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CIRCULAR ECONOMY STRATEGIES FOR CONSTRUCTION AND DEMOLITION WASTE MANAGEMENT AT THE DESIGN AND PLANNING STAGES OF THE PROJECT LIFE CYCLE

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Abstract — Most Construction and Demolition (C&D) waste management strategies, both locally and globally, still emphasise end-of-life treatment, leaving limited attention to waste prevention during the early stages of the construction project life cycle. This paper investigates circular economy (CE) strategies for C&D waste management during the design and planning stages, with particular attention to waste minimisation in Malaysia. A systematic literature review (SLR) was conducted using Web of Science and Scopus as the primary bibliographic databases, with Google Scholar used for supplementary discovery, Scite AI for supplementary discovery and citation support, and Connected Papers for citation-link exploration. This process retained 130 relevant records for detailed analysis. The review shows that the literature remains dominated by downstream waste treatment, while early-stage intervention is comparatively underdeveloped. It also shows that effective CE implementation depends on coordinated actions across micro, meso and macro levels involving design decisions, stakeholder collaboration, technology adoption, economic support, and regulatory direction. Based on these findings, the study develops the D.E.M.S.T.E.R.P. conceptual framework, comprising Design (Early), Education, Material, Stakeholder, Technology, Economic, Regulatory and Policy, as a structured early-stage approach for reducing C&D waste. The framework provides a conceptual basis for more proactive and integrated waste minimisation in the Malaysian construction industry.

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***Keywords*:** circular economy, construction and demolition, waste management, design and planning stage, systematic review

1.0 INTRODUCTION

According to Esa [1], urbanisation continues to intensify construction demand, and this trend is expected to increase Construction and Demolition (C&D) waste generation in Malaysia. Malaysia has already experienced persistent waste management pressure, including limited landfill capacity, weak waste recovery performance, and substantial public expenditure on waste handling [1–4]. These conditions make waste minimisation a strategic priority rather than a downstream operational concern.

Current construction practice still relies heavily on linear take-make-dispose patterns, with many waste management efforts concentrating on collection, disposal, recycling, and other post-generation measures [5, 6]. Although circular economy (CE) has been widely promoted as a route towards sustainable construction, existing studies remain weighted towards end-of-life treatment and broad life cycle discussions, while comparatively less attention is given to decisions made during the design and planning stages that shape waste before construction begins. This limitation is important because early-stage design choices, material selection, coordination, and planning arrangements strongly influence later waste outcomes.

Accordingly, the objective of this paper is to explore the current CE approaches and related practices applied to C&D waste management at the design and planning stages and to synthesise the literature into a structured early-

stage waste minimisation approach. To address this objective, the study undertakes a systematic literature review and develops the D.E.M.S.T.E.R.P. conceptual framework, comprising Design (Early), Education, Material, Stakeholder, Technology, Economic, Regulatory and Policy, as a broader CE-based structure for early-stage intervention.

The remainder of the paper is organised as follows. Section 2 reviews the literature on early-stage waste minimisation, project life cycles, waste prediction, drivers, and implementation challenges. Section 3 explains the systematic literature review procedure. Section 4 presents the literature-derived findings and the proposed conceptual framework. Section 5 concludes the paper by highlighting the main findings and their implications for early-stage C&D waste management.

2.0 LITERATURE REVIEW

In this sub-topic, we present a comprehensive review of the existing literature on CE strategies and application to C&D waste management. This review serves as the foundation for the subsequent discussion on the integration of these strategies into early-stage construction processes. Following the literature review, we will analyse the findings and synthesise them in the form of a conceptual framework.

2.1. A Review of the Early-Stage Waste Minimisation Strategy

This sub-topic reviews the key strategies identified in the literature for minimising waste during the early stages of construction, with a particular focus on CE approaches.

Over time, C&D waste management has embraced the environmentally friendly 3R (reduce, reuse, and recycle) practices. However, Esa [1] suggested it goes beyond the basic 3R principles of "reduce, reuse, and recycle". Thus, the authors investigate new paradigms that could reshape our approach to resource efficiency and minimisation. Therefore, we conducted an intensive study to develop a new alternative to address CE's suitability as a waste minimisation strategy that will be used during the design and planning stages.

With increasing C&D waste generation, proper waste segregation, on-site minimisation, and CE principles are required to deal with it [7–9]. The National Strategic Plan for Solid Waste Management and the National Recycling Programme in Malaysia are examples of national initiatives applying these principles [10]. In general, this means it is essential to adopt systematic waste management practices through integrating CE approaches, as reflected in national initiatives in Malaysia [10]. The CE is a model-based shift from linear to circular systems that could lead to waste materials re-entering value chains that can be utilised to advance sustainable development and improve environmental quality [5, 11].

