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Circular Economy in the Built Environment: A Systematic Literature Review 2005–2025

Thao T. P. Bui[1] | Dat Tien Doan[2] | Francesco Pomponi[3] | Vivian W. Y. Tam[4] | Suzanne Wilkinson[1] | Ali GhaffarianHoseini[2]

[1]Faculty of Design and Creative Technologies, Auckland University of Technology, Auckland, New Zealand | [2]School of Future Environments, Faculty of Design and Creative Technologies, Auckland University of Technology, Auckland, New Zealand | [3]School of Architecture, University of York, York, UK | [4]School of Engineering, Design and Built Environment, Western Sydney University, Penrith, New South Wales, Australia

Correspondence: Thao T. P. Bui (alice.bui@aut.ac.nz)

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ABSTRACT

The circular economy (CE) offers a viable pathway for advancing sustainable development in the built environment (BE) due to its potential to reduce waste, resource extraction, and environmental impacts. This study conducts a systematic literature review (2005–2025) to examine CE research through a unifying analytical perspective across the micro, meso, and macro levels of the BE and their integration with the Sustainable Development Goals (SDGs). It applies a sequential two-stage design combining science mapping and critical content analysis. Findings show that existing research in the field remains conceptually fragmented across the three levels. CE-SDG linkages remain generic and rarely operationalised within the BE. Seven cross-level enabling mechanisms including life-cycle analysis, circular design strategies, circular business models, circularity assessment, digital technologies, stakeholders collaboration, and integration with the SDGs, emerge as the connective tissue linking levels together. Building on these findings, the study proposes a conceptual framework that operationalises cross-level linkages to support CE implementation in the BE. The framework offers a diagnostic tool that practitioners and policymakers can use to identify level-specific characteristics, cross-level relationships, enabling mechanisms, and remaining gaps. The study contributes to the existing knowledge by providing an integrative approach and recommendations for future CE research, policy, and implementation in the BE.

1 | Introduction and Theoretical Background

The built environment (BE) is central to the transformative changes required to decarbonise the global economy (WGBC 2025), as the sector accounts for approximately 34% of global emissions and remains a major source of construction waste (UNEP 2025). These outcomes are symptomatic of a dominant linear economic paradigm, characterised by the 'take-make-dispose' approach according to the Ellen MacArthur Foundation (EMF) (EMF 2015). Given the central role of the BE in economic development and societal wellbeing, this trajectory is increasingly difficult to justify. Reframing construction practices around circularity is therefore essential to reconcile environmental priorities with socioeconomic development.

The circular economy (CE) has emerged as a systemic response to the tension between economic growth and environmental limits, seeking to minimise waste, retain products and materials in use for as long as possible and at their highest possible value, and regenerate natural systems (EMF 2015). In the

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BE, these ambitions are commonly expressed through narrowing, slowing, closing, and regenerating resource loops (Konietzko et al. 2020; Nußholz et al. 2023). Their implementation involves reducing resource demand, designing for adaptability and disassembly, enabling component reuse, specifying low-impact and secondary materials, and supporting nature-positive interventions (EMF 2019). CE thus extends beyond conventional green-building approaches and broader sustainability frameworks by considering how the value of materials, components, and built assets can be retained across multiple life-cycles, rather than focusing solely on reducing the impacts of individual buildings (Ossio et al. 2023).

Despite this systemic ambition, the conceptualisation of CE in the BE remains fragmented. The widely cited micro–meso–macro formulation originally distinguishes products, companies, and consumers; eco-industrial systems; and cities, regions, and nations (Kirchherr et al. 2017). Its translation into the BE has produced substantially different interpretations. Some studies organise these levels by the physical composition of the BE, moving from materials and components through buildings to cities, positioning the building as an intermediary between product-level decisions and wider urban systems (Pomponi and Moncaster 2017; Ossio et al. 2023). Other classifications combine materials, products, supply chains, industrial systems, design activities, cities, and national structures (Cottafava and Ritzen 2021; Harris et al. 2021), while another approach distinguishes projects, the construction sector, and government levels (Dautremont and Gobbo 2025). These differences are analytically significant because they conflate physical scales with organisations, stakeholders, industrial networks, and governance arrangements. Consequently, studies using the same micro, meso, and macro terminology may analyse different phenomena, limiting comparison and obscuring how circular actions are transmitted across the BE.

Existing reviews have substantially advanced knowledge of CE in construction and the BE, but their organising logics have generally reinforced rather than overcome this fragmentation (see Appendix A). Broad reviews classify CE research according to strategies, life-cycle stages, subjects, or implementation areas (Benachio et al. 2020; Munaro et al. 2020; Çimen 2021; Ossio et al. 2023). Others develop deeper knowledge of particular domains, including information brokerage, policy, digital technologies, and circularity measurement (Wijewickrama et al. 2021; Yu et al. 2022; Keles et al. 2025; Peng and Cao 2025). Although valuable, these studies primarily explain what CE strategies, barriers, enablers, tools, or actors are present. They offer less explanation of how interventions operating at different system levels depend on one another, how outcomes at one level reshape conditions at another, or why progress in one part of the BE may fail to generate system-wide transition.

This matters because circularity in the BE does not develop through a simple progression from materials to buildings to cities. Material and component innovations shape the technical possibilities available to building projects, but their implementation depends on design decisions, procurement structures, market demand, standards, and supply-chain capacity. Building practices, in turn, generate demand for circular products and produce the information required for material-stock analysis, urban mining, and city-level resource planning. Municipal regulation, infrastructure, procurement, and investment can enable or constrain circular decisions at both building and product levels. Previous multi-level accounts predominantly locate CE activities within particular levels but give less attention to these reciprocal relationships as feedback mechanisms through which circularity may be reinforced or restricted across the system (Pomponi and Moncaster 2017; Çimen 2021; Ossio et al. 2023). The unresolved issue is therefore not only how CE research should be classified, but how the relationships among its domains can be explained.

The fragmented treatment of enabling mechanisms further restricts this understanding. Life-cycle analysis, circular design strategies, business models, circularity assessment, digital technologies, and stakeholder collaboration are well-established areas of CE research, but they are often examined as separate themes or assigned to particular stages and scales (Wijewickrama et al. 2021; Larsen et al. 2022; Keles et al. 2025; Peng and Cao 2025), which underplays their cross-level functions. Assessment methods translate environmental and circularity performance across materials, buildings, and urban stocks; digital technologies transfer information between these domains; business models redistribute value and responsibility over time; and stakeholder collaboration coordinates decisions across fragmented project and supply-chain structures. Analysing these mechanisms as connective processes, rather than as an additional list of CE themes, is therefore necessary to explain how cross-level relationships operate and where they break down.

A related limitation concerns the relationship between CE and sustainable development. CE is increasingly positioned as a strategic framework for advancing sustainability at national and global levels (Rodriguez-Anton et al. 2019) and as an important mechanism for achieving the United Nations Sustainable Development Goals (SDGs) (European Commission 2015a). CE practices are associated with SDGs concerning water, energy, economic development, innovation, sustainable cities, responsible production, and climate action, among others (Schroeder et al. 2019; Rao et al. 2025). However, these connections are generally expressed through broad conceptual alignment rather than specific SDG targets, measurable outcomes, or empirically established mechanisms. Such treatment gives limited insight into which CE strategies relate to particular sustainability objectives, where within the BE these relationships arise, or how their effects extend across system levels, and it can conceal potential trade-offs, since an intervention framed as circular may not simultaneously produce positive environmental, social, and economic outcomes (ISEP 2026). CE–SDG integration in the BE therefore remains conceptually acknowledged but insufficiently operationalised.

Taken together, the literature reveals a field rich in CE strategies, applications, and specialised frameworks but lacking an integrated explanation of how they function collectively across the BE. The gap is consequently not an absence of CE themes, nor simply an inconsistent definition of system levels, but the absence of an analytical structure that connects level-specific strategies with the mechanisms carrying interactions between levels, identifies the feedback relationships through which change is reinforced or constrained, and relates these processes to specific

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sustainable-development priorities. Responding to this gap, the present study conducts a systematic literature review (SLR) of CE research in the BE between 2005 and 2025. The recurring distinction among materials and components, buildings, and cities provides an initial organising structure rather than a predetermined hierarchy. Through sequential science mapping and critical content analysis, this structure is examined and refined to identify how CE strategies operate within and across these domains, how cross-level enabling mechanisms support or constrain their interaction, and how the identified strategies connect to SDG targets.

The novelty of this study lies in shifting the analytical focus from classifying CE activities to explaining their systemic interdependence. Previous frameworks principally organise circular strategies by level, scale, subject, or life-cycle stage. However, the framework developed here treats the levels as a coupled system connected through bidirectional feedback loops, and positions seven enabling mechanisms as the evaluative, operational, informational, incentive-based, coordinative, and normative processes through which these loops function, rather than as a parallel collection of themes. By integrating these relationships with target-level SDG mapping and the gaps identified through the review, the framework provides a diagnostic structure for locating where circular implementation is constrained and which cross-level mechanism requires attention. In doing so, the study offers a more integrated explanation of how circular transition can be enabled across the BE.

2 | Research Methods

2.1 | Systematic Literature Review

An SLR was conducted from June to December 2025, following the standardised Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to enhance transparency and procedural rigour (Page et al. 2021). The review adopted a sequential two-stage design, comprising quantitative bibliometric analysis followed by qualitative content analysis. Combining science mapping with content analysis offsets the limitations of each, pairing a reproducible overview of the field's structure with the interpretive depth needed to explain how circular strategies operate across system levels (Snyder 2019; Antwi-Afari et al. 2021). Scopus was chosen as the primary data source for its extensive interdisciplinary coverage, particularly across built environment engineering and sustainability. It also offers advanced search and citation analysis functions and rigorous quality-assurance processes (Harzing and Alakangas 2015; Schotten et al. 2017). Using a single database was a deliberate choice to ensure data consistency and analytical coherence. Integrating multiple databases such as Web of Science or Google Scholar may increase coverage but can introduce redundancy, indexing inconsistencies, and metadata harmonisation challenges, particularly in bibliometric analyses (Darko et al. 2020; Donthu et al. 2021). This approach is consistent with established practice in the field, where single comprehensive databases are commonly used (Antwi-Afari et al. 2021; Ossio et al. 2023). Reliance on a single database may nonetheless limit dataset completeness, a trade-off between coverage and analytical consistency that is acknowledged as a limitation.

The search strategy targeted literature on CE in building-related contexts while excluding broader infrastructure systems. Accordingly, the Boolean search string ('circular economy' OR 'circular*') AND ('building' OR 'build*' OR 'built environment') was specified to prioritise conceptual relevance and domain specificity. Adding terms such as 'construction' would raise recall but also capture 'infrastructure' studies beyond the intended scope. The following inclusion criteria were applied: (1) publications from 2005 to 2025; (2) peer-reviewed and English-language journal articles; (3) subject areas of Environmental Science, Energy, Engineering, Social Sciences, Materials Science, Earth and Planetary Sciences, and Multidisciplinary. The initial search returned 644 records. After excluding 273 records by document type and language and 50 by subject area, 321 papers were retained for screening.

Initial screening reviewed titles, abstracts, and keywords to confirm article relevance to the BE. Studies focusing on non-building sectors were excluded. This produced a dataset of 269 articles for science mapping. Full-text screening then evaluated quality and relevance to the research objectives using predefined inclusion criteria: (i) explicit focus on CE concepts, principles, strategies, or applications in the BE; (ii) relevance to building-related contexts across lifecycle stages; and (iii) substantive conceptual or empirical contribution to CE in the BE. During this assessment, 46 articles were excluded for lack of substantive CE focus and 16 for full-text inaccessibility. Screening decisions were documented in a structured coding framework in Microsoft Excel, with categorisation refined iteratively to ensure consistency.

Of the remaining 207 articles, 77 review papers were excluded to avoid bias from secondary syntheses, prevent thematic repetition, and keep the focus on empirical and primary conceptual contributions for the in-depth content analysis (Wijewickrama et al. 2021). Excluding review papers may, however, limit engagement with integrated insights from prior reviews. Key review studies were therefore incorporated in the Introduction and Discussion to contextualise findings and support gap identification. The final selection for critical content analysis comprised 130 articles. Although based on partially overlapping datasets, the two stages were analytically complementary rather than fully integrated, with science mapping informing the interpretation of the content analysis findings. Figure 1 illustrates each step in retrieving, screening, and analysing the literature sample.

2.2 | Science Mapping

A scientometric analysis was conducted using a science mapping approach that visualises and analyses the domain of subject areas (Donthu et al. 2021). The study combined VOSviewer, a science mapping tool based on Visualisation of Similarities (VOS) technology (van Eck and Waltman 2010), with Biblioshiny, an R-tool for science mapping built on the Bibliometrix R package (Aria and Cuccurullo 2017, 2026). Combining the tools paired VOSviewer's strength in network visualisation with Biblioshiny's capacity for in-depth statistical and thematic analysis. This dual approach strengthened the findings by capturing both the structural relationships and the evolutionary trends within the literature (Arshad et al. 2025). Detailed explanations of each approach are provided with the corresponding results in the science mapping section.

