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Circular economy in built environment – Literature review and theory development

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ABSTRACT

Circular economy (CE) has evolved gradually since its inception in the late 90s and has been implemented differently in various sectors across different countries. The implementation of CE in built-environment has vast benefits owing to the potential to reduce the ecological & carbon footprint of the construction industry. Numerous research articles have been published on the potential of CE in the built environment. This article aims to present a review of the evolution of literature and the development of theory in the given field. Bibliometric review on the topic is done using R software. For content analysis, the authors have analyzed the literature in the following subcategories – interpretation of CE in built-environment, CE business models, CE enablers, end-of-life management, circular building materials, material stocks, and environmental impact. The development of the theory of CE in the built-environment is analyzed by categorizing the conducted researches into various stages of theory – observation, categorization and association along with understanding if the research has been original, replicated or validated in its form. The article further points out the gaps in the literature and future scope using theory development models and suggests research implications for academicians and practitioners.

1. Introduction

The excessive utilization of the available pool of resources and the ever-inflating urban centers have brought repercussions in terms of pollution and ecological imbalance [1]. The construction industry (CI) is the largest consumer of materials, using 35–45% of the resources and consuming around 25–40% of the global energy [2]. Notably, the sector and its local and global supply chains are responsible for a significant amount of resource misallocation and energy exploitation, combined with greenhouse gases (GHGs) emissions [3,4]. The resource and energy-intensive nature of the CI necessitates that all the stakeholders to take into account the need to restore the environment and make an immediate shift towards the adoption of sustainable practices.

Sustainability is a broad term encompassing triple bottom line aspects of – environmental conservation, social equality, and economic security. Owing to the humongous nature of the CI, a gradual approach is required to achieve sustainability in the built environment sector. According to Ref. [5]; the adoption of circular economy (CE hereafter) is a prerequisite to sustainability. The concept of CE has its foundations in the principles of regenerative design (Lyle, 1996), cradle-to-cradle school of thought [6], industrial ecology [7], and bio-mimicry [8]. The Ellen MacArthur Foundation defines CE as "an industrial economy that is restorative or regenerative by intention" [9]. The fundamental idea of CE revolves around replacing the end-of-life (EoL) concept with redesign, reduce, reuse, refurbish, repair, material recovery, and recycle in production and consumption processes at micro, meso, and macro levels [10].

Current literature highlights the adoption of CE in built-environment as a means to ensure intergenerational availability of resources along with minimization of wastage of energy and resources by closing (reuse, remanufacture & recycle), slowing (repair & maintenance), and narrowing (reduce & resource optimization) the loop of resources [5]. CE, with its foundation laid in the 3R principles, has been adopted as legislation for construction and demolition waste management (CDWM) in many countries [11,12]. Research papers published on CE in built-environment have been diversified and have spanned across the globe, exploring different structures and stages of construction, alternative building materials, circular business models, material stocks, and the environmental impact of CE implementation. However, none of the existing papers present a comprehensive analysis of the literature and the implications of the existing research on the implementation of CE in the built-environment. Further, there is a gap in under-

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standing how the research in this field has evolved and built-up over a period of time. Consequently, this research article aims to address the following research questions:

1. What is the trend of publication in CE in built-environment across the world, and how has the theory evolved?
2. What are the directions for future research and managerial and theoretical implications of the research?

The proposed work filled research gaps and accomplished the specified objectives by performing a bibliometric analysis on the existing literature, analyzing the research papers using systematic literature review, and presenting a subsequent model for theory development. The article is structured in such a way that section 2 illustrates the methodology adopted for bibliometric analysis, literature review, and theory development. The bibliometric analysis is described in section 3, followed by a literature review and theory development in sections 4 and 5. Section 6 discusses the different aspects of CE in built-environment and further suggests the theoretical and managerial implications of this research and future scope. Finally, in section 7, titled Conclusion, the final research outcome is described along with the limitations.

2. Methodology

This research article presents a bibliometric analysis, followed by a systematic literature review and, finally, a detailed analysis of the development of theory in the context of CE in the built-environment.

