, and local government-led recycling activities encourage active community participation in waste reduction efforts, encouraging long-term sustainability in the building industry. Table 3 presents a structured review of previous research relevant to this topic. It highlights major findings, techniques, and research needs from a variety of studies that have looked into building waste management, CE concepts, technical breakthroughs, financial incentives, and policy mechanisms. This table lays the groundwork for the current study by highlighting significant concerns, emerging trends, and areas that require more investigation. By systematically analysing previous studies, this review expands on their findings to propose effective strategies for improving construction waste management while addressing existing gaps, such as the need for large-scale digital tool implementation, waste reduction economic modeling, and policy effectiveness in developing countries.

3.3 Case study 1

Sweden is regarded as a global leader in construction and demolition (C&D) waste management, having achieved a 90% recycling and reuse rate through strict waste sorting regulations and landfill bans, with waste-derived aggregates replacing 20–30% of virgin materials in new construction projects (Moschen-Schimek et al., 2023). This success is the result of stringent regulatory laws, landfill prohibitions, financial incentives, and technological advancements targeted at reducing trash at the source, encouraging material recovery, and minimizing environmental damage (Moschen-Schimek et al., 2023). One of Sweden's important projects is the Swedish Waste Management Plan, which requires mandatory garbage sorting on construction sites, guaranteeing that materials like concrete, wood, steel, and plastics are separated for recycling rather than being dumped in landfills. Furthermore, Sweden has imposed

TABLE 3 Summary of key studies on sustainable construction waste management.

No.	Sources	Key findings	Methodology	Gaps in literature
1	Ajayi et al. (2017)	Identified financial and regulatory barriers in sustainable construction waste management.	Qualitative interviews with industry experts.	Lack of empirical data on cost–benefit analysis of sustainable practices.
2	Kazancoglu et al. (2021)	Explored the circular economy model and its impact on construction waste reduction.	Comparative analysis of circular economy models in developed countries.	Limited research on circular economy adoption in developing countries.
3	Moschen-Schimek et al. (2023)	Analyzed global construction waste policies and their effectiveness in achieving sustainability.	Policy review and cross-country comparison of waste management frameworks.	Need for more standardized metrics to evaluate policy effectiveness.
4	Charef and Emmitt (2021)	Demonstrated the role of digital tools like BIM in optimizing material efficiency.	Case study analysis of BIM applications in construction waste management.	Absence of large-scale implementation studies on BIM for waste reduction.
5	Devaki and Shanmugapriya (2022)	Reviewed automation and AI-driven sorting technologies for enhancing recycling efficiency.	Experimental study on AI-powered robotic sorting systems for C&D waste.	Limited integration of AI-based waste sorting in real-world construction projects.
6	Li et al. (2022)	Analyzed the role of GIS and AI in tracking material flow and optimizing waste management.	Data-driven analysis using GIS and AI models in construction projects.	Need for empirical validation of AI-driven waste tracking in construction.
7	Purohit et al. (2021)	Explored challenges faced by developing countries in adopting sustainable construction waste practices.	Case study research on waste management practices in developing nations.	Lack of large-scale implementation studies on policy effectiveness in emerging economies.

high landfill costs, prohibited the dumping of useable goods and encouraged recycling behaviors (Kazancoglu et al., 2021). The Stockholm Royal Seaport Project, one of Europe's most ambitious sustainable urban constructions, exemplifies Sweden's accomplishment in eliminating waste. This project incorporates CE ideas, emphasizing waste reduction, material reuse, and sustainable sourcing. It uses pre-fabricated components to reduce onsite waste and digital tools like BIM to increase material efficiency and reduce waste output (Charef and Emmitt, 2021). Furthermore, public-private partnerships and government incentives, such as recycled material subsidies and tax credits for sustainable construction, have prompted businesses to adopt environmentally friendly building practices and invest in sustainable waste management technologies (Kazancoglu et al., 2021). These findings show the need for a combination of tight rules, financial incentives, circular economy ideas, and digital technologies.

3.4 Case study 2

Germany has successfully implemented a circular economy (CE) approach to managing construction and demolition (C&D) waste, achieving an 80% recycling rate through its Circular Economy Act, which allows for the repurposing of over 12 million tons of construction debris each year, significantly reducing landfill dependence and material extraction (Kazancoglu et al., 2021). The German Circular Economy Act requires waste prevention, reuse, and high material recovery rates, guaranteeing that construction materials are recycled into new building projects rather than discarded. This method is supported by stringent legislative frameworks, financial incentives, and cutting-edge digital tracking technologies that encourage sustainable waste management practices. Germany's Construction Materials Passport System is a key innovation that digitally tracks building components and materials throughout their lifecycle, assisting in determining which materials can be reused, repurposed, or recycled to facilitate a closed-loop material cycle in the construction industry (Charef and Emmitt, 2021). Furthermore, modern technology, like AI-powered robotic sorting. Furthermore, modern technologies such as AI-powered robotic sorting systems and 3D printing using recycled construction materials have considerably increased trash recovery rates and resource efficiency by automating material separation and repurposing operations (Devaki and Shanmugapriya, 2022). The EUREF-Campus project in Berlin is a prominent example of German waste reduction innovation, as it combines waste-efficient construction practices, circular economy strategies and digital tools. This project used AI-powered robotic demolition systems to separate precious elements like steel, wood, and concrete for reuse in new buildings. Furthermore, 3D printing technology was used to recycle construction waste into new building components, considerably lowering reliance on virgin resources (Devaki and Shanmugapriya, 2022). Furthermore, industry collaboration and financial incentives, such as tax credits and government subsidies for sustainable construction, have encouraged businesses to incorporate recycled materials into new constructions, cementing Germany's leadership in circular economy practices. These strategies demonstrate how a mix of regulatory enforcement, digital tracking, automation, and financial incentives can provide a highly efficient and sustainable construction waste management system.