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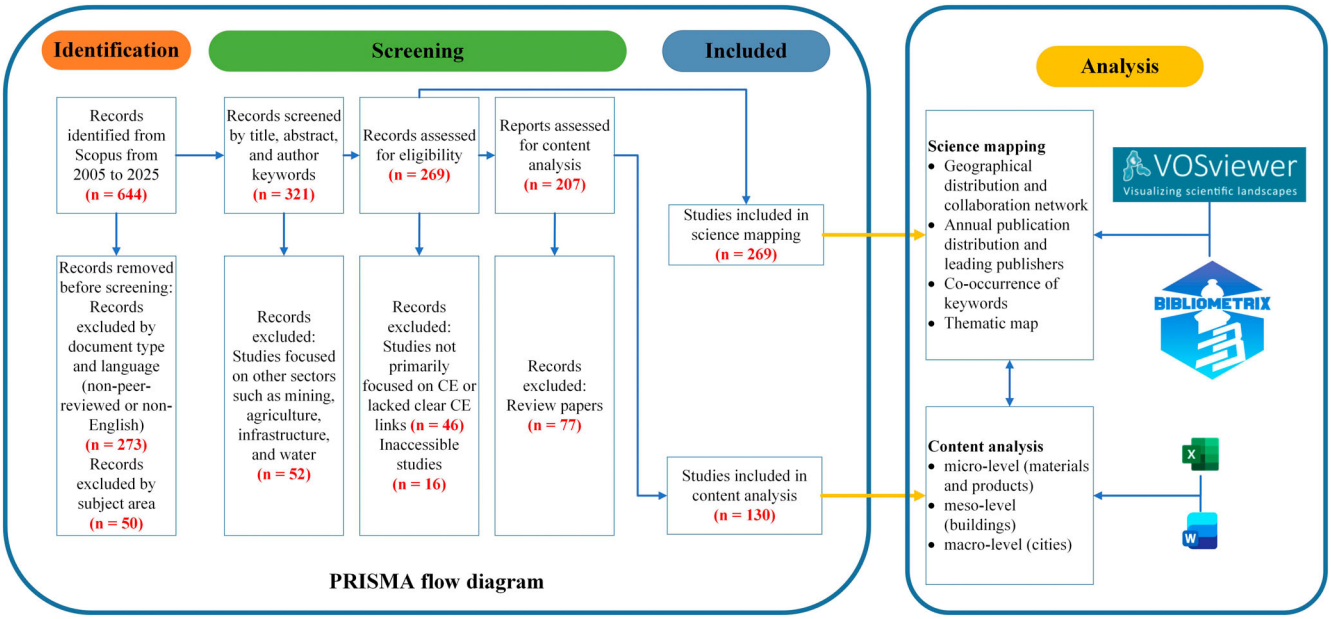


FIGURE 1 | PRISMA flow diagram of the SLR process.

2.3 | Content Analysis

Content analysis was adopted because it offers flexibility in handling structured and contextualised data and knowledge building and theory development (Finfgeld-Connett 2013). Papers were critically reviewed to explore the breadth of existing CE research, identify dominant themes, and synthesise knowledge gaps. Consistent with qualitative research principles, analysis was performed concurrently with data collection to refine the research direction and capture emerging themes (Saunders et al. 2009).

The three system levels (micro, meso, and macro) and their interconnections are the central focus of this study. Initial themes were informed by the science mapping results, which provided useful starting points. These results did not, however, distinguish between system levels and their interconnections and therefore required further refinement. Building on the conceptual synthesis in the Introduction, an analytical framework was developed to align the analysis with system levels and their cross-level enabling mechanisms. Within this framework, the science mapping results were not treated as independent outputs but informed the identification and interpretation of themes. This translated the science mapping outputs into analytically meaningful categories, enabling an integrated understanding of circularity in the BE.

The coding process was iterative, developing codes, sub-themes, and overarching themes. To enhance reliability, the coding and thematic mapping were independently cross-checked by a second researcher to ensure consistent interpretation and categorisation (O'Connor and Joffe 2020). Discrepancies were resolved through iterative refinement of the coding framework. An audit trail of coding decisions and revisions was maintained to ensure transparency and replicability. The overall findings were also reviewed and validated by all authors to ensure robustness and interpretive rigour (Wijewickrama et al. 2021). The final coding system comprises four main dimensions with associated themes, sub-themes, and selection criteria (see Table 1). The extracted data were coded into thematic categories using Microsoft Excel and Word, supporting systematic pattern recognition and organisation.

3 | Findings

3.1 | Science Mapping Analysis

3.1.1 | Geographical Distribution and Collaboration Network

Among the included studies, the Netherlands led with 126 articles, followed by the United Kingdom (UK) (105), Italy (68), the United States (US) (63), Australia (60), and China (55). Counts are based on all co-authors' country affiliations, so one article may count towards several countries. In Europe, the Netherlands's top position may be linked to a consistent and evolving national strategy for circularity, most recently the National Circular Economy Programme 2023–2030 (Government of the Netherlands 2023). In Oceania, Australia's position may coincide with the recent launch of the National Waste Policy Action Plan and the National Circular Economy Framework (NCEF) in 2024 (DCCEEW 2024a, 2024b), which prioritise construction and demolition waste (CDW) and the broader BE as pillars for circular transformation (Senaratne et al. 2025).

Within the reviewed sample, research collaboration networks were particularly strong within Europe. This prominence may stem from the 2015 introduction of the European Union Circular Economy Action Plan (European Commission 2015b), which established a cohesive policy framework and facilitated financial support across member states. The plan has nurtured transnational research partnerships and emphasised key sectors such as the BE. The EMF in the UK has further accelerated CE strategies and methodologies, providing adaptable frameworks embraced by cities and academic institutions. Collectively, these initiatives

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TABLE 1 | The coding framework for the content analysis.

Level	Themes	Sub-themes	Criteria for classification
Micro (materials and products)	Circular material innovation and practices	• Innovative materials and products • End-of-life treatment	Studies are classified at the micro level when they primarily focus on material properties, product-level design, or component-level processes
Meso (buildings)	Circular building implementation	• Circular buildings • Building refurbishment and adaptive reuse	Studies are classified at the meso level when they primarily focus on whole-building practices
Macro (cities)	Circular cities and resource flows	• Material stock and flow analysis • Circular cities	Studies are classified at the macro level when they primarily analyse urban-scale or system-wide processes
Cross-level enabling mechanisms	Integrative and enabling processes across scales	• Life-cycle analysis • Circular design and construction strategies • Circular business models • Circularity assessment • Digital technologies • Stakeholders' roles and collaboration • Integration with Sustainable Development Goals (SDGs)	Themes are classified as cross-level when they operate across multiple system levels

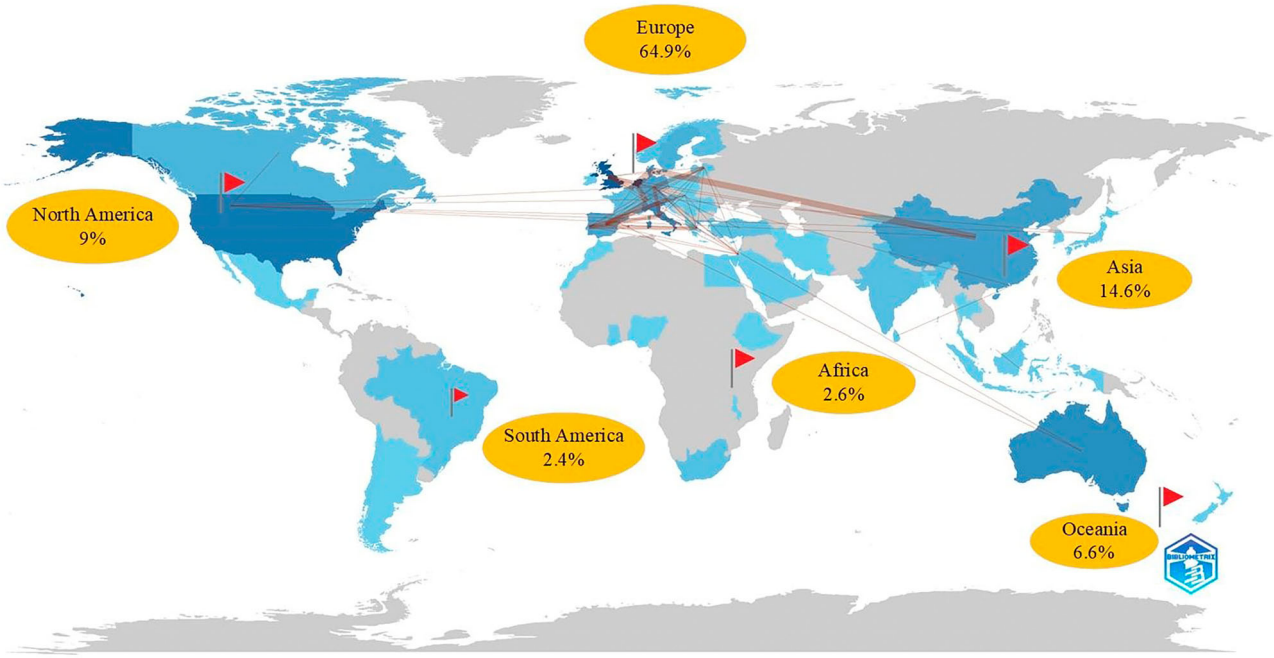


FIGURE 2 | Geographical distribution of research output and collaboration. Darker shading indicates countries with higher publication output; line thickness indicates the strength of international collaboration.

have solidified Europe's role as a global leader and innovation hub in CE research. Figure 2 maps regional scientific production and collaboration.

These findings indicated that leadership in CE research and collaboration was predominantly situated in economically advanced countries and regions. In contrast, many developing nations (e.g., Indonesia, Ghana, Bangladesh, Mexico) remained at an early stage of engagement. These patterns partly reflect the markedly higher per-capita resource extraction and material demand of high-income regions, which have historically consumed and constructed at such scale that they now face a pronounced legacy of accumulated material 'stock' requiring ongoing management (UNEP 2024). The analysis also highlighted the pivotal influence of governmental policies and initiatives in advancing CE within the BE. Government bodies shape regulatory frameworks, set ambitious targets, and drive industry standards that encourage circular practices at every scale.

The geographical distribution and collaboration network reflect the search protocol and studies included in this analysis. Countries publishing substantially in other languages or regional databases are likely under-represented. The findings are therefore presented as indicative rather than as a definitive measure of national research output or collaboration in this field.

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3.1.2 | Publication Distribution

The annual publication distribution shows that sustained scholarly attention to the field emerged in the late 2010s. Its earliest contributions were isolated, with single papers appearing in 2007 and 2014. Accelerated diffusion followed the widely cited EMF reports from 2012 onward, with marked growth after 2017. This growth may be associated with the 2015 adoption of the Paris Climate Agreement. In this context, CE gained prominence because reducing material extraction, extending product lifetimes, and improving resource efficiency are increasingly recognised as essential pathways for decarbonisation (UNDP 2023). The trend culminated in 2024, the highest-output year with 59 publications, underscoring the field's rapid expansion and current prominence (see Figure 3).

The journals most engaged in the research domain were identified through the most-relevant-sources analysis in Biblioshiny. Foremost are the *Journal of Cleaner Production* (33) and *Sustainability* (33), followed by *Buildings* (22) and *Resources, Conservation and Recycling* (21), and then *Building Research and Information* (7) and the *Journal of Building Engineering* (7). An H-index analysis of local source impact highlighted the *Journal of Cleaner Production* and *Resources, Conservation and Recycling* as the most influential in the field. These leading journals are predominantly in engineering, energy, environmental science, and sustainability, which have led the dissemination of CE research. This dominance highlights the interdisciplinary nature of CE research and the need to address circular BE challenges through innovative research.

3.1.3 | Co-Occurrence of Keywords

A comprehensive keyword network reveals the knowledge structure and organisation of research themes within the field. It maps the current landscape and the relationships among themes, offering insight into present and future research trajectories. In VOSviewer and Biblioshiny, keywords with a minimum occurrence of 5 were retained, and after merging semantically similar terms and removing general terms such as 'construction' and 'building' using text-removal and thesaurus files, 88 keywords with 1756 links were selected for analysis (see Figure 4). The words with the highest occurrences and greatest connection in both VOSviewer and Biblioshiny were: 'CE' (Frequency (Feq.) = 188, Total Link Strength (TLS) = 879), 'built environment' (Feq. = 137, TLS = 733), 'sustainable development' (Feq. = 77, TLS = 480), 'life-cycle analysis' (Feq. = 65, TLS = 370), 'recycling' (Feq. = 42, TLS = 312), 'architectural design' (Feq. = 40, TLS = 276), and 'environmental impact' (Feq. = 36, TLS = 242).

To determine the field's hotspots, keywords were grouped into distinct clusters in VOSviewer, capturing the relationships that reveal prevailing research trends. Studies within a cluster tend to share greater similarity with each other than with those in other clusters. Four colour-coded clusters were identified, each representing an underlying semantic theme. Cluster #1 (31 items) 'Circular Cities and Urban System' focused on urban planning, material and resource flows, industrial ecology and economics, spatial and temporal analysis. Cluster #2 (24 items) 'Circular Design and Construction' centred on circular design and construction strategies. Cluster #3 (20 items) 'Circular Materials and Resource Recovery' emphasised materials, resource efficiency, and waste management. Cluster #4 (13 items) 'Life Cycle and Circularity Assessment' highlighted life-cycle analysis, circularity assessment, sustainability assessment, and decision support. Figure 5 illustrates the main research keywords, clusters, and their interrelationships.