In addition, the literature suggests a trend toward adopting Fourth Industrial Revolution (IR 4.0) technologies into C&D waste management practices, including Artificial Intelligence (AI) and Building Information Modelling (BIM), which also help with waste prediction and management in construction design and planning, thus increasing resource productivity [12–14]. AI and BIM enhance construction processes and lower waste.

Besides that, sustainable practices are regulated by regulatory structures such as the C&D Waste Management Municipal Plan in Brazil [15] or the decrees of Catalonia [16]. According to Gangolells et al. [16], early stakeholder collaboration and waste reduction strategies implemented during the design stage are essential.

Complementary measures include construction material storage and incentive policies for construction waste reduction [17]. The CE approach views buildings as material banks and stresses future recycling, reuse, and dismantling to support environmentally friendly C&D waste management [18]. Concerted efforts must reach these objectives, more study, and customised solutions for Malaysia's situation.

The above statements are required to achieve sustainable construction practices and have fewer environmental effects. Early design factors like life cycle evaluations and Design for Disassembly (DfD) are stressed, emphasising the need for proactive planning. However, serious obstacles that include stakeholder alignment, regulatory compliance, and technology adoption beset the practical application of these tactics. It will take coordinated effort to create customised solutions and promote a sustainable culture in the sector to address these issues.

2.2. Project Life Cycles (Linear Economy)

The following review examines the concept of project life cycles in sub-topic 2.2.1, 2.2.2 and 2.2.3, particularly the transition from linear to circular economic models within construction. Figure 1 summarizes the conventional linear project life cycle used as the baseline for discussing how CE strategies can intervene, particularly during the design and planning stages.