3.5 Lessons, global contributions, and mitigation strategies

Industries outside construction, such as manufacturing, food processing, and technology, have successfully adopted zero-waste strategies, providing valuable lessons. The automotive sector uses closed-loop manufacturing, recovering materials from end-of-life vehicles to minimize landfill waste (Kazancoglu et al., 2021). Similarly, the food industry employs waste valorisation techniques, repurposing byproducts into biofuels and animal feed (Purohit et al., 2021). The electronics industry enforces extended producer responsibility laws, requiring manufacturers to recycle outdated devices, and promoting circularity (Charef and Emmitt, 2021). These industries highlight resource efficiency, material circularity, and producer responsibility—principles the construction sector can adopt for sustainable waste management. Sustainable C&D waste management is vital for achieving the United Nations' SDGs, particularly SDG 11 (Sustainable Cities), SDG 12 (Responsible Consumption), and SDG 13 (Climate Action). It minimizes raw material extraction, landfill waste, and carbon emissions (Moschen-Schimek et al., 2023). SDG 6 (Clean Water and Sanitation) is also supported by reducing water contamination from construction debris, while SDG 8 (Decent Work and Economic Growth) benefits from green jobs in recycling and eco-friendly material production (Ajayi et al., 2017). Despite its significance, C&D waste is often landfilled or illegally dumped, worsening GHG emissions, ecological degradation, and public health risks, especially in developing countries with weak waste management systems (Ghailani et al., 2023; Jin et al., 2019). The CE offers a long-term solution by reusing, recycling, and reintegrating materials. However, challenges remain, including regulatory inconsistencies, lack of supply chain coordination, and weak market demand for recycled materials (Charef and Emmitt, 2021). Developers often prefer new materials due to concerns about durability and cost (Devaki and Shanmugapriya, 2022). Addressing these issues requires stronger policies, landfill diversion targets, and financial incentives to promote circular construction models (Kazancoglu et al., 2021). Bio-based and recycled materials like hempcrete, mycelium composites, bamboo, and recycled concrete aggregate (RCA) are gaining popularity due to their low-carbon footprint and durability (Purohit et al., 2021). Geopolymer concrete, which incorporates fly ash and slag, significantly reduces carbon emissions (Li et al., 2022). However, market acceptance, cost variability, and standardization hinder widespread use. Future research should focus on enhancing production efficiency, performance benchmarks, and financial incentives to increase the adoption of sustainable materials in construction.

3.6 Sustainability in construction waste management

Government rules and regulations are essential for sustainable construction waste management, with many countries implementing waste reduction, recycling, and disposal control policies. The EU Waste Framework Directive (2008/98/EC) set a 70% recycling target for non-hazardous C&D waste by 2020, reinforced by the Circular Economy Action Plan 2020, though implementation varies across member states. In the United States, the Resource Conservation and Recovery Act and EPA's Sustainable Materials Management Program promote waste reduction, but LEED certification remains voluntary, leading to inconsistent adoption. China's Circular Economy Promotion Law (2008) and Technical Code for Building Waste Recycling (2019) encourage recycling, though weak enforcement limits effectiveness (Duan et al., 2019). Australia's National Waste Policy (2018) prioritizes recycling, achieving 70% recovery rates, though infrastructure gaps persist (Australian Government, 2020). The UAE mandates C&D waste separation, while Saudi Arabia's Vision 2030 promotes landfill diversion. Recycling rates vary significantly between developed and developing countries. Nations like Germany, the Netherlands, and Denmark achieve 80% recycling rates due to strict policies and financial incentives (Moschen-Schimek et al., 2023). In contrast, India, Brazil, and South Africa struggle with weak regulations, inadequate waste treatment, and limited incentives (Purohit et al., 2021).

Despite the existence of construction and demolition (C&D) waste legislation in poor nations, enforcement is severely inefficient due to inadequate institutional structures, a lack of finance, and a lack of technical expertise. Many national and municipal governments lack the capacity to monitor, regulate, and enforce compliance, resulting in widespread unlawful dumping, open burning, and landfill usage (Ferronato and Torretta, 2019; Purohit et al., 2021). In India, for example, the Construction and Demolition Waste Management Rules (2016) require waste segregation and recycling, but enforcement is poor due to fragmented municipal governance and inadequate infrastructure, with only 1% of C&D waste recycled (Duan et al., 2019; Low et al., 2020). Similarly, in Brazil, despite regulatory frameworks that promote waste minimization, compliance is hampered by informal construction practices, a lack of waste tracking mechanisms, and corruption in waste management contracts, resulting in over 50% of C&D waste being illegally dumped (Tam and Shen, 2018; Moschen-Schimek et al., 2023). China, despite enacting its Circular Economy Promotion Law (2008), still faces challenges in enforcing waste sorting regulations, as local governments frequently prioritize rapid urbanization over sustainable waste policies, resulting in C&D waste recycling rates of <10% in some regions (Li et al., 2022). A major barrier to sustainable waste management is a lack of financial incentives; in most developing countries, recycling facilities are underfunded, and there are no subsidies or tax breaks for green building materials or circular economy practices, discouraging industry-wide adoption (Kazancoglu et al., 2021; Charef and Emmitt, 2021).