3.1.4 | Thematic Map

A thematic map was used to uncover recurring themes and patterns in the data (Aria and Cuccurullo 2017; Ghorbani 2024). It organises topics on a two-dimensional map according to density (how well-developed a theme is) and centrality (how relevant it

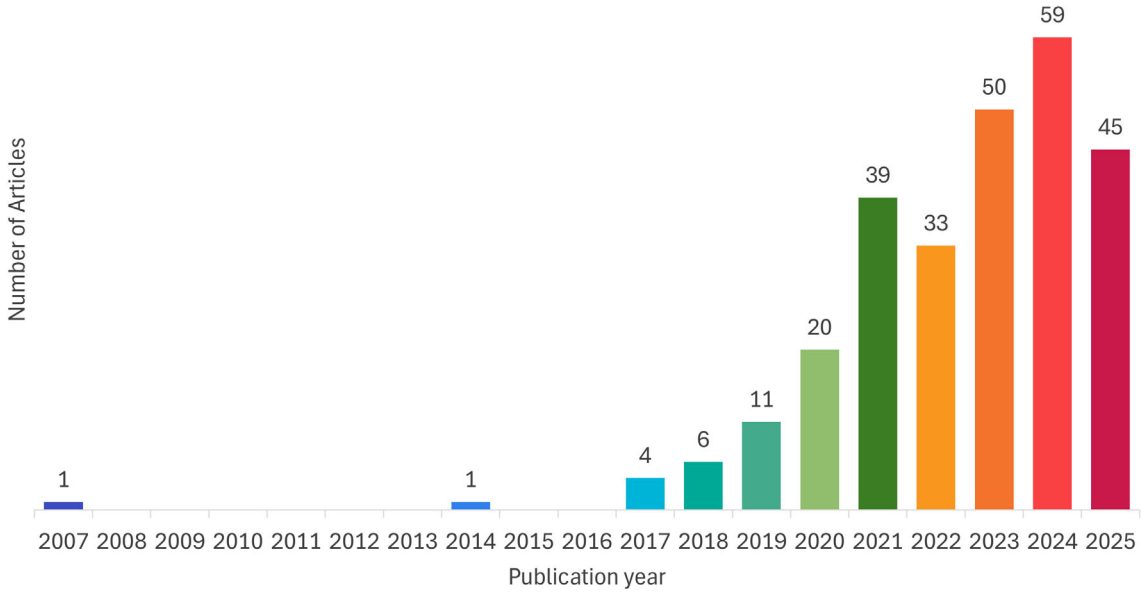


FIGURE 3 | Annual distribution of publications from 2007 to 2025.

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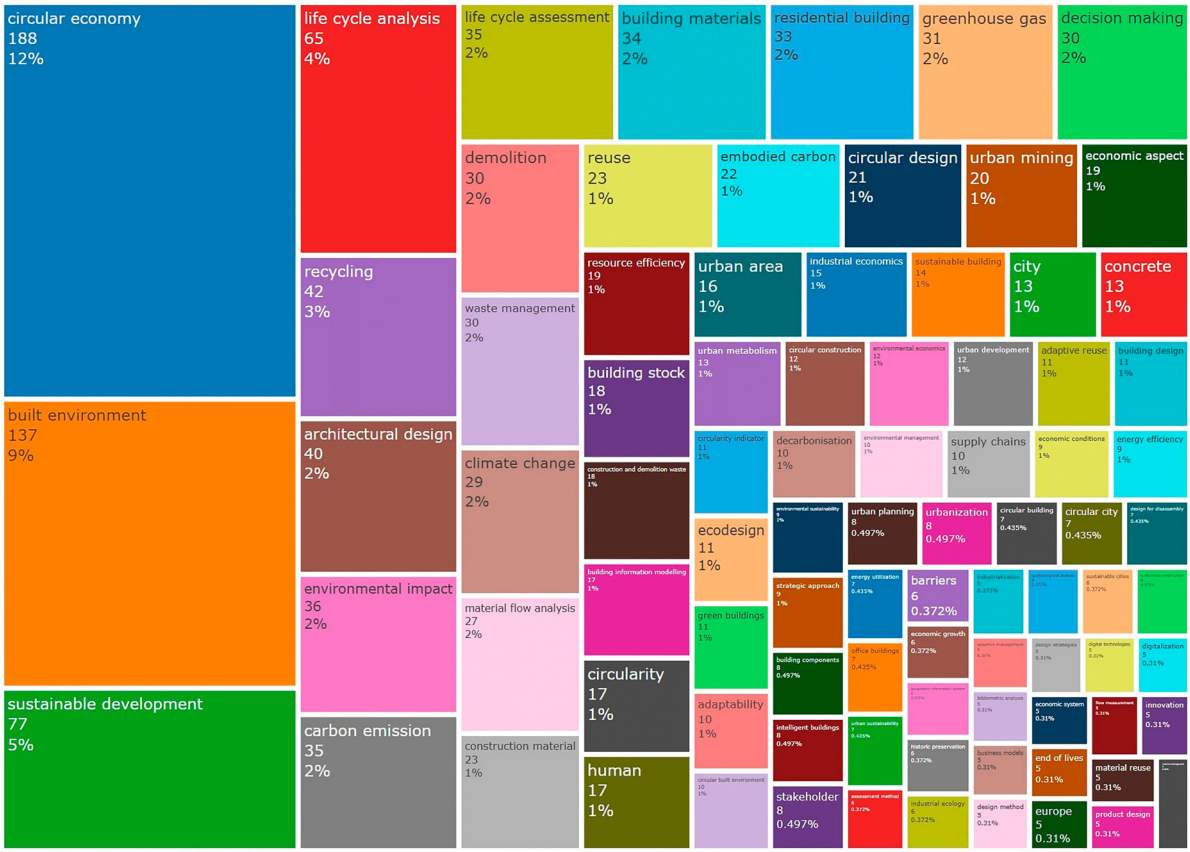


FIGURE 4 | Tree map of co-occurring keywords. Box size is proportional to frequency; each box is labelled with its occurrence count and percentage share; colour distinguishes individual keywords rather than indicating a shared theme or hierarchy.

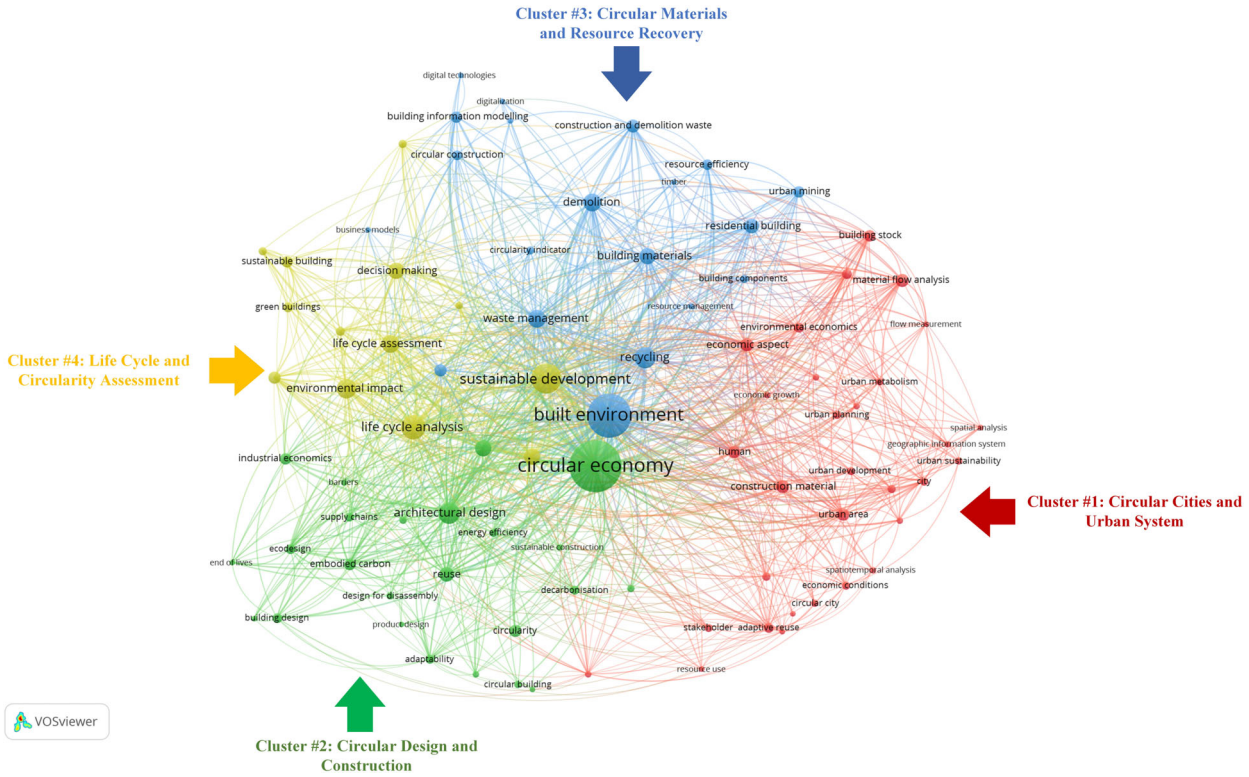


FIGURE 5 | Network map of keyword co-occurrence. Node size reflects keyword prominence; colour distinguishes the four clusters identified in VOSviewer.

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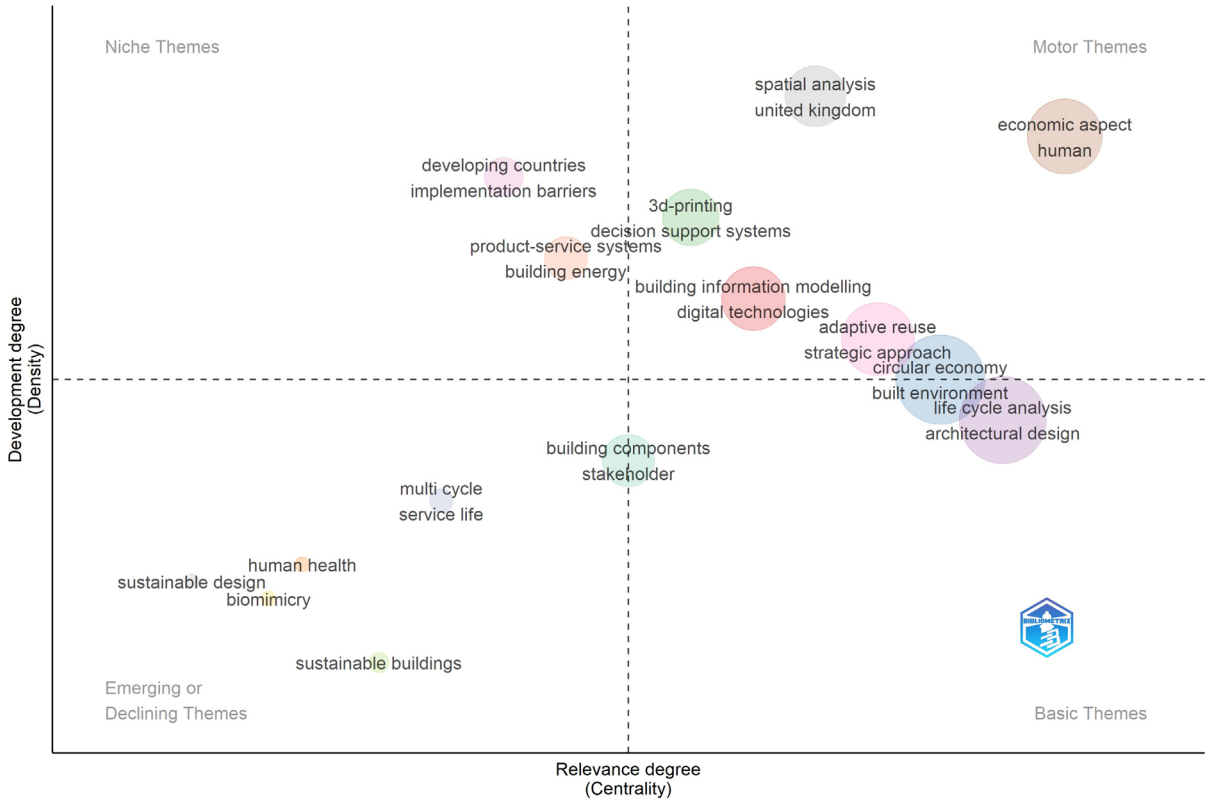


FIGURE 6 | Thematic map. Themes are plotted by density and centrality, with quadrant position indicating theme type (motor, niche, basic, emerging/declining) and bubble size reflecting theme prominence.

is to the overall research). Motor themes are both highly developed and central, representing well-established and substantial topics. Niche themes are well-developed (high density) but less relevant (low centrality) to the main research focus. Emerging or declining themes show low density and low centrality, attracting little attention and sitting at the fringe of current research, though they may gain importance in future studies. Basic themes are not yet fully developed but highly central, indicating strong potential for future research and development (Singh 2022; Arshad et al. 2025). The thematic map highlighted important themes, including digital technologies, decision-support systems, adaptive reuse, waste management, and life-cycle analysis. Areas with potential for further development include circular business models, building components, energy retrofit, implementation pathways, and stakeholder involvement. Emerging areas such as sustainable design, biomimicry, human health, product service life, and multi-cycle approaches present promising avenues for future investigation (see Figure 6).