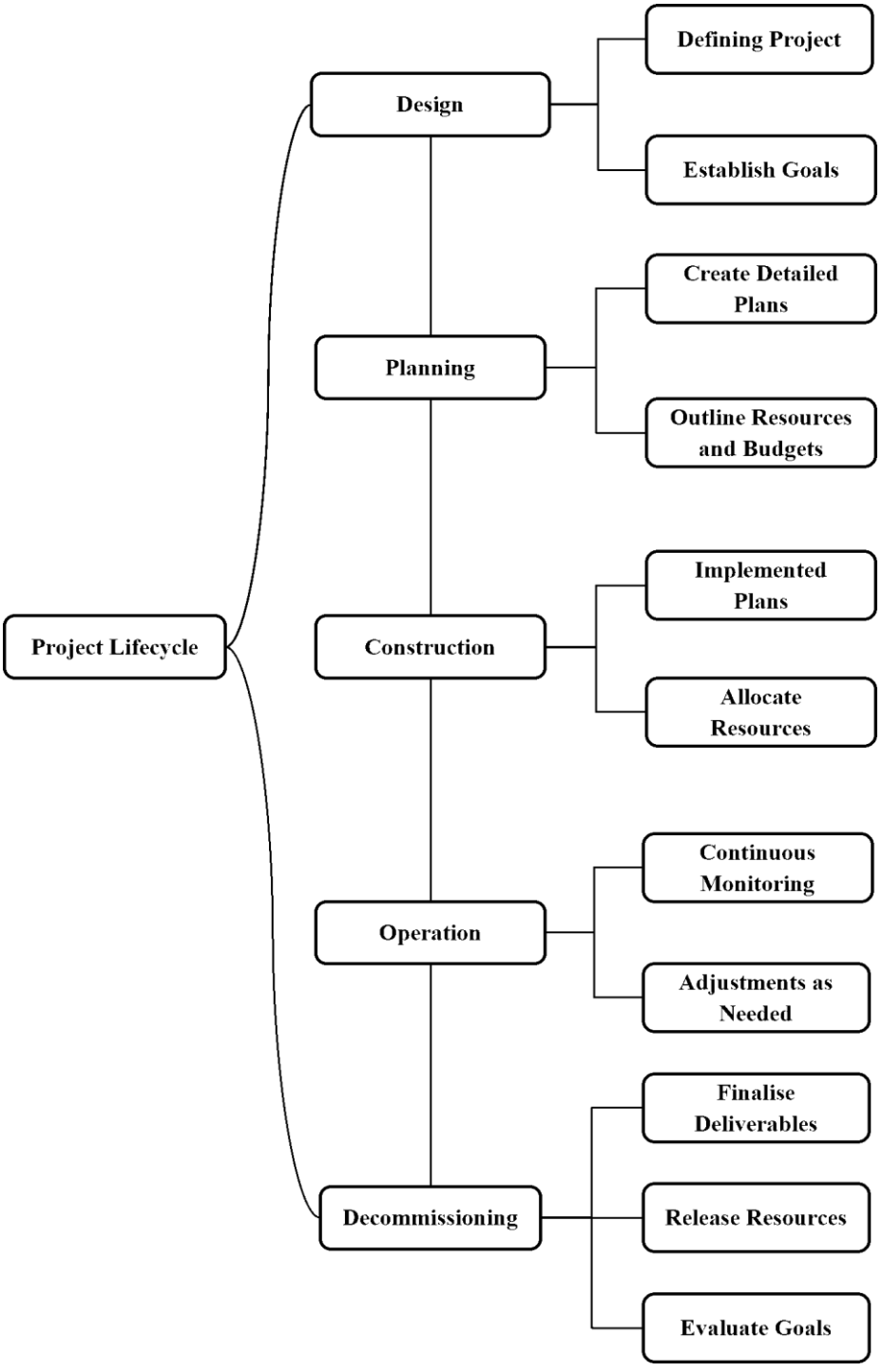


Figure 1 Project life cycle timeline [19]

2.2.1. Defining project life cycles or linear economy

According to Yang [19], a project life cycle is defined as the integration of an entire life journey of a project, going through all phases, such as design and planning, construction, operation, and decommissioning. Detailed plans and specifications are developed in the design phase. Meanwhile, project objectives are set, and feasibility studies are carried out during the planning phase. Therefore, construction is realising a project in the physical world according to its design. The project is a practical operation, maintenance, and management resource. Finally, decommissioning is associated with End-of-Life (EOL) activities such as demolition or re-purposing [19].

2.2.2. Advancing circular economy (CE) strategies through all stages of project life cycles

Expanding based on Yang [19] linear project life cycle; this part explores how CE strategies can be effectively integrated across all construction stages. As the industry shifts towards circular models, these strategies are key to enhancing sustainability, efficiency, and challenging traditional practices. Embedding CE throughout the project life cycle transforms construction into a more resilient and sustainable process.

- Design and Planning Stages: CE strategies like Life Cycle Assessment (LCA), DfD, prefabrication and 3D printing redefine the early stages of construction [20–24]. For instance, LCA forces a re-evaluation of material choices based on long-term environmental impact, moving beyond cost-focused decisions [24]. Similarly, DfD ensures that buildings are designed with future deconstruction in mind, promoting reuse and recycling [23, 25]. Moreover, prefabrication and 3D printing disrupt conventional methods by enhancing precision and reducing waste in controlled environments, setting a new standard for efficiency [21, 22]. Additionally, modular construction and adaptive reuse further challenge the linear approach, minimising the need for new resources by optimising existing structures [20].

- Construction Stage: During construction, CE strategies shift the focus from mere waste management to a more proactive, efficient process. For example, modular construction accelerates assembly, thereby reducing on-site waste and labour costs [20], while Internet of Things (IoT) technology revolutionises material management by enabling real-time monitoring and minimising resource waste [26]. These approaches not only improve efficiency but also push the industry towards a more data-driven and sustainable practice.

- Operation Stage: In the operation stage, CE strategies emphasise continuous resource efficiency. For instance, buildings designed with LCA consideration maintain energy efficiency and reduce resource consumption [23]. Furthermore, IoT and Artificial Intelligence (AI) can support building energy management and reduce energy consumption [27]. Additionally, Material Passports (MP) play a crucial role, ensuring ongoing sustainability, as they facilitate the recovery and reuse of materials throughout the building's maintenance life [28].

- Decommissioning Stage: At the decommissioning stage, CE strategies challenge traditional demolition practices. For example, DfD principles guide a deconstruction process focused on material recovery rather than disposal [23, 25]. Additionally, material passports support systematic documentation and recovery planning for building materials [28], thereby facilitating reuse. This approach redefines the end of a building's life cycle, viewing it instead as an opportunity to source materials for future projects.

By advancing CE strategies through all stages—from design to decommissioning—construction projects not only achieve significant waste reductions but also fundamentally challenge and improve traditional construction practices. This comprehensive approach ensures that sustainability is central to every phase of the project life cycle, driving the industry towards a CE.