2.1. Bibliometric analysis

Bibliometric analysis is a method to analyze, estimate, and visualize the development of scientific fields. The authors have referred to Ref. [13,14] for the methodology of bibliometric analysis. Scopus database was used, and the authors obtained the literature till June 2020 using the following string of keywords:

- “circular economy” AND “construction”,
- “circular economy” AND “built-environment”.

The number of articles obtained were 676. These articles were further limited to document type of ‘article’ and ‘review’ papers. The source type of ‘Journals’ and ‘English’ language were selected. The final number of articles obtained was 368. A.bibtex file was imported from the Scopus database, and bibliometric analysis was performed using the Biblioshiny interface of the R studio software. The data was analyzed for information on the sources, authors, documents, keywords, and geographic origin. The procedure for selecting the literature for bibliometric analysis and the subsequent flow of analysis is depicted in Fig. 1.

2.2. Literature review

For the literature review, the same string of keywords was used as that for bibliometric analysis. Science, Scopus, and Web of Science databases were used to find the literature. Repetitive research papers were removed, and only those research papers were filtered, which aligned with the context of this article, i.e., the research papers which focused on the concept, implementation, or impact of the adoption of CE in the built-environment. Research papers were selected by initially reading the title, followed by a careful understanding of the abstract and, finally, a critical reading of the entire paper, to determine if the research paper fits in the scope of the review or not. Finally, a total of 80 research papers are selected for the literature review. Further, the selected papers were categorized into seven broad groups:

1. *Interpretation of CE in the built-environment:* In this group, the research papers which define the concept of CE in the context of the built-environment and its quantification in terms of indicators and proposed frameworks are reviewed.
2. *CE business models*: This category presents the review of strategies or models used by construction firms or organizations for the implementation of CE.
3. *CE enablers*: Various tools or actions which have been adopted to facilitate CE have been illustrated in this group.
4. *End-of-life management*: This group presents a critical analysis of the literature on the management of buildings/structures and their components at the end of their service life, based on the CE principles.
5. *Circular building materials*: The literature illustrating the use of secondary materials or describing reuse/recycle of construction materials have been reviewed in this group.
6. *Material stocks*: This group lists research that focusses on the determination of resource/material stock in a structure or at the regional level as well as urban mining potential.