3.2 | Content Analysis

3.2.1 | Micro-Level

3.2.1.1 | Innovative Materials, Products, and Manufacturing Techniques. Interest is growing in more environmentally friendly materials that incorporate waste and enable carbon adsorption (e.g., waste-based geopolymers (Khan et al. 2023); date palm fibre–clay insulation (Yousaf et al. 2024); PLA/olive wood composites (Fico et al. 2022); carbonated reactive magnesia cement (Grünhäuser et al. 2022); bio-concretes from wood, bamboo, and rice husk (Araujo et al. 2025); and agricultural waste products (Aldeek and Ayyoub 2025)). However, technical and performance risks remain, such as the mechanical degradation of waste-derived bio-composites (Fico et al. 2022) and the time-dependent behaviour of materials such as compacted mineral mixtures (Bühler et al. 2023). This indicates a need for further empirical validation, particularly of long-term performance and integration within existing construction systems. Waste streams within the broader bioeconomy, such as those from agriculture, aquaculture, and forestry, are potential but underexplored resources for advanced construction materials. Valorising these bio-based residues reduces waste while driving innovation and economic development.

Similarly, additive manufacturing techniques such as 3D printing are gaining recognition for reducing waste and enabling efficient, on-demand production, particularly with recycled or bio-based feedstocks (Yousaf et al. 2024). However, this potential is not unconditional. Printing CDW-based geopolymer mixes remains an energy-intensive process, so whether the printed structures genuinely outperform conventional construction on full life-cycle performance is still being investigated rather than established (Khan et al. 2023), and higher fibre content, while improving thermal and mechanical performance, introduces extrusion difficulties and buildability constraints (Carcassi et al. 2024).

A growing body of literature recognises the role of circular building components, centred on designing products for disassembly,

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reuse, and modularity. However, practical feasibility lags behind conceptual design. Even for the well-studied kitchen component, knowledge of which technical, industrial, and business models work in the field remains limited, and ownership questions, fragmented supply chains, a lack of universal methods and other barriers continue to constrain implementation (Ollár et al. 2020; Wouterszoon et al. 2023). At the structural scale, connections in hybrid structures still hinder deconstruction, and low awareness of design-for-deconstruction principles, even in higher education, remains an underlying barrier (Derikvand and Fink 2023). Circular building components are therefore better validated as design concepts than as components with demonstrated feasibility across diverse project contexts.

3.2.1.2 | End-of-Life Treatment. The literature consistently prioritises 'slowing, closing, and narrowing' material loops at the micro level. These are operationalised through a broad set of R-strategies beyond the traditional 'reduce, reuse, recycle' (3Rs), including refuse, rethink, repair, refurbish, remanufacture, repurpose, recover, regenerate and replace (Çimen 2021; Ho et al. 2024). However, their implementation reveals several important tensions and limitations. A key debate concerns the distinction between technical and biological material loops. Technical materials offer high durability and reusability but carry high upfront costs and overlooked carbon impacts of demolition prior to construction (Kanyilmaz et al. 2023; Dewagoda et al. 2024). Biological materials can act as carbon sinks and generally have lower initial impacts, but chemical treatments often hinder their recyclability and reuse (Finch et al. 2021). This highlights a fundamental trade-off between durability, environmental performance, and circular recoverability.

A common assumption is that reusing salvaged components directly displaces the production of new materials (Zhuang et al. 2023; Berglund-Brown and Ochsendorf 2025). In practice, however, this one-to-one substitution is rarely achieved, as market dynamics, quality uncertainties, fragmented supply chains and social acceptance limit the realised environmental benefits of reuse (Hartwell et al. 2021; Kanyilmaz et al. 2023; Mhatre et al. 2024). Significant data gaps also persist regarding salvaged material stocks, the environmental and health impacts of recovery processes, and the long-term performance of reused elements under ageing and repeated use (Daly 2023; Dorignon et al. 2024; Mayer 2025). These limitations are compounded by limited research into innovative end-of-life treatment technologies. Gebremariam et al. (2020) developed large-scale processes such as Advanced Dry Recovery (ADR) and Heating Air Classification Systems (HAS) to recycle end-of-life concrete into coarse, fine, and ultrafine particles. Such technologies show strong potential for greener end-of-life treatment and improved resource recovery. However, comparable advances remain underexplored for widely used materials such as timber and steel, and for the broader range of construction materials.

3.2.2 | Meso-Level

3.2.2.1 | Circular Buildings. Research into the barriers and enablers of circular buildings is expanding globally (see Appendix B); however, most work addresses planning and design rather than construction, operation, and demolition. Adoption is shaped by interrelated economic, regulatory, technical, and socio-cultural factors that act as both barriers and enablers. Economically, the high upfront costs of circular material procurement remain a dominant constraint (Çetin, Gruis, and Straub 2021; Guerra and Leite 2021), while enablers such as green financing, subsidies, and VAT reform are presented as potential rather than empirically demonstrated (Gillott et al. 2022; Stoiljković et al. 2023; Evertsen and Knotten 2024). Regulatory factors show a similar tension: rigid building codes and the absence of binding legislation hinder reuse (Guerra and Leite 2021; van den Berg et al. 2024; Izquierdo et al. 2024), whereas proposed measures such as mandatory whole-of-life carbon assessments and government-led recycling and reuse thresholds are positioned as necessary drivers (Ghaffar et al. 2020; Gillott et al. 2022). Technically, complex building systems, limited material information, and a shortage of expertise are significant challenges (Guerra and Leite 2021; van den Berg et al. 2024), though digital technologies and design strategies are consistently cited as solutions (Gillott et al. 2022; Izquierdo et al. 2024). Persistent linear mindsets and stigma towards reused materials reflect socio-cultural resistance (Çetin, Gruis, and Straub 2021; Izquierdo et al. 2024; Kaewunruen et al. 2024), with leadership commitment and education identified as key, yet insufficiently examined enablers.

Few circular building case studies demonstrate the move from circular strategies to actions. Nußholz et al. (2023) made a first attempt, analysing 65 real-world European cases, yet the reported decarbonisation potentials are highly case-specific and not comparable. Ho et al. (2024) extended the scope to five countries (Australia, India, Sri Lanka, Thailand, and Kyrgyzstan), showing how CE strategies apply across contexts, though the proposed conceptual model for integrating CE in the BE remains unvalidated across wider regions and cases. Such empirically grounded studies could nonetheless help policymakers and building stakeholders understand CE principles and adopt a circular mindset.

Modern construction methods are increasingly recognised as effective for operationalising CE principles. Offsite/modular construction, prefabrication, and zero-waste site practices are both visionary and practical for minimising waste and closing material loops (Dewagoda et al. 2024; Koronaki et al. 2025). Lean construction can cut construction waste by 25%–50%, exceeding 50% when combined with automation and robotics (Jain et al. 2023). Several limitations nonetheless constrain their uptake. Modular and prefabricated systems are often restricted by factory capacities and transport regulations, limiting architectural versatility and usability (Kyrö et al. 2019). Logistics is a further bottleneck, as long transport distances and limited infrastructure for storing and processing reclaimed components hinder market efficiency (Ghaffar et al. 2020; Griffiths et al. 2025). Higher upfront costs and perceived financial risks also deter adoption, particularly among small and medium-sized enterprises (SMEs), despite long-term benefits (Guerra and Leite 2021; Hasibuan et al. 2025). Continued efforts are therefore needed to scale and standardise best practices across the sector.

3.2.2.2 | Building Refurbishment and Adaptive Reuse. Research on building refurbishment and adaptive reuse has shifted from energy efficiency toward reducing whole-of-life carbon emissions (Bui et al. 2023), aligning with CE principles that prioritise direct building reuse. Adaptive reuse has been

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a major focus, with circular building adaptability central to it, defined as the capacity to sustain usefulness while keeping assets in a closed, reversible value chain (Rodrigues and Freire 2017; Hamida et al. 2025). Key CE strategies include planning, assessment, and management; configuration flexibility; product dismantlability; material reversibility; functional convertibility; and maintainability (Eray et al. 2019; Hamida et al. 2025).

However, the scope of circular interventions remains debated. 'Minor' measures are seen as more circular, retaining higher value with minimal intervention, whereas 'major' ones may deliver greater long-term benefits despite higher initial resource and cost demand (Lundgren 2023; Dragonetti et al. 2025). Outcomes are also highly context-dependent, varying with building condition, occupancy, and decision-maker priorities (Dragonetti et al. 2025), which limits the transferability of best practices. Most research addresses isolated aspects rather than integrated, step-by-step systems spanning different refurbishment types and scales. Refurbishment can further deliver social benefits, such as reduced community disruption and heritage preservation (Josa and Borrion 2025). Yet these depend on occupant participation and are undermined when interventions ignore occupant needs (Feijter 2023). Circularity ultimately depends on how well interventions respond to the needs, behaviours, and values of end-users.

3.2.3 | Macro-Level

3.2.3.1 | Material Stock and Flow Analysis. Research on material stock and flow analysis (MSFA) in the BE is advancing rapidly. Diverse methodologies have been developed to quantify and map stocks and flows across scales, often focused on improving resolution, accuracy, and practical applicability. A summary of MSFA studies is provided in Appendix C.

Many MSFA models draw on cadastre, building typologies, material intensities, and spatial analysis, with advances in dynamic and forecasting methods (Marinova et al. 2020; Kolkwitz et al. 2023). Material flow analysis and material intensity coefficients are widely used to quantify flows and stocks through top-down and bottom-up approaches (Schiller et al. 2017; Tudela et al. 2020). However, comparisons of the two reveal significant disparities, with bottom-up total inflows representing as little as 53% of top-down values. This divergence reflects not mere error but systematic 'data gaps' in statistical reporting, such as ancillary structures (Schiller et al. 2017). Advanced modelling is emerging to address these granularity limits, integrating digital technologies such as geographic information systems (GIS), machine learning, Light Detection and Ranging (LiDAR), and building information modelling (BIM) to better estimate existing stock at building, element, and material levels (Dai et al. 2025; Parezanović et al. 2025). Hybrid approaches enable high-resolution 3D models and refined element-level estimates, but cannot identify underground levels, interior structures, or changes from energy-efficient refurbishments (Parezanović et al. 2025). Non-structural and short-life materials and their maintenance flows also carry significant environmental impacts and recurrent embodied footprints (Stephan and Athanassiadis 2018; Soonsawad et al. 2024). Future research should therefore prioritise integrated multi-dimensional frameworks that combine diverse data sources for more comprehensive and accurate stock assessments.

MSFA has evolved beyond its original descriptive role and is now integral to urban mining strategies that maximise resource efficiency. Studies such as Arora et al. (2020) and Luciano et al. (2023) demonstrate the feasibility of estimating material stocks and recovery potential, viewing existing buildings as dynamic material reservoirs (Schiller et al. 2017; Çimen 2021). A major concern remains the modelling of material outflow, which may not reflect observed demolition statistics. Current models rely on simplified assumptions about building lifetimes or treat population as the sole driver. In practice, demolition decisions are shaped more by socio-economic factors, including urban regeneration pressures, land value dynamics, and policy interventions, than by physical degradation alone (Kolkwitz et al. 2023; Böcher et al. 2025). This systemic gap between modelled and actual material retention highlights the need for integrated dynamic models that better estimate the true secondary resource potential of the urban mine.

3.2.3.2 | Circular Cities. The circular city conceptualises urban systems as regenerative and self-sustaining, extending beyond urban metabolism to the continuous renewal of human, social, natural, and built capital (Gravagnuolo et al. 2019). Within this system, building and property assets form a critical subsystem interacting with socio-productive, energy-mobility, and natural-ecological systems (Soto et al. 2024). Nature-based solutions (NbS) are increasingly recognised as promising regenerative design strategies for buildings that could support circular city transitions. They remain under-prioritised, however, given the lack of robust, standardised frameworks to monitor their environmental, social, and economic impacts. Existing studies also highlight persistent challenges of fragmented policy support, insufficient public engagement, and limited technological integration, which together hinder large-scale implementation (Atanasova et al. 2021; Bona et al. 2023). Advancing NbS within circular city agendas therefore requires both stronger empirical evidence and a more integrated approach to regulatory, socio-institutional, and technological barriers.