2.2.3. Impact on project life cycles

Integrating sustainable practices into construction projects' design and planning stage is critical for improving environmental, economic, and social outcomes. LCA and Life cycle Costing (LCC) provide cradle-to-grave evaluations to support sustainable, cost-effective solutions that reduce carbon footprints and waste [24]. Material selection, such as Cross-Laminated Timber (CLT) and secondary materials, lowers embodied carbon and increases

resource efficiency [29, 30]. Energy-efficient building materials can reduce energy consumption and greenhouse gas emissions [31].

Planning for the EOL phase of materials reduces future waste, albeit with economic and logistical challenges [24, 29]. Collaborative working and information sharing among project teams are important for circular modular construction projects [32]. Regulatory standards can support sustainability, but implementation may require updated regulations and coordinated stakeholder engagement [33].

A holistic design approach that balances environmental and financial considerations is critical for project sustainability [34]. It necessitates significant changes in traditional planning and execution methodologies. Addressing practical and theoretical challenges, finding innovative solutions, and ensuring strong stakeholder commitment are critical to benefiting from these practices and carefully achieving full sustainability.

It is imperative to incorporate sustainable practices starting from the design and planning stages of the construction projects to attain enduring environmental, economic, and social advantages. Nevertheless, it is crucial to tackle obstacles such as resource-intensive LCA and LCC methodologies, elevated expenses of sustainable materials, compatibility concerns, supply chain obstacles, changing corporate priorities, and superficial regulatory compliance. Full sustainability adoption necessitates a comprehensive approach that entails substantial modifications to conventional methods, implementation of innovative solutions, and an intense stakeholder commitment.

2.3. Predicting C&D Waste Volume at the Early Stage

Building on the discussion of project life cycles, this sub-topic explores the literature on predictive tools and methodologies used to estimate C&D waste volumes at early project stages. The emphasis here is on advancements such as AI, BIM, and Machine Learning (ML) that are increasingly integrated into sustainable construction practices [12–14, 35–37].

C&D waste prediction and management in the construction industry have changed dramatically due to technological advancements and, more importantly, paradigm shifts towards sustainability and efficiency. AI, BIM, and ML were implemented in response to the industry's environmental footprint, increasing early-stage waste prediction and effectively supporting a CE [12–14, 35–37].

Machine-learning models can achieve high predictive performance when applied to construction-waste estimation [35]. BIM-based predictive models can support early waste estimation and corresponding adjustments to project design and modelling [36]. However, advancements are still dependent on accurate, high-quality data, which necessitates iterative improvements in data validation and processing [37].

Material Flow Analysis (MFA), combined with policy analysis, can support more sustainable construction resource management [38]. However, many issues remain to be addressed, particularly in data management and infrastructure, to fully realise the potential of these predictive models in sustainable C&D waste management.

Advanced technologies such as AI, BIM, and ML have significantly improved C&D waste predictability and management. These advances aid in waste forecasting and support better processes. Nonetheless, more work must be done to achieve a scientific trajectory, including ensuring high-quality data, improving data infrastructure, and developing comprehensive policy frameworks to harness these technological innovations for sustainable C&D waste management [35–37].

2.4. Key Drivers for Adopting Early Waste Minimisation Strategies

Furthermore, in this part, we delve into the literature that identifies and analyses the main drivers influencing the adoption of early waste minimization strategies in construction.

Stakeholder engagement, regulatory frameworks, economic incentives, technological integration, education, and market development all play important roles in effective C&D waste management. It is important to enhance cooperation between the government, business leaders, and communities to improve C&D waste management [39, 40].

Promoting sustainable practices requires policies such as landfill levies and green public procurement. Meanwhile, Torgautov et al. [41] stressed government policies' role in easing the shift to sustainable practices, and Condotta and Zatta [42] argued for well-defined regulatory boundaries. Financial and regulatory support are important for sustainable C&D waste management [43].

Jahan et al. [44] and Izquierdo et al. [45] mentioned how technologies like advanced assessment tools and BIM are enhancing waste reduction and project planning. Moreover, training and education guarantee that the experts in the construction industry have the abilities and information required to carry out efficient waste management strategies. Suleman et al. [46] and Amudjie et al. [47] underlined the need for professional growth in advancing sustainable practices.

A market for recycled materials must be created to progress CE strategies. Ding et al. [48] and Christensen et al. [49] underlined the need to foster secondary construction materials and create secondary markets. Tackling the practical issues of switching to a CE calls for robust data management, regulatory backing, and market development.