Many developing countries rely on informal waste management, leading to illegal dumping, burning, and environmental hazards (Ferronato and Torretta, 2019). Public awareness, financial constraints, and lack of expertise further hinder effective implementation, increasing landfill dependence and missed material recovery opportunities. To address this, stronger regulatory enforcement, financial aid for infrastructure, and international cooperation are needed. Economic incentives, such as tax breaks, subsidies, and financial awards, promote sustainable waste management. Germany and Sweden offer tax benefits for projects using recycled materials (Moschen-Schimek et al., 2023), while the UK's landfill tax has driven higher recycling rates. Japan's Green Building Program provides low-interest loans and tax incentives for sustainable materials (Tam and Shen, 2018), and China offers land-use fee reductions for recycling facilities (Duan et al., 2019). In the United States, tax credits and state subsidies encourage green building adoption. However, financial support remains scarce in developing nations, limiting investment in advanced recycling technologies. Bridging this gap requires public funding, international collaboration, and private-sector engagement to enable the global transition to sustainable construction waste management.

Regulatory frameworks play an important role in construction and demolition (C&D) waste management, but their efficiency varies greatly among countries due to enforcement issues, discrepancies in policy implementation, and inadequate incentives for compliance. While the European Union (EU) Waste Framework Directive (2008/98/EC) established a 70% recycling target for non-hazardous C&D waste by 2020, many member states continue to struggle with policy enforcement and infrastructure limitations, resulting in uneven recycling rates across countries (Moschen-Schimek et al., 2023; Mahpour, 2018). In contrast, Germany and Sweden have successfully implemented strong landfill prohibitions and circular economy incentives, resulting in recycling rates of 80–90%, but Italy and Spain continue to fall below 50% due to lax regulatory monitoring (Tam and Shen, 2018; Duan et al., 2019). The Circular Economy Promotion Law (2008) and Technical Code for Building Waste Recycling (2019) encourage recycling in China, but weak enforcement and inconsistent local policies have limited their impact, with recycling rates in some provinces remaining below 10% (Li et al., 2022; Low et al., 2020). Similarly, in developing countries such as India and Brazil, C&D waste legislation exist but are not well enforced, resulting in significant landfill dependency and illicit dumping (Ferronato and Torretta, 2019; Purohit et al., 2021). While the United States has EPA-led Sustainable Materials Management programs and LEED certification incentives, there are no federal mandates for C&D waste reduction, resulting in state-by-state policy disparities and inconsistent adoption of sustainable waste management practices (Charef and Emmitt, 2021). A major challenge across all regions is that most regulatory frameworks prioritize recycling over source reduction, despite evidence that source reduction reduces waste output from the start and leads to improved long-term sustainability.

Sustainable construction waste management aims to minimize environmental impact by promoting recycling, reuse, and waste reduction through efficient project design. The goal is to preserve natural resources, reduce landfill waste, and lower GHG emissions. Key recommendations include proper material auditing before deconstruction, off-site manufacturing, and buy-back negotiations for non-customized items (Kibert, 2016). Reducing waste at the design and procurement stages and fostering employee awareness are also crucial for sustainability (del Río Merino et al., 2010). Deconstruction reduces disposal and transportation costs (Roslan et al., 2016), while landfill limitations, emissions, and water contamination make C&D waste a key challenge for urban sustainability (Ghailani et al., 2023; Jin et al., 2019). The sustainability movement emerged to improve waste diversion through reduction, reuse, and recycling (Jin et al., 2017). Technology, management, and regulations are essential in tackling C&D waste, which impacts social, economic, and environmental systems (Jin et al., 2019). The C&D waste disposal hierarchy plays a crucial role in waste management (Huang et al., 2018). Sustainable construction emphasizes maximizing resource reuse, minimizing consumption, and promoting renewable materials, supporting a CE where materials are continuously repurposed (Ismam and Ismail, 2014). Figure 5 illustrates the fundamental concepts of sustainability, focusing on critical techniques for resource efficiency and environmental preservation. The maximizing of resource reuse and the minimum of resource consumption emphasize the importance of waste reduction and material efficiency in the built environment. The use of renewable and recyclable resources promotes a CE by reducing reliance on nonrenewable materials. Furthermore, conserving the natural environment and creating a healthy, non-toxic environment benefits both the ecosystem and people in the long run. Finally, promoting quality in built environments guarantees that sustainable design principles improve livability, durability, and energy efficiency in construction and urban planning. Finally, emphasizing quality in built environments ensures long-term resilience and sustainability by improving the efficiency and longevity of structures while also adding to its aesthetical and practical worth. These behaviors, when combined, provide a thorough strategy for creating a sustainable future.