Circular city case studies that trace the progression from high-level strategies to concrete actions remain scarce. Cities mainly implement CE through municipal leadership, strategic planning, and piloting rather than deep structural change (Prendeville et al. 2018), raising concerns about whether reported 'circular' practices reflect incremental adaptation or genuine socio-technical transition. Most empirical case studies also focus on high-income contexts (e.g., Soto et al. 2024; Avdiushchenko and Meinrenken 2025). Methodologies and governance lessons therefore derive from well-resourced settings with established institutions and data infrastructures. This bias limits the transferability of current CE frameworks to low-income contexts, where urban systems are often shaped by informality, distinct material stock dynamics, and limited data availability. In contrast, comparative case studies of Shenzhen and Suzhou in China show that construction waste circularity in emerging economies began with developing recycling, supported by strong government intervention and economic incentives (Bao 2023). Comparative case studies from both developed and developing regions are therefore essential, enabling more robust theory-building, revealing context-sensitive implementation pathways, and supporting a more globally representative understanding of circular cities.

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This could foster broader and more equitable adoption of CE practices across diverse urban contexts (Carrière et al. 2020).

3.2.4 | Cross-Level Enabling Mechanisms

3.2.4.1 | Life-Cycle Analysis. At the micro level, Life Cycle Assessment (LCA) remains the most effective method for assessing the environmental performance of building materials and components. However, no consensus exists on how allocation methods should represent the benefits of reuse, recovery, and recycling across the multiple life-cycles that CE emphasises. Existing approaches include the EN 15804/15978 cut-off, the Circular Footprint Formula (CFF), the 50:50, the linearly degressive (LD), and the new CE-LD method, which better aligns allocation with circularity objectives (Eberhardt et al. 2020). LCA studies should therefore test allocation choices through sensitivity analysis to clarify whether circular design consistently improves performance, particularly around tipping points shaped by use cycles, material lifespans, and method choice (van Stijn et al. 2022).

At the meso level, building LCA evaluates circular design strategies such as disassembly, flexibility, adaptability, and deconstruction to support design decisions (Eberhardt et al. 2019; Kröhnert et al. 2022). However, the allocation problem identified at the micro level recurs across multiple building cycles, where future reuse benefits remain uncertain (Eberhardt et al. 2019; Roberts et al. 2023). Simplified, transparent allocation is needed to show how longer lifespans and added reuse cycles affect performance. Yet reusing structural elements does not always yield net benefits (Kontra et al. 2025), so the conditions for beneficial reuse warrant further study. Lifespan assumptions are a further concern. Building layers and component-based approaches are both promoted as best practice but can give differing outcomes (Davis et al. 2025), underscoring the need for standardised lifespan modelling.

Across micro and meso levels, LCA often incorporates Life Cycle Costing (LCC) to show environmental–economic trade-offs, whereas Social Life Cycle Assessment (SLCA) remains underdeveloped for materials, components, and buildings. A recent exception is Josa and Borrion (2025), who applied SLCA to a London university retrofit, though SLCA still needs primary data and testing across contexts. Integrating LCA, LCC, and SLCA into Life Cycle Sustainability Assessment (LCSA) can support the BE's CE transition (Larsen et al. 2022), but balancing the three dimensions remains challenging and needs further research.

At the macro level, LCA examines the environmental impact of building material stocks, identifying mitigation 'hotspots', baseline scenarios for national decarbonisation, and urban mining potential (Marinova et al. 2020; Meijer et al. 2024). Its main challenges are data selection, granularity, and bias. Process-based data is often chosen over input–output tables for consistency with common LCA practice and tools, though this can markedly shift impact estimates (Sharmina et al. 2023; Hoxha et al. 2024). Unitary material intensity coefficients assign single average values to archetypes, ignoring intra-archetype variability and producing stock-estimate discrepancies (Hoxha et al. 2024; Dai et al. 2025), while coarse data on building and floor heights distort floor-area and thus aggregate impact estimates (Böcher et al. 2025). Macro-level LCA thus offers strategic insight but is constrained by data simplifications requiring more transparent uncertainty handling.

3.2.4.2 | Circular Design Strategies. Circular design strategies are interconnected across micro, meso, and macro levels. Core strategies in the literature include designing for adaptability, durability, disassembly, deconstruction, and resilience, alongside resource efficiency and regenerative approaches throughout the building lifecycle (Akanbi et al. 2019; O'Grady et al. 2021). A critical debate, however, questions whether 'circular' is synonymous with 'sustainable'. Design for disassembly, for instance, can be energy- and carbon-intensive, negating environmental benefits when logistics and reprocessing energy exceed the impacts of new material production (van Stijn et al. 2022; Berglund-Brown and Ochsendorf 2025). Design for adaptability often requires over-capacity, such as greater floor-to-ceiling heights or over-dimensioned structures, to accommodate future use (Watt et al. 2023; Ollár 2024). This directly contradicts material optimisation, which minimises material use to reduce embodied carbon (Passoni et al. 2022; Watt et al. 2023). Integrating circular principles therefore requires moving from prescriptive checklists to performance-based design that explicitly accounts for environmental trade-offs across all life-cycle stages.

Fewer studies examine social circular design strategies focused on occupant health and well-being. A key tension exists between the hedonic perspective (short-term comfort and pleasure) and the eudaimonic perspective (long-term human flourishing, meaning, and aesthetics) (Clube and Tennant 2023). Scurtu et al. (2024) argue that modern design is too focused on hedonic needs, whereas CE requires a eudaimonic emphasis to foster building longevity and care. The underlying assumption is that occupants who feel happier and more comfortable will maintain and use a building longer, extending product life. This is often undermined, however, by a technological-fix mentality that assumes predictable user behaviour and overlooks the subjective nature of human attachment to space (Feijter 2023). Gaps also persist between initial design performance and actual in-use impacts over time, yet these remain largely unverified owing to limited post-occupancy evaluation (Roberts and Edwards 2022). Future research must therefore move beyond isolated indicators to holistic models that align circularity with genuine social sustainability.

3.2.4.3 | Circular Business Models. Circular business models (CBMs) shift from the linear 'take-make-dispose' model toward systems that retain value, slow material loops, and deliver performance over ownership. At the micro level, CBMs focus on individual building elements (product-service systems), keeping them in technical or biological cycles through innovative ownership and design, and shifting manufacturers from selling products towards leasing, take-back and service-based offers (van Stijn et al. 2022; Zhuang et al. 2023). However, the evidence base remains largely techno-centric, with limited validation of long-term provider finances and user willingness to adopt service-based models (Lee et al. 2024). At the meso level, CBMs operate through building-scale strategies such as building-as-a-service and adaptive reuse, aligning asset performance with long-term value. Although supported conceptually

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by total-value-of-ownership frameworks, a persistent tension exists between their theorised economic advantages and practical constraints, particularly legal ownership structures and financing risks (Azcarate-Aguerre et al. 2022). At the macro level, CBMs are seen as needed to drive urban and market transformation through circular material flows and collaborative governance (Brglez et al. 2024), yet empirical testing at this scale remains scarce, especially of measurable economic outcomes. Overall, CBMs act as integrative mechanisms linking product-level innovation to systemic change, but how far firm-level innovations translate into city-scale outcomes remains unclear, limiting theoretical clarity and cross-context comparability.

3.2.4.4 | Circularity Assessment. CE assessment indicators and frameworks are a prominent topic, crucial for measuring, communicating, and improving circularity. At the micro level, they evaluate the environmental and economic performance of components (Jansen et al. 2020; van Stijn et al. 2022). In addition, multi-criteria decision-making techniques prioritise design indicators, ranking joint design and material selection as most critical for reusable modular components (Zhuang et al. 2023). The shift towards integrated multi-criteria approaches is evident but fragmented. Future research must develop holistic frameworks integrating environmental, economic, social, and functional value to identify tipping points where the cost of circularity outweighs its environmental benefits or where social acceptance becomes decisive.

At the meso level, Building Circularity Indicators (BCIs) have evolved from EMF's Material Circularity Indicator (Verberne 2016) to versions incorporating diverse key performance indicators (Cottafava and Ritzen 2021; Khadim et al. 2023; Lau et al. 2025). Yet most remain mass-based and few have been standardised or certified for use in practice, capturing circularity potential rather than actual environmental performance. Combining these indicators with LCA has therefore been proposed to reflect real environmental outcomes rather than mass-based scores alone (Saadé et al. 2022). Current methods otherwise remain inconsistent and highly case-specific, constraining benchmarking and comparability across projects.

Green Building Rating Systems (GBRSs) offer established frameworks with strong market influence. Though not designed for circularity, they increasingly incorporate CE-related principles. BREEAM-C, tailored for circular buildings, aligns with CE strategies across impact areas, structural layers, and life-cycle stages (Wong et al. 2024). CE practices have been shown to reduce life-cycle carbon emissions in LEED- and LBC-certified buildings (Temizel-Sekeryan et al. 2023). However, GBRSs still prioritise broader sustainability objectives, resulting in only partial CE integration. They therefore need to evolve, and future research should explore how they can be revised or expanded to assess building circularity in practice.

At the macro level, scholars have proposed multi-criteria frameworks to translate CE principles into actionable strategies for circular cities (Paiho et al. 2020; Soto et al. 2024). These emphasise systems thinking, cross-sectoral integration, socio-economic strategies, and governance as key enablers (Brglez et al. 2024; Soto et al. 2024). However, their practical application remains limited, particularly in municipal decision-making and procurement (Chartier and Pot 2024). This reflects a broader cross-scale challenge: conceptual CE assessment frameworks are increasingly sophisticated, yet their translation into actionable policies and decision-support tools remains underdeveloped. Addressing this requires standardised, multi-scalar frameworks that integrate environmental, economic, social, and functional dimensions while remaining robust and practical across industry and governance settings.

3.2.4.5 | Digital Technologies. Digital technologies are critical enablers of the transition from linear to circular systems across micro, meso, and macro levels, providing the data, modelling, and connectivity needed for informed decision-making. Key technologies include building information modelling (BIM), digital twins (DTw), artificial intelligence (AI), Internet of Things (IoT), blockchain (BCT), material passports (MPs), digital platforms (DP), digital marketplaces (DM), big data analytics (BDA), additive and robotic manufacturing (AM/RM), geographic information systems (GIS), and augmented and virtual reality (AR/VR) (Keles et al. 2025).

These technologies are rarely deployed in isolation; their value emerges through integration into digital decision-support systems that combine multi-source data and complementary functions (see Appendix D). AM/RM, for example, support production and remanufacturing that reduce resource consumption and waste, while enabling regenerative bio-based materials and improving occupational safety (Çetin, De Wolf, and Bocken 2021; Yousaf et al. 2024). Similarly, DTw supports dynamic resource management and predictive data-driven maintenance, enabled by integrating external scanning data with internally modelled information using AI (Çetin et al. 2022). BIM-GIS integration supports city information models valuable for pre-demolition audits and energy refurbishment planning, bridging meso-level building data and macro-level urban planning (Parezanović et al. 2025).

Despite these advances, research remains heavily skewed towards design-stage simulations and projected benefits. Longitudinal and empirical studies of whether digitally enabled assumptions hold over time are notably lacking, particularly as components reach end-of-life decades later (Çetin et al. 2022). Digital technologies are often advocated for material traceability, yet their long-term economic viability is contested, given the cost of maintaining and updating digital models across a building's life-cycle (Çetin et al. 2022; Hasibuan et al. 2025). Conventional approaches such as visual inspection and traditional deconstruction planning may sometimes remain more cost-effective. Applications also remain predominantly technocentric, with little exploration of social innovations such as community-led sharing models or participatory data collection with occupants (Bullinger and Schiller 2025). These gaps underscore the need for longitudinal, real-world, and socio-technical research to validate and realise the potential of digital technologies for circularity in the BE. An emerging cross-sectoral example illustrates one direction such validation could take. Machine learning-based surrogate modelling has been used to validate multi-scale, cross-scale circular-economy strategies, including reuse of retired electric-vehicle batteries in buildings (Dan et al. 2024). This

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application has not yet been tested in the BE, but its validation approach may be transferable.

3.2.4.6 | Stakeholders Collaboration. The CE transition in the BE is fundamentally stakeholder-driven, shaped by asymmetries in power, knowledge, and incentives. Governments, municipalities, asset owners and investors are the most influential actors, able to mandate and incentivise paradigm shifts (Kaewunruen et al. 2024). Yet a persistent gap remains between ambition and implementation. Clients often lack ownership of end-of-life practices, since financial returns are realised well before dismantling. This misalignment of incentives, with no standardised national regulations, drives inconsistent CE adoption (Atik et al. 2024).

The operationalisation of circularity depends on coordinated action among architecture, engineering, and construction (AEC) professionals, who must manage both technical complexity and cost constraints. As architects and engineers design adaptable, resource-efficient structures, their role is shifting from object-centric design to orchestrating a broader design ecosystem. This requires integrating contractors, suppliers, and facility managers to account for lifecycle and end-of-life implications (van den Berg et al. 2024). Yet traditional procurement involves contractors too late, after design is finalised, limiting material recovery and circular performance (Hartwell et al. 2021; Izquierdo et al. 2024). This exposes a contradiction between early lifecycle integration and sequential project delivery.

The literature therefore emphasises collaborative value chains underpinned by trust, but the sector remains fragmented, with uneven CE knowledge (Griffiths et al. 2025). Diverging disciplinary priorities, for example architects' focus on material reuse versus industrial designers' emphasis on circular business models, further hinder coherent strategy (Lau et al. 2025). Emerging research advocates circular construction ecosystems uniting heterogeneous actors around a shared value proposition and co-created vision (Evertsen and Knotten 2024). Pilot projects suggest early disciplinary integration through collaborative design significantly enhances circular outcomes (Leising et al. 2018). Nevertheless, such approaches remain limited in practice, indicating that collaboration challenges are not only organisational but also rooted in deeper institutional and cognitive divides.