For C&D waste management to be successful, market development, technology integration, financial incentives, regulatory frameworks, and stakeholder participation are required. Communities, businesses, and governmental agencies can all work together to improve waste management. However, priorities may cause disputes. Two policies that help with sustainability are landfill levies and green public procurement, but they must be followed consistently. Meanwhile, financial incentives like subsidies may drive CE strategies, but focusing too narrowly on immediate profit is usually unhelpful. Moreover, BIM and other technologies improve planning and cut waste, and drawbacks include high costs and the requirement for trained personnel. Professionals will have the necessary skills from education and training, but overcoming industry resistance is just as crucial. Recycled material markets and a seamless shift to sustainable practices need strong data management, regulatory backing, and market incentives.

2.5. Challenges for Adopting Early Waste Minimisation Strategies

Moreover, this sub-topic assesses the challenges documented in the literature that impede the implementation of CE practices in construction.

Implementing CE practices in construction presents significant challenges. According to Jahan et al. [44] and Esa [1], insufficient infrastructure and technical expertise impeded development and implementation. Financial constraints and emphasis on short-term profits have resulted in unsustainable waste management solutions [48, 50]. Suleman et al. [46] and Al-Otaibi et al. [43] argued that cultural and behavioural resistance within the industry, which stems from a reluctance to abandon traditional methods, hampers adoption.

Regulatory and market barriers, such as insufficient design standards and regulatory uncertainties, have complicated the integration of reclaimed materials and caused project delays [41, 42]. Furthermore, project complexity and frequent design changes disrupted waste management plans, resulting in high C&D waste [45, 46]. Effective communication and coordination among stakeholders are critical for successful C&D waste management. However, shortcomings in these areas frequently resulted in implementation failures [51, 52].

Despite these challenges, the construction industry has a positive trend of adopting CE practices. Increased awareness and knowledge, regulatory frameworks, and economic incentives have propelled the transition to more sustainable practices. The commitment of various stakeholders, including government agencies and industry leaders, reflects a promising trend toward achieving long-term sustainability objectives. This comprehensive approach shows the potential for significant progress in waste reduction and resource efficiency in construction.

3.0 METHODOLOGY

A systematic literature review (SLR) was undertaken to address the study objective by identifying and synthesising CE strategies relevant to C&D waste minimisation during the design and planning stages [53, 54]. The review was guided by the following research question: How is the concept of CE translated into practical implementation during the design and planning stages of the built environment to strengthen early-stage waste minimisation? Using a defined review question helped maintain consistency during source selection, screening, and synthesis [53].

Web of Science (WoS) and Scopus were the primary bibliographic databases. Google Scholar was used as a supplementary discovery source, Scite AI supported supplementary discovery and citation support, and Connected Papers supported supplementary citation-link exploration. Search concepts combined the construction and C&D waste context with CE and waste-minimisation concepts, the design and planning stages, relevant practices and technologies, and implementation conditions. The principal publication boundary was 2012–2024, with one relevant 2011 life cycle assessment record retained because it contributed pertinent evidence to the review. The range was therefore applied as a principal boundary rather than as an automatic exclusion rule. Selection considered relevance to the early-stage construction scope, appraisal evidence and availability of sufficient content. After screening and eligibility checking, 130 records were retained for detailed analysis. Table 1 summarises the review protocol, and Figure 2 presents the flow of the literature review.