For several reasons, it is essential to have a sustainable system for managing construction trash. Less trash going to landfills and less pollution means it can help keep the planet habitable. Metals, wood, and concrete are finite resources that may be preserved via recycling and reuse. Additionally, recycling frequently uses less energy than making new materials, so energy can be saved. Another benefit of effective waste management is spending less on materials and their disposal. Additionally, it safeguards against legal trouble, protects public health by keeping the environment clean, and guarantees compliance with rules. A firm may get an edge in the market and improve its reputation by implementing sustainable practices. Customers are increasingly drawn to organizations that care about the environment. The final aim is to develop a constructed environment that is more sustainable and robust for future generations by supporting the idea of a CE, which is one where resources are reused to derive maximum value. Many different approaches are part of the sustainable management of construction waste, which tries to lessen the toll that building takes on the environment. Methods such as reusing, recycling, composting, etc. fall under this category. The term "reuse" describes the practice of recovering a product's byproducts for further use in the same or similar products (Aslam et al., 2020). An item or substance may be effectively reused if its current structure is maintained and no more effort or time is needed to make it useful again. Immediate on-site material reuse during demolition or deconstruction projects is one type of reuse, as is the transfer of surplus materials to another location for use in a different project. To recycle is to take materials that would otherwise be discarded and put them through a series of processes including sorting, collecting, processing, marketing, and finally, use (Yeheyis et al., 2013). It is critical to evaluate the different disposal options for C&D waste (Table 2). Composting bacteria use anaerobic digestion in an oxygen-rich environment to transform biodegradable organic matter into CO_2 and water. Soil improvement in agriculture and land reclamation are two potential uses for the organic-rich composting residue. By recycling the biodegradable portion of C&D debris, composting helps keep landfills from overflowing with harmful gasses like methane and other GHGs, as well as the liquid that drains from them, leachate (Yeheyis et al., 2013). The last report for building debris disposal is landfilling. Many things might be put to better use instead of ending up in landfills. The release of C&D waste into bodies of water and landfills poses a significant environmental danger. In addition to water and soil fertility contamination, landfilling causes waste degradation and an increase in nitrates, both of which are detrimental to human health (Ajayi et al., 2017). In a single year, a 1,000 m^2 C&D waste in the landfill causes approximately 52.5 kg of soil fertility degradation and 1,500 tons of freshwater loss, under a laboratory test (Ding T. et al., 2016). Worse still, groundwater contamination from oil, solvents, and gasoline in construction waste is a real possibility (Seror et al., 2014). Cochran et al. (2007) and other recent studies have highlighted the huge social and environmental effect of C&D waste. The rate of landfill usage has been on the rise and is expected to stay that way for the foreseeable future, adding to the shortage of appropriate land areas in large cities (Akinade et al., 2017). Land scarcity, increasing landfill prices, safeguarding the environment, resource conservation, and sustainable growth for Human welfare constitutes the key drivers of C&D waste management (Poon, 2007).

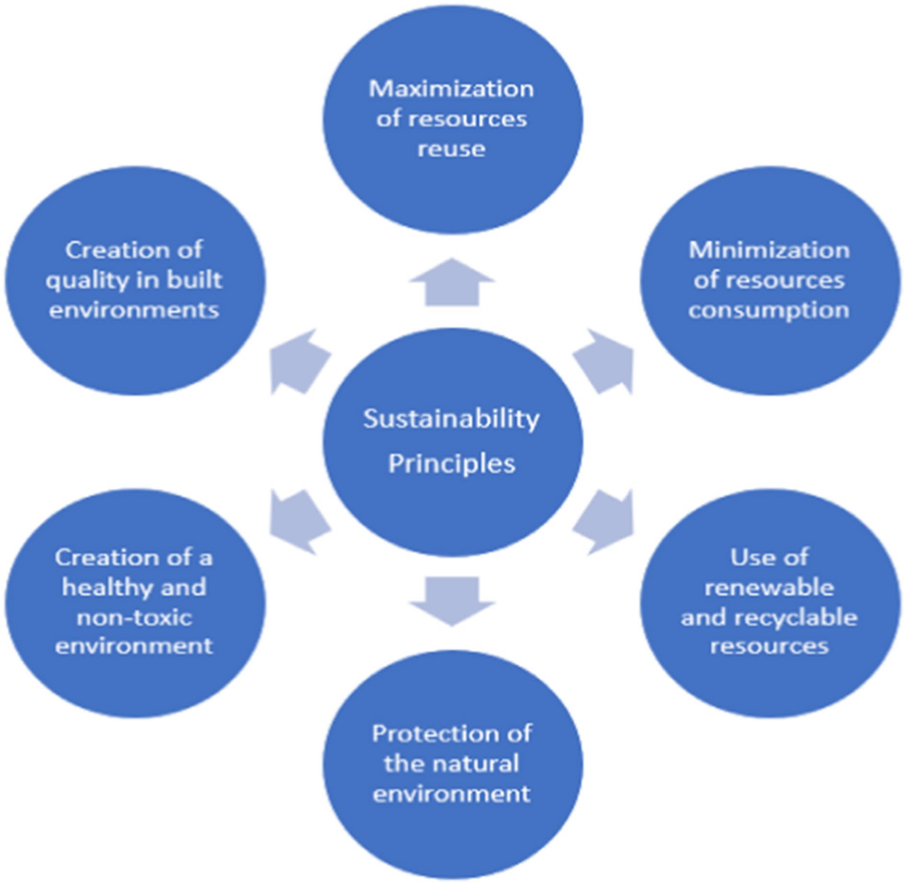

FIGURE 5
Sustainable principles (Ismam and Ismail, 2014).