3.2.4.7 | Integration With Sustainable Development Goals (SDGs). Consistent with the science mapping, sustainable development is a highly connected concept, yet the content analysis shows that explicit, methodologically grounded CE–SDG linkages are rarely articulated. In this study, CE strategies were inductively derived as content themes from the reviewed literature, reflecting how CE is conceptualised and applied in the BE. Their relationship with SDGs was then mapped at the SDG-target level, linking each theme to targets through references in the papers and interpretative alignment based on the themes' functional characteristics and intended outcomes. Where a theme corresponded to multiple targets, each linkage was recorded. The resulting frequencies generated the Sankey diagram (Figure 7), which visualises the distribution of linkages across CE themes and SDGs, with detailed mapping in Appendix E.

The most frequently associated goals are SDGs 7, 8, 9, 11, 12, 13, whereas SDGs 3, 4, 5, 6, 10, 15, 16, and 17 appear less often. For instance, Lucchi et al. (2024) emphasised heritage strategies involving multi-stakeholder collaboration among public administrations, heritage authorities, local companies and citizens, extending from a heritage property to its surrounding municipality, connecting to SDGs 4, 8, 9, 11, 12, 16, and 17. Overall, linkages concentrate most strongly around SDGs 8, 9,

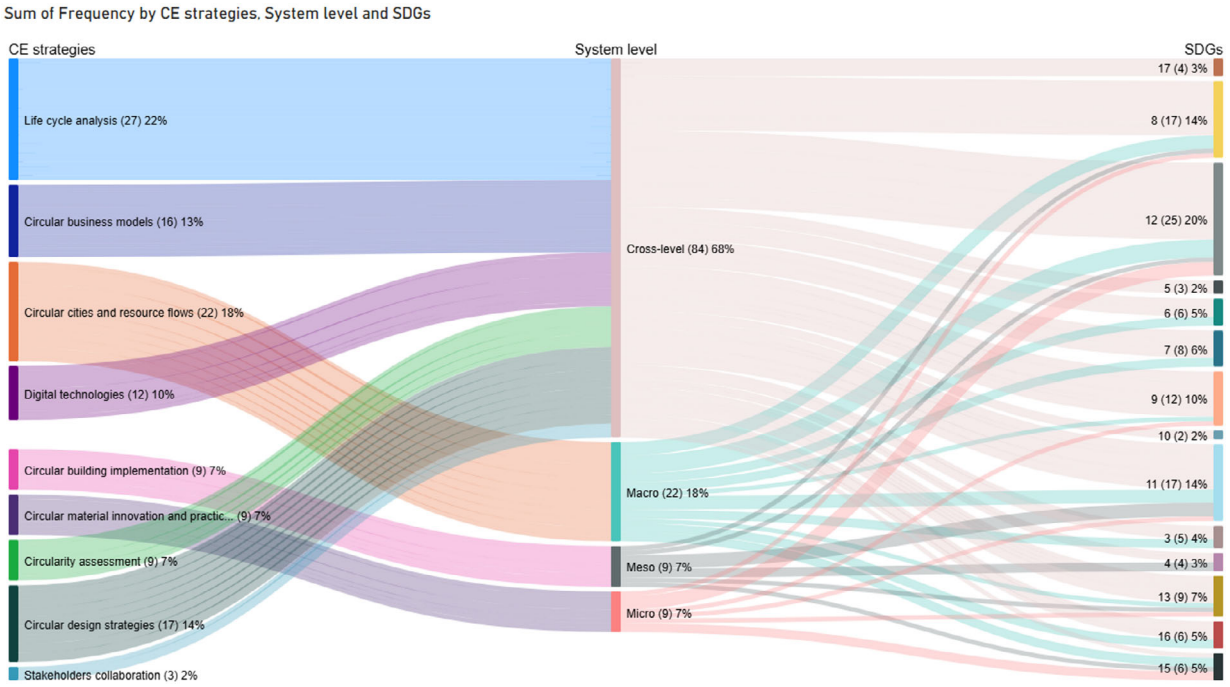


FIGURE 7 | Sankey diagram linking CE strategies to system levels and SDGs. The flow width is proportional to the frequency of each linkage.

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11, 12, and 13, reflecting dominant priorities of resource efficiency, waste minimisation, innovation, and decarbonisation, while social and institutional goals remain peripheral. LCSA is increasingly recognised as a promising way to operationalise these linkages by integrating environmental, economic, and social dimensions. SDG 13 emerges as a cross-cutting priority, as CE interventions such as embodied carbon reduction, adaptive reuse, and urban mining directly support climate mitigation and decarbonisation.

The analysis represents not causal relationships or quantified impacts but a frequency-based synthesis of how CE–SDG linkages are constructed in the literature. It also exposes a structural limitation. Even where SDGs are explicitly referenced, linkages are typically normative and author-declared, with limited articulation of underlying mechanisms or empirical validation. The analysis also predominantly reflects positively framed linkages, largely owing to limitations in the existing literature and interpretative approach, leaving potential trade-offs underexplored. Recycling may increase energy consumption; design for disassembly may conflict with affordability and housing accessibility; and bio-based materials may create land-use pressures or compete with food production. This study therefore reframes CE–SDG mapping not as a definitive result but as a diagnostic synthesis, revealing how CE–SDG relationships are implicitly constructed. It also exposes the absence of robust methodologies for systematically linking CE strategies to SDGs in the BE, a key priority for future research. Two very recent tools suggest one direction for such quantification. CIRCLE scores circularity across 10 R-principles on a point-based system (Mansour et al. 2025), while SUSTAIN scores broader sustainability performance against all 17 SDGs based on a similar approach (Mansour and Bedair 2025). Neither has yet been applied to the BE, but their approach could be adapted into a sector-specific CE–SDG mapping tool.

4 | Discussion

4.1 | Global North vs. Global South

This study finds a maturity imbalance between the Global North and the Global South. This imbalance is not surprising. CE knowledge in the BE is generated largely in, and for, economically advanced institutional settings, and contributions from the Global South tend to emerge sporadically rather than through sustained, cumulative research programmes. The contribution of this analysis lies in explaining how the imbalance plays out across regulatory capacity and research agendas, not in establishing that it exists. This structural disparity has important implications for the global applicability of CE strategies, since approaches developed in the Global North may not transfer to Global South settings.

The dominant Global North agenda, centred on digital technologies, circular business models, life-cycle analysis, and circularity assessment, presupposes institutional, methodological, financial, cultural, and infrastructural conditions that most Global South contexts may lack. In the Global North, CE adoption is increasingly mandated through frameworks such as the EU Green Deal and the Circular Economy Action Plan, whereas many developing regions still face incomplete regulation and weak enforcement (Stoiljković et al. 2023; Hasibuan et al. 2025). Where Global North cities integrate circular criteria into municipal tenders and voluntary green certifications (Chartier and Pot 2024; Wong et al. 2024), evidence from emerging economies suggests that directive state intervention may be more effective in shifting entrenched linear patterns (Bao 2023). Similarly, product–service systems require stable supply chains and regulatory oversight (van Stijn et al. 2022; Zhuang et al. 2023), conditions that may not hold where recycling markets are economically unviable and waste is often disposed of without formal treatment (Mhatre et al. 2024).

This divergence in regulatory capacity is mirrored in the strategic focus of CE research. Global North studies increasingly target 'slowing' resource loops, extending the life of an already developed and documented building stock through adaptive reuse and embodied-carbon quantification toward net-zero targets (Gravagnuolo et al. 2019; Sharmina et al. 2023). Global South studies, by contrast, more often prioritise closing loops via the 3Rs, reflecting the more urgent problem of managing waste from rapid urbanisation and a less formally documented building stock (Bao 2023; Ho et al. 2024). The two are thus responding to structurally different conditions, a mature, slow-growing stock in one case and rapid urban growth with weaker data and regulatory infrastructure in the other, and each strategy is arguably well matched to its context.

Global South studies frequently emphasise contextually grounded practices, including vernacular architecture, locally sourced materials, and low-cost material substitution (Dabaieh et al. 2022; Matsimbe et al. 2023; Ho et al. 2024). These demonstrate adaptive capacity but are constrained by persistent financial, institutional, and socio-cultural barriers. The absence of formalised secondary material markets often forces a return to virgin materials, while negative perceptions of reused or recycled materials continue to hinder societal acceptance (Mhatre et al. 2024).

Overall, these patterns indicate a critical lack of context-sensitive CE strategies and frameworks across system levels in emerging economies. In particular, the socio-economic dimensions of circularity remain underexplored, including the informal recycling and reuse sector, community liveability, rapid urbanisation, differing regulatory environments, and financial and cultural constraints. Consistent with science mapping analysis (Section 3.1.1), this geographical bias is not incidental but structurally embedded, reflecting the uneven distribution of research capacity, funding, and publication infrastructure. Addressing it requires moving from universalised one-size-fits-all models to locally grounded approaches attuned to specific geological, climatic, economic, and cultural conditions. More fundamentally, mitigating the imbalance will depend on more equitable international collaboration and knowledge exchange that empower Global South actors to adapt and co-produce CE solutions for their own contexts.

4.2 | Synthesis and Future Directions

Although multiple perspectives and interpretations exist, CE in the BE is best understood in this study as a multi-level

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socio-technical system. It operates across interconnected levels, optimising material efficiency at the product level, enabling adaptability and longevity at the building level, and supporting systemic resource circulation and urban metabolism at the macro level. This framing reflects both the intrinsic nested structure of the BE and the interdisciplinary nature of the research, and it maps onto two established lenses. The multi-level perspective on socio-technical transitions (Geels and Schot 2007; Geels 2011) casts micro-level material and component innovations as niches, meso-level building practices as the regime, and macro-level city pressures as the landscape. Systems thinking supplies the second lens, treating the levels as a coupled system in which reinforcing and balancing feedback determine the net direction of change (Sterman 2002), and in which leverage points matter more than any single strategy (Meadows 2008).

The reinforcing feedback takes two forms. The first is a bottom-up innovation loop (R1). Material and product innovation at the micro level drives industry adoption in building practice at the meso level, where it becomes practice evidence and data (Çetin et al. 2022; van den Berg et al. 2024; Evertsen and Knotten 2024). This aggregated innovation and evidence reaches the macro level, attracting policy support and resources for stock and flow analysis, urban mining, and governance (Schiller et al. 2017; Chartier and Pot 2024; Evertsen and Knotten 2024; Böcher et al. 2025), which feeds back to stimulate further innovation, closing the loop. The second is a top-down policy loop (R2). Macro-level policies and instruments set the methodologies and governance shaping standards and implementation at the meso level (Ghaffar et al. 2020; Chartier and Pot 2024; Sharma et al. 2024). These cascade priorities downward as lifecycle specifications and demand in standards and industry implementation, reshaping firm behaviour and material choices at the micro level (Ollár et al. 2020; van den Berg et al. 2024; Evertsen and Knotten 2024). The resulting improvement in CE performance provides the evidence for stronger policies, closing the loop. Buildings act as the pivot in both loops, so the micro and macro levels connect through building practice. These virtuous cycles are not self-sustaining. They are held in check by four cross-cutting balancing loops, corresponding to the economic, institutional, technical, and socio-cultural constraints that structure the gaps at every level and cross-level in the review. Each constraint operates not as a single barrier but as a self-reinforcing lock-in that recurs across levels and counteracts the reinforcing loops.

This review also identifies seven cross-level enabling mechanisms, which are not a parallel, disconnected list of themes. Rather, they are connective tissue through which the loops above operate, each carrying a distinct function. Life-cycle analysis and circularity assessment act as the evaluative and benchmarking mechanisms, translating and comparing performance across scales. Circular design and construction strategies operationalise these into physical practice, chiefly at the micro–meso interface. Circular business models function as the incentive-realigning mechanism, restructuring ownership and responsibility across scales. Digital technologies carry the informational flow between levels, and stakeholder collaboration is the coordinating mechanism aligning actors and governance across the value chain. Integration with the SDGs acts as the normative frame that orients actions at each level and across levels. None of these mechanisms is unqualified, however. The specific limitations of each are discussed in the corresponding Findings subsection.

Drawing these together, the study proposes a conceptual framework operationalising cross-level linkages to support CE implementation in the BE (see Figure 8). Read through these lenses, the review's evidence names concrete regime lock-ins rather than isolated barriers. This differentiates the framework from prior micro–meso–macro accounts, which position strategies within levels as a typology (Pomponi and Moncaster 2017), classify the field by scale, stage, and subject (Çimen 2021), or concentrate at the city scale (Brglez et al. 2024). It instead treats the levels as coupled by directional feedback and shows where change is reinforced or constrained. Applied in practice, the framework offers a stepwise diagnostic logic rather than a single prescriptive pathway. A practitioner or policymaker can enter at their own level, locate where a level or cross-level flow is weak, and identify which mechanism and which specific limitation within it sustains the balancing loop responsible. Relieving that limitation is the leverage point that flips the coupling from constraint back toward reinforcement.