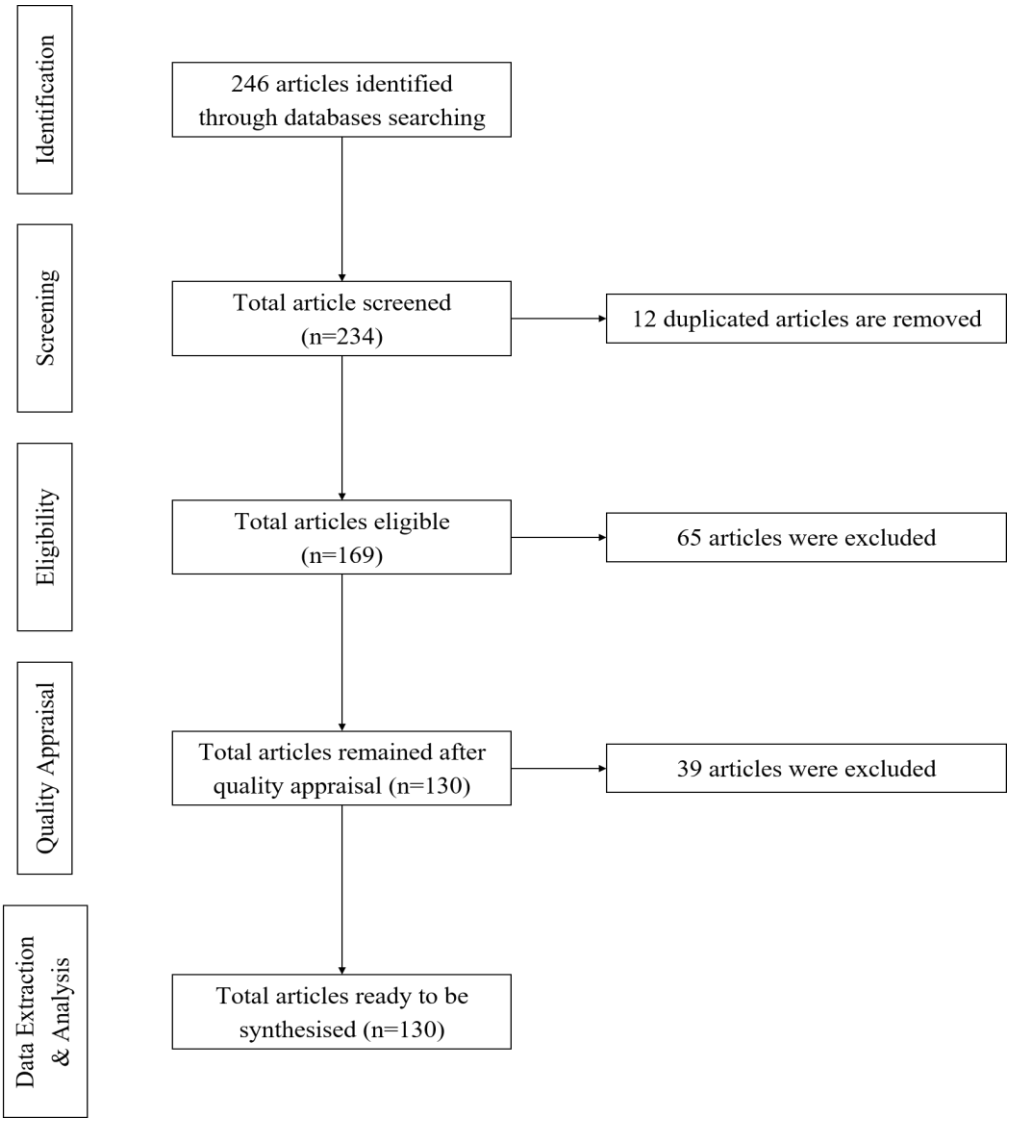


Figure 2 The flow of literature review

Table 1 Summary of Research Method

Area	Peer-reviewed papers, government documentation, conference proceedings, and published reports on C&D waste management were included where relevant to the review scope.
Principal time boundary	2012–2024, with one relevant 2011 life cycle assessment record retained.
Information sources	Web of Science (WoS) and Scopus as primary bibliographic databases; Google Scholar as a supplementary discovery source; Scite AI as a supplementary discovery and citation-support tool; and Connected Papers as a supplementary citation-link exploration tool.
Keyword used	Construction waste generation, prediction, the impact of waste management outcome, design and planning stages, current waste management practices, challenges and opportunities, benefits and challenges, circular economy principles.
Targeted Journal	Journal of Cleaner Production, Waste Management, Sustainability, MDPI, Resources, Conservation and Recycling, Journal of Building Engineering, and Waste Management and Research.
Selection logic	Relevance to the early-stage construction scope, appraisal evidence and availability of sufficient content were used to guide selection and appraisal.
Total retained records	130.

4.0 RESULTS AND DISCUSSION

The reviewed literature was synthesised to identify the main dimensions through which CE can support early-stage waste minimisation in C&D waste management. Rather than limiting the analysis to the traditional 3R perspective, the synthesis highlights a broader set of interrelated design, organisational, technological, economic and regulatory conditions.

4.1. Circular Economy (CE) Approach: A New Paradigm

The literature consistently indicates that the construction industry needs to move from a linear model towards a more regenerative and resource-efficient approach. Within this transition, the design and planning stages are particularly important because many waste outcomes are shaped before construction begins. However, the reviewed studies also show that early-stage CE implementation remains less developed than downstream practices such as recycling, recovery and disposal.

For clearer interpretation, the literature can be organised across micro, meso and macro levels [55]. The micro level captures project and design-stage decisions, the meso level captures inter-organisational coordination and enabling mechanisms, and the macro level captures policy and institutional conditions. This multi-level structure helps explain why CE adoption in construction cannot be reduced to technical design choices alone.