Source reduction initiatives, improved stakeholder compliance with handling waste legislation, and increased reuse and recycling of construction waste are important solutions to reduce unlawful dumping and relieve landfill strain (Ding Z. et al., 2016).

According to its biodegradability, landfill appropriateness, and incineration potential, Table 2 classifies different kinds of C&D waste. Bricks and blocks, ceramics, glass, and concrete are all landfill-friendly despite their lack of biodegradability, but metals like steel and aluminum are too precious to be properly disposed of in landfills or incinerators. Even if they do not break down in nature, insulation, plastics, and paints may all be burned, and even some of those materials are disposable. Landfilling and incineration are viable options for dealing with biodegradable materials like wood and cardboard. However, burning is not an option for biodegradable gypsum boards, and landfilling is the only safe option for asbestos because of the material's dangerous properties. By drawing attention to the best disposal practices for each material type, this classification helps in creating efficient waste management plans. To protect both the environment and financial resources, practicing sustainable building waste management is essential. The most successful strategy out of all the ones offered is source minimization. It is more effective than other strategies in decreasing environmental impact since it stops trash from being generated in the first place, which means less material needs to be managed. This method reduces the demand for energy-intensive production and processing, which in turn helps save scarce materials like metals, wood, and concrete. In addition, cutting down at the source improves efficiency by reducing material acquisition and waste disposal costs. Compliance with rules, mitigation of legal risks, and promotion of public health through the prevention of environmental pollution are all achieved through the implementation of source reduction techniques. A company's reputation is boosted, giving them an advantage in a market where sustainability is becoming important. Sustainable building waste management includes practices like recycling, composting, and material reuse; however, these methods often deal with the issue after it has already occurred. To build a world with a CE, source reduction is the most effective approach as it prevents waste at its origin. The construction industry can play a significant role in creating a built environment that is more sustainable and resilient by concentrating on source reduction. This will help to preserve resources for years to come. The factors that affect the governance of C&D waste have also been the subject of several studies. Source reduction is critical for efficient C&D waste management; nevertheless, much of this research fails to adequately address this issue. Reducing waste at its source is what is meant by "source reduction" (Ding T. et al., 2016). Ordering just the right quantity of supplies for the job site is the result of using source reduction strategies like calculated procurement (Omeje et al., 2020). This provides more evidence that the additional materials that were originally designated for waste during construction tenders must be removed (Ma, 2017). To rephrase, it is possible to avoid making the mistakes of over- or under-ordering materials (Adewuyi and Otali, 2013). The majority of initiatives have failed to formally catalog or identify the components that lead to efficient C&D waste management, particularly in the area of source reduction (Pantini and Rigamonti, 2020). The crucial function of source reduction has been generally disregarded, despite the frequent emphasis on "prevention" and the belief that reusing building materials is one of the greatest ways to decrease excessive waste production and decouple the growth of the economy from resource usage. The majority of recyclables end up in landfills instead of recycling bins, even though recycling is the waste hierarchy's preferred method of recycling. While studies on building part reuse and the variables that drive their adoption have been going on for quite some time, the literature on source reduction, a crucial method, is noticeably lacking. Figure 6 illustrates the benefits of adopting source reduction in the management of C&D waste, emphasizing its importance in promoting sustainable behaviors. It shows data from multiple peer-reviewed sources, including studies by Ajayi et al. (2017), Kazancoglu et al. (2021), and Duan et al. (2019), which quantify the effectiveness of source reduction in reducing waste generation, costs, and carbon emissions.

Reduced trash creation is the first benefit of source reduction, which in turn reduces the total amount of garbage that requires management, processing, or disposal. By cutting down on materials used and removal costs, this decrease not only simplifies the disposal of waste but also saves money. In addition to preserving limited natural resources, source reduction improves resource efficiency by making the most effective usage of goods. The result of less waste formation, environmental damage, emissions of GHG, and shortages of resources are all reduced, further reducing the environmental effect. Advanced technologies, like 3D printing, can eliminate excess wastage during the construction process. Improving compliance with environmental rules and meeting sustainability goals are two additional benefits of incorporating source reduction into trash management. The flow diagram further demonstrates how reducing trash at the source improves waste management by making recycling and reuse easier. Another major perk is that it helps with preparing for the project. By embracing source reduction, sustainable building practices are fostered from the very beginning of the project through deliberate design and choosing the materials. In addition, stakeholders who care about the environment will be more interested in doing business with firms on emphasize source reduction since they will regard them as sustainability leaders. Contributing to sustainable development, which aims to maximize the efficiency of material usage and their retention within the economy, source reduction promotes long-term sustainability. Finally, the flow diagram highlights how reducing waste at the source lessens the need for landfills, which in turn makes these facilities last longer and operate more efficiently. Considering all of these benefits, it is clear that reducing waste at its source is the key to long-term sustainability in the building and demolition industries. Digital tools, especially BIM, can significantly

FIGURE 6
Advantages of source reduction on management of C&D waste.