5 | Conclusion

This review examined CE research through a unifying analytical perspective across the micro, meso, and macro levels of the BE and their integration with the SDGs. The main contribution is not a further inventory of CE strategies but a conceptual framework that shows how these levels depend on one another and where that dependency currently breaks down. The framework draws directly on the obstacles this review documents, among them fragmented supply chains, the absence of standardised assessment methods and material databases, and limited institutional, economic and socio-cultural perspectives. These are not treated as an unordered list of barriers but as named lock-ins within a coupled system. A practitioner or policymaker can enter the framework at their own level. From there they can locate gaps at each level and cross-level as well as identify the mechanism and limitation responsible for them.

Three patterns in the evidence support this reading of the field. Research leadership sits overwhelmingly in the Global North. Its regulatory and institutional assumptions do not travel to Global South contexts, which face rapid urbanisation rather than a mature and already-documented stock. Case-study evidence for either remains thin, and it is drawn overwhelmingly from a handful of high-income settings. CE-SDG linkages are asserted far more often than they are demonstrated, a gap that quantitative scoring tools have yet to close for the BE. The seven enabling mechanisms this review identifies function as connective tissue between levels, not as a parallel set of themes. Each does a distinct job, and each falls short of that job in a specific and documented way.

These findings carry policy and practice implications. They scale with the framework, so each level calls for a different lever. At the micro level, standardised testing, certification, and warranty protocols would resolve the quality and ownership uncertainties that deter reuse of reclaimed components. Emerging materials and

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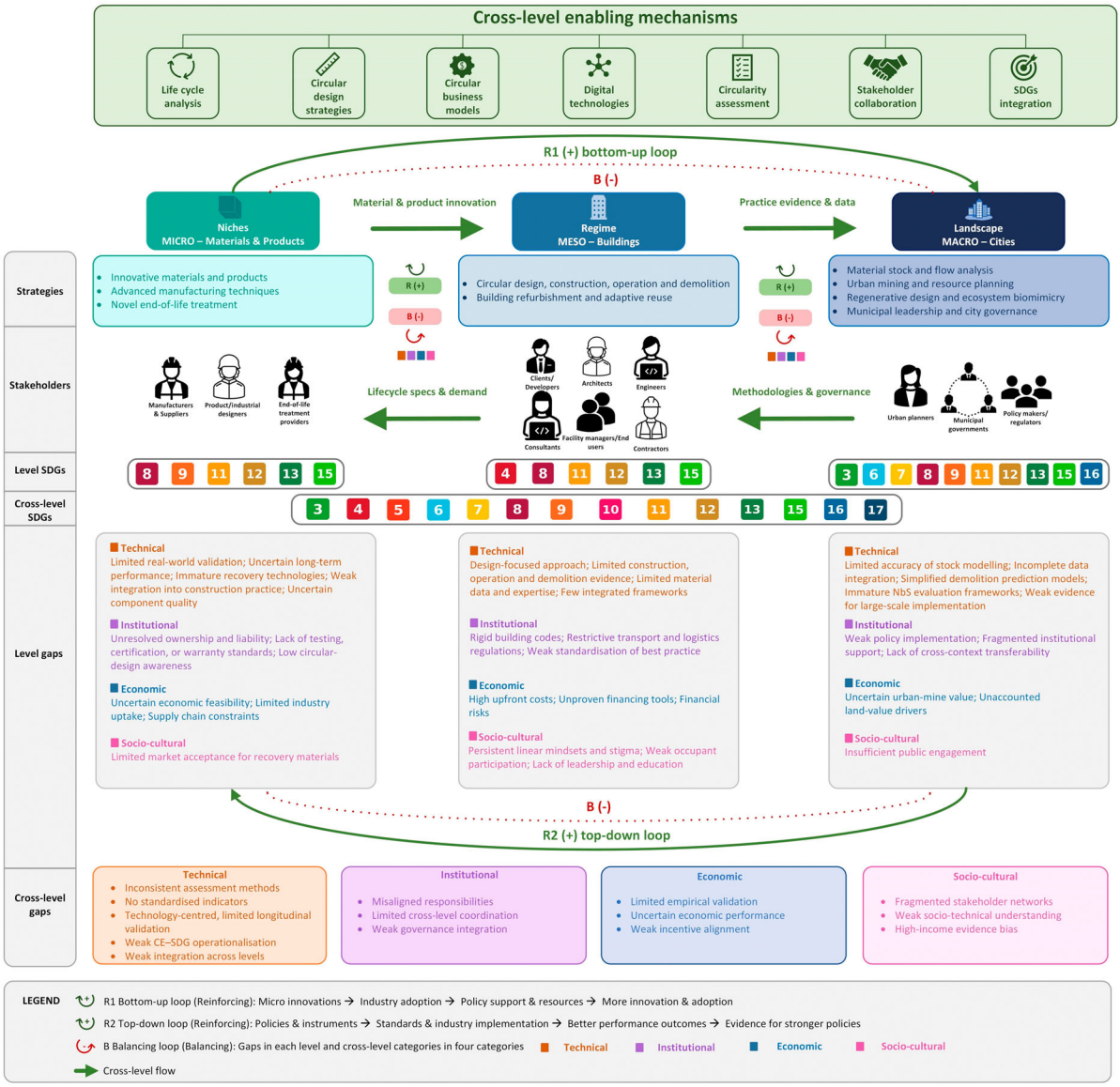


FIGURE 8 | The conceptual framework operationalising cross-level linkages to support CE implementation.

techniques also require validated pathways from lab-scale performance to site-level feasibility. Stronger substitution-rate evidence, shared material databases, and recovery technologies are needed. At the meso level, procurement must engage suppliers and contractors before design is finalised. Circularity indicators should be integrated in green building rating systems, certification schemes, and building codes. Financing and regulatory tools such as green finance, reuse thresholds, and whole-of-life carbon assessment call for empirical testing rather than assumed effectiveness. Refurbishment guidance can shift from isolated measures to integrated, occupant-centred frameworks. Leadership and education can address cultural resistance. At the macro level, material-stock and demolition models should incorporate the land-value and regeneration-policy data that drive material release. Regenerative strategies such as biomimicry and nature-based solutions await standardised monitoring frameworks for scaling with confidence.

Several levers also cut across all levels. Assessment methods and indicators require standardisation and links to governance tools. Digital technologies warrant longitudinal, socio-technical validation, not design-stage simulation alone. Business models should be empirically tested across scales. CE–SDG links demand operational, target-level tools rather than broad alignment. None of this depends on new technology. It depends on institutions, standards bodies, and planning authorities willing to move first, and on more equitable international collaboration.

However, this review inevitably has several limitations inevitably. Its evidence base rests on a single database and on English-language, peer-reviewed journal articles. This choice was made for consistency, but it underrepresents grey literature, non-English scholarship, and the Global South research most likely to fill the gap this review identifies. In addition, its scope excludes infrastructure beyond buildings. The proposed framework remains conceptual, as it was developed through the synthesis of secondary evidence rather than primary empirical investigation. Empirical validation was beyond the methodological scope of this review and therefore represents an important direction for future research. Future studies could evaluate the

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framework through expert consultation, apply it in case studies to examine the proposed feedback loops, and use system-dynamics modelling to investigate their relative strength and timing.

Author Contributions

Thao T. P. Bui: conceptualization, methodology, software, data curation, investigation, validation, formal analysis, visualization, project administration, writing – original draft, writing – review and editing. **Dat Tien Doan:** conceptualization, writing – review and editing, validation, methodology, investigation, formal analysis. **Francesco Pomponi:** writing – review and editing, validation. **Vivian W. Y. Tam:** validation, writing – review and editing. **Suzanne Wilkinson:** conceptualization, validation. **Ali GhaffarianHoseini:** conceptualization, validation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data will be made available on request.

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Appendix A: A Summary of Prior SLRs in Circular Economy in the Built Environment

Authors	Keywords	Database	Timeframe	Number of reviewed papers	Analysis techniques	Focused areas and limitations
Rao et al. (2025)	Circular economy, circular buildings, built environment, building information modelling	Science Direct, Scopus, Taylor & Francis, Emerald	2012–2023	125	– Thematic analysis	– Organised the literature thematically as motivators, challenges, and strategies for CE adoption, grouped into areas such as legal and regulatory framework, knowledge, education and training, infrastructure, technology and innovation, awareness promotion and support, collaboration and information sharing, standardisation, circular business model, positive finance and economics – Barriers and enablers are catalogued by category rather than examined for how they interact across system levels
Keles et al. (2025)	Circular economy, circular city, built environment, building, construction, digitalization, digital technology, Industry 4.0	Scopus	2015–2023	71	– Content analysis – Thematic analysis	– Confined to 10 digital technologies and their lifecycle applications and integrations, addressing a single enabling area rather than CE in the built environment as a whole.
Peng and Cao (2025)	Circular economy, circularity, construction industry, building, infrastructure, stakeholder, measurement, assessment, evaluation, indicator, indices, index, metric	Scopus	2013–2023	305	– Descriptive analysis – Content analysis	– Confined to circularity measurement from a stakeholder perspective (seven stakeholder groups and their needs and dilemmas, and alignment of measurement methods with stakeholder requirements), addressing a single enabling area rather than the broader field.
Ossio et al. (2023)	Circular economy, circularity, circular, construction	Scopus	2013–2022	316	– Descriptive analysis – Conceptual-affinity clustering	– Grouped the literature by conceptual affinity into five clusters (R strategies, CDW management, building design approaches, business models, and life cycle assessment) to define the circular-construction concept. – The clusters organised CE concepts thematically rather than showing how they connect across system levels.
Yu et al. (2022)	Circular Economy, circularity, closed-loop, construction, demolition waste management, building information modelling, big data, geographic information systems, internet of things, radio-frequency identification, blockchain, modelling, simulation, decision, support, tool making, information, platform system, construction, demolition, building	Web of Science	2010–2021	62	– Descriptive analysis – Content analysis	– Confined to ICT-based decision-support tools, addressing a single enabling area rather than the wider field. – Proposed a Circularity Information Platform.

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Authors	Keywords	Database	Timeframe	Number of reviewed papers	Analysis techniques	Focused areas and limitations
Antwi-Afari et al. (2021)	Circular economy, construction industry, industrial ecology, industrial symbiosis, cradle to cradle, material circularity, built environment, and construction sector	Scopus	Until 2020	486	– Scientometric analysis – Content analysis – SWOT analysis	– Built a research framework of eight themes along the circular value chain (circular design, manufacture and supply, CE adoption strategies, end-of-life, CE outcomes, information exchange, construction process, and waste management). – The framework mapped strategies by value-chain stage rather than system levels.
Çimen (2021)	Construction, built, build, circular economy	Scopus, Science Direct, and Web of Science	2008–2020	238	– Descriptive analysis – Review framework – Literature synthesis	– Applied a review framework that organises CE by subject and scale (development of CE, enablers and barriers, materials, waste, buildings and infrastructure, and areas, cities and regions). – Classified CE research by topic and scale rather than examining the interactions between these scales. – The author noted that the classification of the CE subjects relied substantially on their own interpretation.
Wijewickrama et al. (2021)	Circular econom*, reverse logistics, reverse supply chain, construction industry, data, information, knowledge, flow, shar*, transfer, exchange	Google Scholar, Web of Science, Scopus and ScienceDirect	2002–2020	125	– Descriptive analysis – Content analysis	– Narrow in scope, addressing only information brokerage and the reverse-logistics supply chain rather than CE in the built environment more broadly. – Proposed a conceptual framework for information exchange.
Munaro et al. (2020)	Built environment*, build*, construct*, circular* econom*, building design	Science Direct, Web of Science and Scopus	2016–2019	318	– Descriptive analysis – Thematic analysis	– Organised the literature through a thematic analysis built around five thematic axes (reusable and recycled materials, circular transition, tools and assessment, product and building design, and material stock and flow), from which gaps were identified. – These axes were treated as separate research themes, so the review does not examine how they interact across the material, building, and urban scales.

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Authors	Keywords	Database	Timeframe	Number of reviewed papers	Analysis techniques	Focused areas and limitations
Joensuu et al. (2020)	Circular economy, cradle to cradle, building, urban, city, district, neighbourhood, construction, infrastructure	Web of Science	2007–2018	282	– Thematic analysis	– Classified the literature into three thematic approaches to urban circularity (management for sustainable cities, urban services and consumer practices, and cleaner production and construction). – The thematic categories were organised mainly at the city scale and do not clearly demonstrate the relationship to building- and material-scale decisions.
Benachio et al. (2020)	Circular economy, buildings	Science Direct, Web of Science and Scopus	2015–2019	45	– Descriptive analysis – Content analysis	– Used content analysis to divide the literature into six research areas (development of CE, reuse of materials, material stocks, CE in the built environment, LCA, and material passports). – The areas were catalogued separately rather than examined as interacting parts of a system.
Osobajo et al. (2020)	Built environment, building, construction industry, circular economy, reuse building, reuse building materials, green construction, recycling	Scopus and Web of Science	1990–2019	50	– Descriptive analysis – Thematic analysis	– Used thematic analysis to group the literature into topic areas (resource use, waste management, supply-chain integration, building design, policy, energy efficiency, and cost and risk management). – The topics were treated as separate themes rather than interacting elements.