At the micro level, literature emphasises design-based and material-based strategies such as LCA, DfD, prefabrication, modular construction, adaptive reuse, and digital tools including BIM, IoT and AI [12–14, 20, 21, 23–26, 56, 57]. These strategies are important because they directly influence material selection, constructability, adaptability and waste generation during the earliest project stages.

At the meso level, the literature highlights collaboration, education, stakeholder alignment and economic support mechanisms as necessary conditions for implementation [32, 58–61]. Training programmes, inter-organisational coordination, market development for secondary materials, and financial incentives help translate CE principles into practice. Without these enabling conditions, early-stage technical strategies are less likely to be implemented consistently.

At the macro level, policy, regulation and institutional support are presented as critical drivers of wider adoption. Policy frameworks and stakeholder engagement can help embed CE principles within construction practice [59, 62].

Compared with existing CE frameworks in construction, which often emphasise material loops, recycling hierarchies, or broad life cycle transitions, the present synthesis places stronger emphasis on early-stage waste prevention and on the enabling conditions needed for implementation. This wider framing shows that effective C&D waste minimisation depends not only on technical design strategies, but also on education, stakeholder coordination, economic support, and regulatory direction across multiple levels.

Table 2 summarises the main literature-derived components identified in the review and shows how they operate across the micro, meso and macro levels.

Table 2 Summary of Literature-Derived Circular Economy Components for Early-Stage C&D Waste Minimisation

Component	Relevant level(s)	Literature-derived role in early-stage waste minimisation
Design (Early)	Micro	Integrates LCA, DfD, modular design, prefabrication and adaptive reuse into early project decisions.
Education	Meso	Builds professional awareness and implementation capacity through training, guidance and knowledge sharing.
Material	Micro	Improves material selection, durability, reuse potential and compatibility with circular practices.
Stakeholder	Micro / Meso / Macro	Strengthens coordination among clients, consultants, contractors and other actors during decision-making.
Technology	Micro / Meso	Supports prediction, coordination and waste reduction through BIM, IoT, AI and related digital tools.
Economic	Meso / Macro	Encourages adoption through incentives, cost-benefit reasoning, and market development for secondary materials.
Regulatory	Macro	Establishes enforceable guidelines, monitoring systems and waste management requirements.
Policy	Macro	Provides broader institutional direction and long-term support for circular transition in construction.

For the conceptual framework, these components are consolidated into six interrelated domains. Early Design Consideration, Technological Integration, and Material Selection and Management are positioned principally at the micro level; Stakeholder Collaboration and Education and Economic Models at the meso level; and Regulatory and Policy Frameworks at the macro level. Cross-level influence is nevertheless acknowledged.

4.2. A Literature-Derived Conceptual Framework for Early-Stage Waste Minimisation using the Circular Economy (CE) Concept

This sub-topic develops a literature-derived conceptual framework for early-stage waste minimisation based on the CE concept. It consolidates the literature-derived components into six interrelated domains: Early Design Consideration, Technological Integration, Material Selection and Management, Stakeholder Collaboration and Education, Economic Models, and Regulatory and Policy Frameworks. These domains are positioned principally across micro, meso and macro levels while allowing for cross-level influence. In this way, the framework translates the review findings into a more structured conceptual basis for early-stage waste reduction in construction.

The micro-level focuses on the earliest phases of the construction life cycle, notably the design and planning stages, which have a substantial impact on waste generation [16, 21, 63]. Integrating waste minimisation strategies into a project's life cycle at an early stage necessitates the commitment of stakeholders, including clients, consultants, and contractors [16, 21, 63]. LCA and DfD are identified as the key strategies, but the implementation requires a substantial number of resources and significant changes in industry processes [20, 21, 34, 63]. Technological

innovations such as prefabrication and 3D printing can support productivity and sustainability, although adoption requires investment and industry transition [21, 22].

Meanwhile, at the meso level, collaboration and economic waste management models are crucial. Moreover, effective stakeholder engagement and knowledge acquisition are necessary to manage waste efficiently [39, 40]. Community engagement and economic frameworks, such as cost-benefit assessments and government incentives, are crucial for fostering sustainable practices. However, there are still difficulties in expanding these programmes and sustaining collaboration among stakeholders [11, 64].

Finally, at the macro-level, the regulators, governmental agencies, and industry associations had to establish guidelines for waste management through legislation and policy at a larger scale [8, 16]. Government support and strong regulation are important for CE adoption and sustainable C&D waste management [43, 64]. This study presents a comprehensive and multi-tiered framework for CE aimed at mitigating waste in the construction industry by addressing technological, economic, and social obstacles. An extensive inquiry is necessary to modify and execute the framework in the Malaysian context, guaranteeing its efficacy and pertinence. Figure 3 presents the proposed conceptual framework, which synthesises the literature-derived domains into a structured early-stage CE approach for C&D waste management.