reduce waste, optimize resources, and improve building efficiency. BIM allows for precise material estimation, real-time project visualization, and clash detection, which helps to eliminate design errors and waste (Charef and Emmitt, 2021). By combining 3D modeling, digital twins, and lifecycle analysis, BIM enables efficient material procurement, guaranteeing that just the necessary quantity of building materials is ordered, reducing offcuts and unnecessary waste. Furthermore, BIM promotes prefabrication and modular construction, in which components are built in controlled conditions, resulting in less waste on-site and higher efficiency (Low et al., 2020). Beyond BIM, GIS and artificial intelligence (AI) predictive analytics improve waste management by tracking material movement, finding inefficiencies, and offering sustainable alternatives in real-time (Li et al., 2022). Furthermore, blockchain technology has been linked to material passports, allowing for precise tracking and certification of recycled materials and encouraging the reuse of building waste in future projects (Kazancoglu et al., 2021). In the broader context of digital innovation, AI-powered automated robotic sorting systems are transforming C&D waste separation and recycling, resulting in higher resource recovery rates. Despite these advances, adoption hurdles persist in underdeveloped nations due to high initial prices, a scarcity of experienced specialists, and inadequate digital infrastructure (Charef and Emmitt, 2021). However global initiatives encouraging BIM education, digital integration policies, and financial incentives for smart building technology are helping to close the gap and expedite the global transition to digitally driven, waste-efficient construction methods. Recent breakthroughs in automation, robots, and AI-driven technologies are changing construction waste recycling and reuse, considerably improving the construction industry's sustainability. Automated sorting systems powered by AI and machine learning are increasingly being utilized to precisely separate concrete, wood, metals, and plastics, minimizing contamination and increasing recycling efficiency (Devaki and Shanmugapriya, 2022). Robotic demolition systems with AI-based recognition may selectively dismantle structures, separating and recovering precious elements including as bricks, steel, and timber for reuse (Li et al., 2022). Furthermore, 3D printing with recycled construction debris has emerged as a sustainable alternative, repurposing waste-derived aggregates into new building components while lowering the demand for fresh materials (Olivetti et al., 2021). Mobile trash processing devices now allow for on-site material crushing and repurposing, lowering transportation emissions and landfill dependency (Kazancoglu et al., 2021). Furthermore, blockchain-based material tracking systems increase transparency in CE models, guaranteeing that recycled materials are effectively restored into new projects (Charef and Emmitt, 2021). Robotics and automation improve waste recovery rates while also lowering labor costs, increasing safety, and promoting higher-quality recovered materials. However, high initial investment costs, a lack of regulatory frameworks, and low uptake in poor nations remain significant problems. Addressing these limitations through governmental incentives, research funding, and industry-wide collaboration is critical to realizing the full promise of advanced recycling technologies in creating a more sustainable built environment.

Implementing source reduction strategies in construction provides substantial benefits compared to traditional practices by minimizing waste generation, enhancing material efficiency, and lowering environmental impact. Table 4 displays a comparative analysis of traditional construction practices versus source reduction strategies, underscoring marked improvements in waste generation, material efficiency, recycling rates, cost savings, environmental impact, and landfill diversion. Traditional construction methods produce 25–30 kg/m^2 of waste, with 40% material wastage, whereas source reduction techniques such as modular prefabrication, lean design, and digital planning cut waste down to 10–15 kg/m^2 and boost material utilization to 85% (Kazancoglu et al., 2021; Ajayi et al., 2017; Charef and Emmitt, 2021). Furthermore, recycling and reuse rates rise from 30–50% to 70–90% through on-site waste segregation and optimized material selection (Moschen-Schimek et al., 2023; Duan et al., 2019). Economically, source reduction leads to a 10–20% reduction in project costs by minimizing purchases of raw materials, transportation expenses, and disposal fees, while traditional methods do not provide any direct cost savings due to excessive material use and landfill disposal costs (Purohit et al., 2021; Tam and Shen, 2018). From an environmental standpoint, source reduction reduces CO_2 emissions by 30–50% as a result of decreased raw material extraction and processing needs, whereas traditional construction heavily depends on virgin materials that carry high carbon footprints (Li et al., 2022; Low et al., 2020). Additionally, landfill diversion rates improve from 50 to 60% (under traditional practices) to 80–90%, as waste is repurposed, reused, or recycled, which minimizes disposal and environmental degradation (Ferronato and Torretta, 2019;

TABLE 4 Impact of source reduction on traditional practices.

Indicator	Traditional practices	After source reduction	References
Waste generation (kg/m^2)	25–30 kg/m^2 (Traditional construction)	10–15 kg/m^2 (Use of modular prefabrication, lean design)	Kazancoglu et al. (2021) and Ajayi et al. (2017)
Material efficiency	60% of materials utilized, 40% wasted	85% utilization, only 15% waste	Charef and Emmitt (2021) and Devaki and Shanmugapriya (2022)
Recycling and reuse rate (%)	30–50%	70–90% (due to material selection and reuse of on-site waste)	Moschen-Schimek et al. (2023) and Duan et al. (2019)
Project cost reduction (%)	No savings (high material costs and disposal fees)	10–20% cost savings (reduced raw material needs and waste disposal fees)	Purohit et al. (2021) and Tam and Shen (2018)
Environmental impact (CO_2 emissions)	Higher emissions from new material production and transportation	30–50% reduction (less material usage, lower transportation needs)	Li et al. (2022) and Low et al. (2020)
Landfill diversion rate (%)	50–60% of waste sent to landfills	80–90% diverted through reuse and recycling	Ferronato and Torretta (2019) and Mahpour (2018)

Mahpour, 2018). These findings underscore that embracing source reduction principles can substantially enhance sustainability in construction, resulting in increased efficiency, cost savings, and decreased environmental impact.