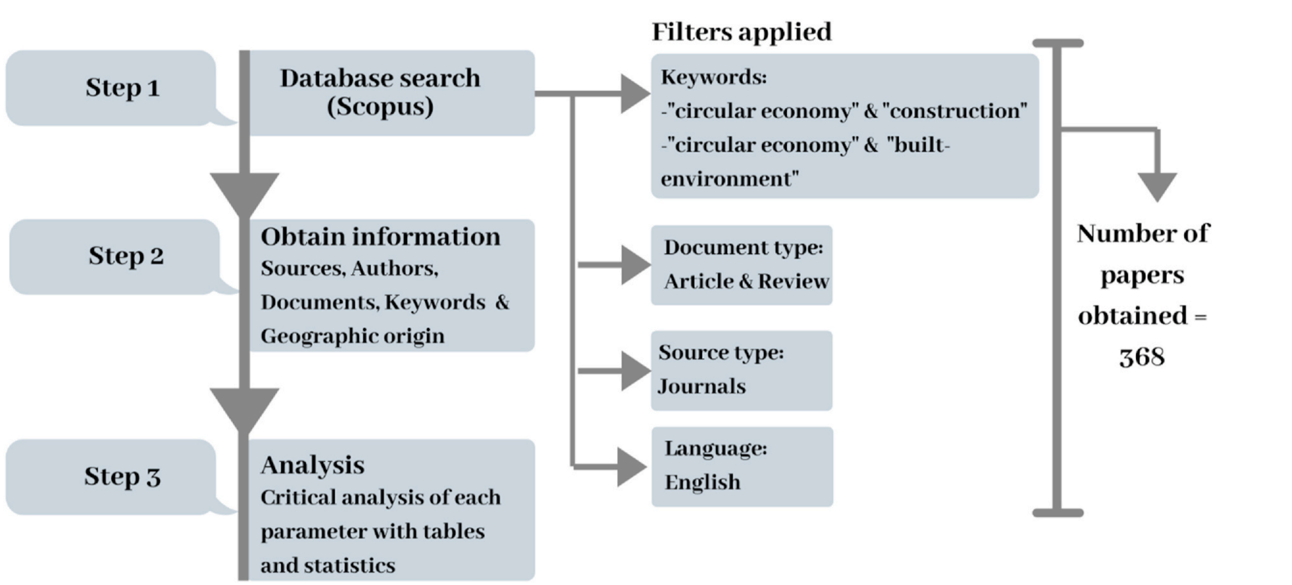

Fig. 1. Procedure for bibliometric analysis.

7. *Environmental impact*: The analysis of research on quantifying the impact of the adoption of CE principles on the environment and greenhouse gas emissions is presented in this group.

Each of the groups has focused on a different aspect of research, and thus facilitates ease in critical review as well as an understanding of the readers. Fig. 2 pictorially describes the methodology for the literature review.

2.3. Theory development

As it is acknowledged, and research aims to ensure addition to the body of knowledge, which is possible only by evaluating existing information. An understanding of available information on a topic facilitates the recognition of knowledge gaps and research direction. With this reference, the authors have used the concept of theory development for describing, explaining, and predicting the phenomenon or research on the subject of CE in a built-environment. Here, three stages of theory development – observation, categorization, and association – as defined by Ref. [15]; are used. The observation type of research aims to observe, describe, or measure a phenomenon, and this type of research is based on developing constructs or concepts. In the categorization type of research, frameworks and typologies are suggested based on the attributes of the phenomena. Finally, in the association stage, the research is based on proving the observations by using various statistical or analytical tools. The authors have extended the theory development process to the same set of research papers and classification that has been identified for the literature review. Further, the authors have categorized the papers into observation, categorization, or association type of research. To further understand the concept, the authors have also categorized the literature in each category into original, replication, or validation type of research [16]. The model for theory development is illustrated in Fig. 3. Every research paper is identified with reference to the theory development stage and grouped accordingly. Based on the theory development process in this field, the authors have determined the trend on research, as well as the future research scope.

3. Bibliometric analysis

Research on CE in the context of the built-environment has evolved since its inception in 2007. In this section, the authors present a bibliometric review of the trend of publications in this field. In Table 1, which illustrates the primary information on research papers published, it can be seen that the number of papers published from 2007 till April 2020 is