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Appendix B: Barriers and Enablers to Circular Buildings

Studies	Countries	Research method	Primary focus areas	Targeted stakeholder group
van den Berg et al. (2024)	The Netherlands	Qualitative method (interviews)	CE practices from the perspective of designers	Designers
Çetin, Gruis, and Straub (2021)	The Netherlands	Delphi method	Housing associations' CE practices in asset management	Social housing professionals
Ghaffar et al. (2020)	The UK	Mixed method (interviews and surveys)	Current practices of CDW management and circular construction (reuse, recycle and recovery of materials) concept awareness	Contracting, demolition and CDW professionals
Gillott et al. (2022)	The UK	Mixed method (interviews and surveys)	Insights on drivers, barriers and enablers of vertical extension	BE professionals
Stoiljković et al. (2023)	Serbia	Mixed method (case study and surveys)	The degree of application of circular principles in architectural design of housing renovation	Architects
Kaewunruen et al. (2024)	Europe	Qualitative method (interviews)	Stakeholders' influences, inter-relationships, and obstacles in the implementation of circular economy concepts on existing building stocks	BE professionals
Izquierdo et al. (2024)	The US (The Pacific Northwest)	Qualitative method (interviews)	CE practices, barriers and enablers	BE professionals
Cruz Rios et al. (2021)	The US	Qualitative method (interviews)	Barriers and enablers to circular building design	Architects
Guerra and Leite (2021)	The US	Mixed method (interviews and surveys)	Stakeholders' awareness of CE	Architecture, engineering and construction professionals
Abdulai et al. (2024)	Ghana	Quantitative method (surveys)	Barriers and drivers of CE adoption and their relationship	BE professionals
Agyekum and Amudjie (2024)	Ghana	Quantitative method (surveys)	Challenges in implementing the principles of CE	BE professionals
Victar et al. (2024)	International	Delphi method	The functions and competencies of Quantity Surveyors (QSs) at the design and building material sourcing stages	Quantity Surveyors
Warren-Myers et al. (2024)	International	Quantitative method (surveys)	Economic and market barriers to CE adoption	BE professionals

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Appendix C: A Summary of Studies on Material Stock and Flow Analysis

Studies	Study focus	Methodology	Geographic scope
Stephan and Athanassiadis (2018)	A framework to quantify future material replacement flows to maintain urban building stocks from 2018 to 2030	Dynamic bottom-up model	Australia
Soonsawad et al. (2024)	A methodology for high-resolution, city-wide mapping of buildings and their material and environmental footprints	LiDAR + building archetypes + statistics model	Australia
Shen et al. (2024)	A comprehensive framework for mapping urban residential building stock	Multisource geographic data	China
Lanau and Liu (2020)	An urban resource cadaster	GIS-based bottom-up + MICs + stock modelling	Denmark
Hoxha et al. (2024)	An approach for 30-year future forecast of expected new building types and related materials	Holt-Winters + LCA	Denmark
Sun et al. (2025)	A novel automated framework to identify roof and facade materials	Sensing technology + deep learning + Google Street View imagery	Denmark
Böcher et al. (2025)	A method for estimating past and future building (material) stocks and flows on a large scale and with a high spatial resolution	Four-step method: data preparation, hindcasting, stock/outflow calculation, future modelling	Europe
Kolkwitz et al. (2023)	An analytical framework for an integrated, spatiotemporal study of urban morphology and urban metabolism of buildings	MFA using building/plot data	Finland
Schiller et al. (2017)	A comprehensive analysis of material stocks, inflows and outflows connected to durable goods	Hybrid top-down + bottom-up MFA	Germany
Ortlepp et al. (2018)	A novel approach to calculate material stocks and flows for domestic buildings	Four-step bottom-up method	Germany
Marinova et al. (2020)	A material intensities database for diverse types of buildings in accordance with the IMAGE regions.	Scenario analysis linked to IMAGE model	Global
Foong et al. (2025)	A comprehensive method to estimate residential floor area and material stock at a fine-scale spatial resolution	Bottom-up GIS + building archetypes + material intensities	Global
Parezanović et al. (2025)	An innovative methodology for estimating building material stock and calculating Material Intensity Coefficients (MICs)	Remote sensing +3DGIS + BIM	Serbia
Arora et al. (2019)	A simpler methodology for estimating material stocks of public housing developments	Bottom-up general model	Singapore
Meijer et al. (2024)	A bottom-up material flow analysis to track concrete, steel, and embodied carbon in all Singapore buildings, from 2010 to 2020	Retrospective bottom-up MFA	Singapore
Tudela et al. (2020)	An approach to quantification of material stocks used to estimate the timber stock in residential buildings	Secondary data + housing database	The UK
Dai et al. (2025)	A geometry-informed MI (GIMI) method to characterise Material Intensity (MI) variability	Machine learning + morphology features	The UK

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Appendix D: A Summary of Digital Decision Support Systems

Authors	Life cycle stage(s)	CE principles addressed	Key contributions
Çetin, De Wolf, and Bocken (2021)	All stages	Regenerate, narrow, slow, close	Framework linking 10 digital technologies to CE
Abadi and Moore (2022)	All stages	Regenerate, narrow, slow, close	An MCDM model for life cycle circularity assessments using AHP
Davari et al. (2023)	All stages	Close	Integrated traceability framework
Charef (2024)	All stages	Regenerate, narrow, slow, close	Expert-informed digital CE framework
Akanbi et al. (2019)	Design	Regenerate, narrow, slow	Disassembly and deconstruction analytics system (D-DAS) for end-of-life performance assessment
Atik et al. (2024)	Design	Regenerate, narrow, slow	LCA-based BIM protocol for early-stage CE integration
Schützenhofer et al. (2024)	Design	Regenerate, narrow, slow	Generative design, VR, and assessment algorithms
Kung et al. (2025)	Design	Regenerate, narrow, slow	A practical decision-support model using a QFD-TOPSIS approach
Xing et al. (2020)	End-of-life	Slow	Cloud-BIM for component tracking and reuse
Gordon et al. (2023)	End-of-life	Slow	A semi-automated assistive process for planning building material deconstruction for reuse
Allam and Nik-Bakht (2025)	End-of-life	Slow, close	IFC and knowledge graphs for automated deconstruction planning

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Appendix E: A Detailed Map of CE Strategies and Their Links to the Specific SDGs

System level	CE strategies	Descriptions	SDGs	SDG targets	Justification
Micro	Circular material innovation and practices	• Use of renewable, recyclable, and low-carbon materials • Innovation in end-of-life treatment	8	8.4	Improves resource efficiency in consumption and production of materials
			9	9.4	Promotes sustainable industrialisation with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes
			11	11.6	Reduces environmental impact through sustainable material choices and waste reduction
			12	12.2, 12.4, 12.5	Supports efficient waste valorisation and sustainable use of natural resources
			13	13.2	Integrates climate considerations into material design and manufacturing
			15	15.1, 15.2	Promotes sustainable use and management of terrestrial and inland freshwater ecosystems
Meso	Circular building implementation	• Adoption of circular buildings • Renovation, retrofitting, and adaptive reuse to extend building life, reduce waste, and improve environmental performance	4	4.4, 4.7	Enables structured workforce training/education for CE practices
			8	8.4	Reduce material footprint and consumption in buildings
			11	11.3, 11.4, 11.6	Reduces environmental impact of buildings and promotes sustainable construction practices, resilient urban development and preserved cultural and natural heritage
			12	12.5	Minimises waste and supports resource-efficient building design
			13	13.2	Contributes to climate mitigation by reducing material consumption and emissions
			15	15.1	Minimises effects to terrestrial and inland freshwater ecosystems
Macro	Circular cities and resource flows	• Quantification and mapping of urban material stocks and flows to improve circularity, forecast outflows, and enable urban mining • Application of CE principles at the urban scale to reduce virgin resource use and waste generation	3	3.4, 3.9	Enhances health and well-being through liveable circular city design and practices
			6	6.3, 6.4	Promotes water reuse, greywater recovery, and stormwater management to ensure sustainable water cycles in cities
			7	7.2, 7.3	Supports renewable energy uptake, energy efficiency in buildings, and urban circular energy systems
			8	8.4, 8.5, 8.8	Improves resource efficiency through material flow analysis. Stimulates green jobs and safe working environments in recycling, deconstruction and circular construction.
			9	9.4	Advances sustainable infrastructure and innovation, digitalisation, and regenerative circularity frameworks
			11	11.3, 11.6, 11.b	Strengthens sustainable urban development by integrating CE into planning and minimising environmental impacts
			12	12.1, 12.2, 12.5, 12.7	Enables responsible consumption and production through reducing virgin extraction, CDW recovery, reuse, recycling, and circular material flows
			13	13.2	Reduces GHG emissions and supports low-carbon transition by lowering material demand and improving urban climate resilience
			15	15.1, 15.3	Protects ecosystems and reduces land degradation by lowering demand for raw material extraction and urban sprawl
			16	16.6, 16.7	Strengthens governance, transparency in tendering, and inclusive decision-making for circular city adoption

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System level	CE strategies	Descriptions	SDGs	SDG targets	Justification
Cross-level enabling mechanisms	Circular business models	• Product-as-a-service, building-as-a-service, urban and market-level transformations	4, 5	4.7; 5.5	Enables potential opportunities for funded training programmes and gender-inclusive workforce policies
			7	7.2, 7.3	Incorporates renewable energy and energy-optimisation measures into operations
			8	8.3, 8.5, 8.8	Stimulates economic growth, decent work, safe working conditions
			9	9.1, 9.2, 9.4	Drives innovation and modernisation
			11	11.6	Enhances waste management and reduces environmental burdens
			12	12.2, 12.5, 12.6, 12.7	Reduces raw material use, prevents waste generation, improves sustainable public procurement and sustainability reporting
			13	13.2	Integrates climate change measures into business development and operations
	Circular design	• Design and construction for modularity, adaptability, durability, regeneration and material efficiency	3	3.4, 3.9	Enhances health and well-being through circular design and construction practices
			6	6.3, 6.4	Incorporates water-efficient systems and promotes closed water loops
			7	7.2, 7.3	Integrates energy-efficient systems and renewable energy adoption
			8	8.2, 8.4	Fosters productivity and resource efficiency through innovation
			9	9.4, 9.5	Accelerates industrial transformation and modernisation of construction infrastructure
			11	11.6, 11.b	Contributes to resource-efficient, resilient, and liveable buildings
			12	12.2, 12.5	Ensures efficient resource use and closed material loops
			13	13.1, 13.2	Reduces carbon emissions and improves resilience in buildings
			15	15.1	Promotes sustainable use of terrestrial and inland freshwater ecosystems through regenerative design and construction practices
	Life cycle analysis	• Use of LCA	6, 7, 11, 12, 13	6.3, 6.4; 7.2, 7.3; 11.3, 11.6; 12.2, 12.4, 12.5; 13.2	Quantifies environmental impacts (energy use, emissions, water, land, waste)
		• Use of LCC	7, 8, 9, 12	7.2, 7.3; 8.2, 8.3, 8.4; 9.4, 9.5; 12.7	Evaluates cost impacts (capital, operation, maintenance, end-of-life)
		• Use of SLCA	3, 4, 5, 8, 10, 12, 16, 17	3.9; 4.7; 5.1, 5.5; 8.5, 8.7, 8.8; 10.2, 10.3; 12.4; 16.7; 17.17	Assesses social impacts of building supply chains (labour rights, health and safety, equity, stakeholder engagement)

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System level	CE strategies	Descriptions	SDGs	SDG targets	Justification
	Circularity assessment	• Frameworks, KPIs, and metrics for evaluating circularity	9	9.5	Enables innovation and optimisation of circular strategies
			11	11.3, 11.6	Supports reduction of environmental impacts and sustainable urban planning
			12	12.2, 12.5, 12.6	Encourages organisations to adopt sustainable practices and reporting
			13	13.2	Supports climate mitigation by extending material lifetimes and reducing emissions.
			16	16.6, 16.7	Enables effective, transparent, inclusive institutions
	Digital technologies	• Digital tools and platforms for circular decision-making and implementation	8	8.4	Supports improved resource efficiency in consumption and production
			9	9.4, 9.5	Enable sustainable industrialisation with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies and industrial processes
			11	11.3, 11.6, 11.b	Supports sustainable and resilient cities through integrated urban planning, smart asset management, predictive maintenance, adaptive reuse, and reduced environmental impacts
			12	12.2, 12.4, 12.5, 12.7	Enables sustainable resource management by improving material traceability, optimising material use, facilitating waste prevention and recovery, supporting circular procurement, and ensuring responsible management of materials
			13	13.2	Enables the integration of climate change measures into planning and implementation processes
			17	17.7	Facilitates knowledge sharing, technology transfer, interoperability, and multi-stakeholder collaboration, enabling coordinated implementation and scaling of circular economy practices
	Stakeholders' roles and collaboration	• Multi-stakeholder partnerships supporting circular decision-making and implementation	16	16.7	Supports transparent, participatory, and inclusive decision-making processes that involve diverse stakeholders
			17	17.16, 17.17	Enables capacity development and partnerships across governments, municipalities, practitioners, end-users to co-develop and implement circular solutions

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