A quantitative comparison of source reduction, recycling, and reuse reveals that, while all three techniques contribute to sustainable construction waste management, source reduction is the most successful at reducing environmental and economic implications. According to studies, source reduction can reduce construction and demolition (C&D) waste by 70–90%, while recycling accomplishes 50–70% waste diversion and reuse results in 75–90% waste minimization (Moschen-Schimek et al., 2023; Mahpour, 2018). Source reduction has the biggest carbon footprint reduction, as it removes waste formation from the start, preventing 250–400 kg CO_2 emissions per ton of material, compared to 50–80 kg CO_2 for recycling and 200–300 kg CO_2 for reuse (Duan et al., 2019; Li et al., 2022). In terms of cost efficiency, source reduction saves 30–50% by reducing procurement needs and avoiding landfill fees, whereas reuse saves 40–70%, and recycling saves 20–40%, primarily due to increased resale value and lower disposal costs. While recycling necessitates additional sorting, reprocessing, and quality control procedures, reuse is more effective at keeping material integrity, but it confronts design limits and logistical issues (Ajayi et al., 2017; Kazancoglu et al., 2021). Source reduction, on the other hand, reduces raw material demand, eliminates unnecessary waste, and increases resource efficiency, making it the most sustainable and cost-effective strategy to controlling C&D waste (Low et al., 2020; Devaki and Shanmugapriya, 2022).

The Framework for Construction and Demolition (C&D) Waste Management, shown in Figure 7, takes a hierarchical approach, prioritizing waste management techniques from most sustainable to least favored. Developed using regulatory criteria from the European Union Waste Framework Directive (2008/98/EC), China's Circular Economy Promotion Law (2008), and empirical findings from case studies in Germany, Sweden, and the UAE (Moschen-Schimek et al., 2023; Tam and Shen, 2018). At the top of the hierarchy is source reduction, which focuses on reducing waste creation at the source through efficient material selection, optimum design, and construction planning approaches such as modular and lean construction. This proactive approach minimizes the use of unnecessary raw materials, minimizing both environmental effects and project costs. Recycling is the process of converting construction waste into useful materials, such as crushing concrete for aggregates or reprocessing wood and metals. Recycling conserves natural resources and lowers landfill waste, but it requires efficient separation and processing facilities. Another important method is reuse, in which materials such as bricks, lumber, doors, and steel components are recovered from demolished structures and reused without considerable processing, extending their lives and reducing the demand for new resources. Treatment is an essential step for garbage that cannot be reused or recycled. This comprises thermal treatment (such as burning with energy recovery), chemical stabilization, and biological processing to make garbage safer and easier to manage. The least desirable and final option in the hierarchy is disposal, which involves sending non-recyclable and non-reusable garbage to landfills. This technology has serious environmental effects, such as pollution and greenhouse gas emissions, making it the least desired option. The framework underlines that by prioritizing source reduction, enhancing recycling and reuse, and using treatment technologies before disposal, the construction sector may considerably improve sustainability and transition to a CE. Source reduction improves project efficiency, decreases disposal costs, and helps conserve resources by lowering the excessive amount and toxicity of waste created during building activities. Less waste to dumps means more progress toward sustainable development objectives and a more conscientious approach to building practices when tactics like careful scheduling, optimizing design, and material selection are put into play. To make waste management initiatives more efficient and sustainable, it is important to prioritize source reduction. This will lay a firm basis for later waste-handling methods. The other waste management approaches like recycling, reuse, treatment, and disposal have reduced benefits compared to source reduction.

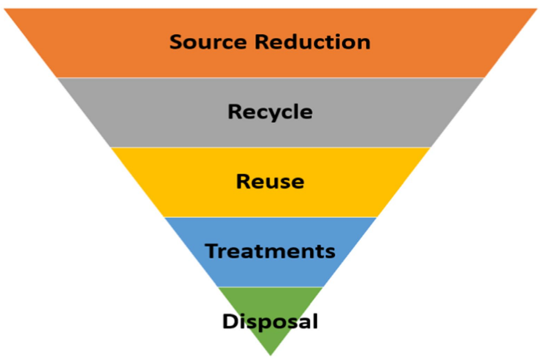

FIGURE 7
Framework for C&D management.

In light of the information gathered, the authors propose that researchers put more effort into creating a systematic framework for assessing C&D waste management approaches, with a particular focus on minimizing their origins. With source reduction as its central tenet, this framework ought to take into account all relevant socioeconomic, and regulatory issues. For instance, gaining the confidence and backing of society might be as simple as incorporating risk-aware C&D waste management strategies into recycling and reuse efforts. In a similar vein, the research community may benefit from insights and methodologies that advance more environmentally friendly methods in building waste management by concentrating on reducing costs and accumulating expertise, especially through source reduction techniques.