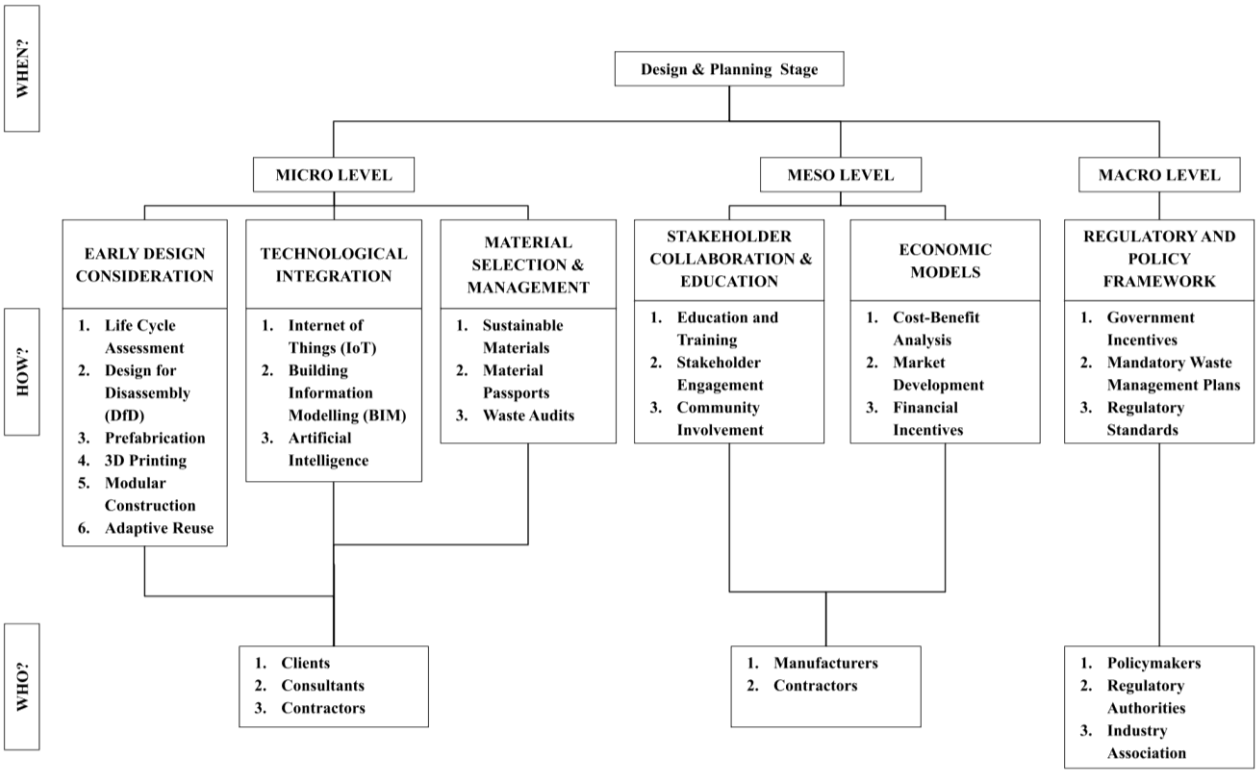


Figure 3 Conceptual framework for early-stage C&D waste management using the concept of CE

5.0 CONCLUSION

This review shows that the current C&D waste literature remains dominated by downstream management measures, while early-stage intervention during design and planning is comparatively underdeveloped. The synthesis also shows that effective CE implementation in construction operates across micro, meso and macro levels, rather than through isolated technical actions alone. At the micro level, design decisions, material strategies, and digital tools shape waste outcomes early in the project life cycle. At the meso level, stakeholder coordination, education, and economic support enable implementation. At the macro level, regulatory and policy instruments provide wider direction and enforcement. Based on these findings, the study presents the D.E.M.S.T.E.R.P. conceptual framework as a broader CE-based structure for early-stage C&D waste minimisation in Malaysia.

5.1. Implications

These findings suggest that CE adoption should begin before construction starts, particularly through stronger design-stage decisions, cross-stakeholder coordination, and policy support.

5.2. Limitations

This study is limited to a literature-based synthesis and therefore does not provide empirical validation of the proposed framework. The relevance of the framework may also vary across regulatory and industry contexts. Future work should therefore test and refine the framework through stakeholder-based empirical assessment in the Malaysian construction industry.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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