4 Conclusion

The findings of this study suggest that source reduction is the most successful technique for reducing construction and demolition (C&D) waste, as it directly prevents waste formation rather than dealing with its effects. Recycling and reuse are important components of a sustainable waste management strategy but do not eradicate waste at its source. By focusing on source reduction, the construction sector can cut greenhouse gas (GHG) emissions, minimize energy usage, and improve material efficiency, reducing environmental impact. However, despite its obvious benefits, various challenges prevent widespread implementation of source reduction strategies, including lax regulation enforcement, a lack of understanding among industry stakeholders, and aversion to abandoning traditional construction methods. Overcoming these obstacles necessitates a multidimensional approach that combines government laws, corporate incentives, and technical advances. Governments must tighten policy enforcement, provide financial incentives such as tax breaks and subsidies for sustainable materials, and foster public-private partnerships (PPPs) to improve recycling infrastructure and material reuse programs.

Furthermore, technology integration is critical for maximizing waste reduction initiatives. Building Information Modeling (BIM), blockchain-based waste tracking, and digital material optimization solutions can help with regulatory compliance, project efficiency, and waste reduction. To reduce waste generation throughout the design and planning stages, the construction industry must adopt circular economy models that include prefabrication, modular construction, and sustainable procurement practices. While source reduction should be the major goal, recycling and reuse are still critical in circumstances when reduction alone cannot eradicate waste output. Until 100% recycling efficiency is reached, waste treatment must be a prerequisite for landfill disposal, ensuring that materials are processed, recovered, or repurposed whenever possible. Developing countries, in particular, must prioritize capacity building, stronger landfill diversion targets, and investments in waste recovery technology to improve compliance and enforcement.

Future research should look into the large-scale implementation of digital waste management systems, as well as the effectiveness of various policy frameworks in promoting sustainable building waste practices. By transitioning from reactive waste management to proactive waste prevention, the construction industry may improve sustainability, reduce resource depletion, and contribute to global environmental conservation objectives. This transformation is crucial not only for long-term environmental advantages, but also for promoting innovation, economic efficiency, and resilience in the built environment.

5 Recommendations and future research directions

To improve sustainable construction waste management, governments can strengthen regulatory frameworks by adopting mandatory waste audits, landfill bans, and circular economy-driven rules that encourage increased recycling and reuse. Countries with inadequate enforcement systems should learn from Sweden and Germany, where financial incentives such as tax breaks and fines for excessive trash disposal have been beneficial. Furthermore, technological innovations such as BIM AI-driven waste tracking, and automated robotic sorting systems should be incorporated into building operations to improve material efficiency and reduce on-site waste generation. The promotion of circular economy principles is also critical, with an emphasis on material reuse, prefabrication, and sustainable procurement to reduce raw materials consumption. Economic incentives, such as low-interest loans for waste-efficient projects, subsidies for environmentally friendly materials, and carbon credit schemes, can also motivate construction companies to implement long-term waste reduction methods. Finally, public awareness initiatives, industry training, and cross-sector cooperation among governments, commercial players, and NGOs should be promoted in order to establish a standardized and effective waste management framework for the construction industry. Future research should focus on developing advanced waste management technologies, such as AI-powered smart sorting systems, blockchain-based material traceability, and automated deconstruction techniques, to boost waste recovery efficiency and material repurposing. Furthermore, while numerous waste reduction initiatives exist, there is a scarcity of empirical studies assessing their real-world effectiveness in construction waste management. Comparative studies of developed and developing countries can assist build worldwide best practices for waste reduction. Another key subject for future research is the economic viability and market potential of recycled construction materials, as well as the feasibility of large-scale implementation of cost-effective recycling procedures. The incorporation of circular economy principles into urban planning should also be investigated, to ensure that waste reduction measures are well-established in city development projects. A key gap in building waste management is the absence of standardized sustainability indicators to quantify waste management success. Future study should concentrate on generating quantitative indicators such as waste diversion rates, material recovery efficiency, embodied carbon reduction, and resource productivity indices to assess the performance of waste reduction projects. Implementing consistent approaches for assessing waste management performance at the project, regional, and national levels will allow for greater data-driven decision-making in sustainable construction. This issue is especially important in developing nations, where increasing urbanization and infrastructure expansion generate more building waste than industrialized countries. Unlike developed countries, which have established regulatory frameworks, waste processing facilities, and advanced recycling technologies, many developing countries struggle with poor waste management policy enforcement, insufficient recycling infrastructure, and limited financial incentives to encourage sustainable practices. The increasing demand for new buildings, roads, and other infrastructure projects in growing nations frequently results in excess raw material consumption and landfill dependence furthering environmental deterioration and resource depletion. As a result, specific research and policy interventions are required to assist developing nations in implementing effective waste management strategies, enhancing waste processing facilities, and encouraging international cooperation for knowledge transfer and best practice adoption.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

HS: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – original draft, Writing – review & editing. MM: Conceptualization, Funding acquisition, Methodology, Project administration, Resources, Supervision, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Glossary

% - Percent

AEC - Architecture, engineering, and construction

AI - Artificial Intelligence

BIM - Building information modeling

C&D - Construction and demolition

CE - Circular economy

CW - Construction waste

EAD - Environment Agency of Abu Dhabi

EPA - Environmental Protection Agency

EU - European Union

GHG - Greenhouse gas

GIS - Geographic information system

LCA - Life cycle assessment

LEED - Leadership in Energy and Environmental Design

Mt - Million tons

NGO - Non-Governmental Organizations

OECD - Organization for Economic Co-operation and Development

PPP - Public Private Partnership

RCA - Recycled concrete aggregate

SDG - Sustainable Development Goal

t/m^2 - Ton per square meter

t/m^3 - Ton per cubic meter

UAE - United Arab Emirates