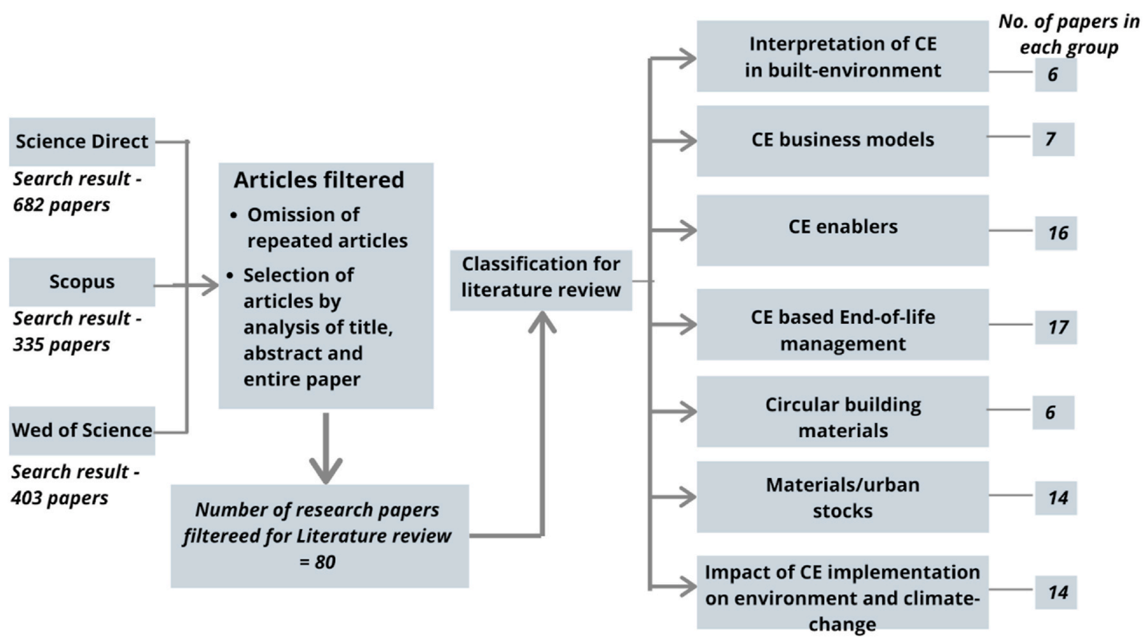

Fig. 2. Procedure for literature review.

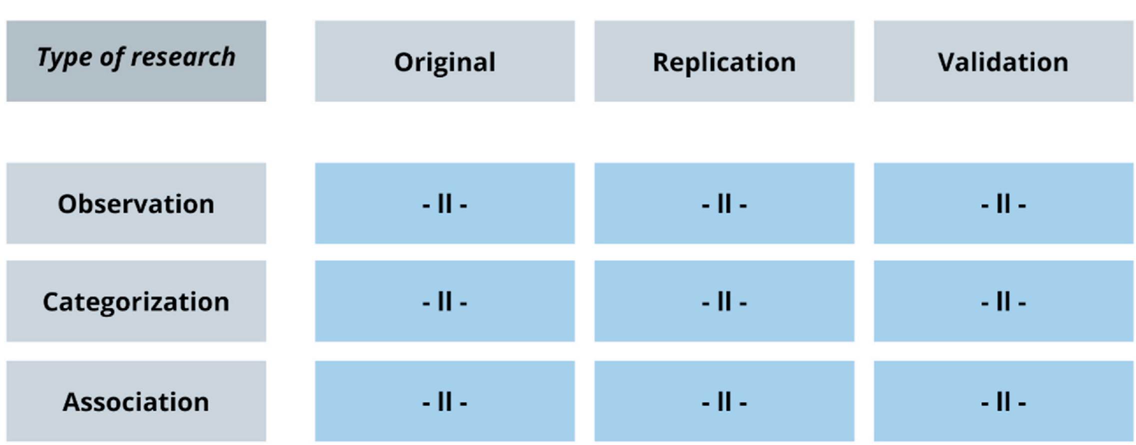

Fig. 3. Model for theory development.

Table 1
Main information.

Main information	Number
Total number of documents	368
No. of articles published	324
No. or Review papers published	44
Sources or no. of Journals of publications	134
Author's Keywords	1272
Time frame	2007–2020
Average citations per research paper	9.644
Authors	1262
Author Appearance	1447
Authors of single-authored articles	28
Authors of multi-authored articles	1234
Documents per author	0.292
Average no. of authors per Document	3.93
Average no. of co-Authors per Documents	3.93
Collaboration Index	3.63

368, with 324 articles and 44 review papers. These articles have been published in 134 different journals, with an average citation index being 9.644 per article. As many as 1262 authors have published these research papers wherein 28 articles are single-authored. The collaboration index among the authors from various countries and institutions was found to be 3.63.

The first research article on this topic was published in 2007. Fig. 4 shows the trend of articles published since 2007 till June 2020. It can be inferred from the figure that there has been an incremental rise in the publication on CE in built-environment since 2016. Also, 105 papers have been published by June 2020, which is almost as much as that published in 2019. This shows the growing popularity of the topic and its imposition on the industry.

3.1. Sources

The publications on CE in built-environment have spanned across 134 journals. Table 2 lists the most relevant Journals that have published the maximum number of articles. The table, apart from giving the number of publications till date, also gives the h-index, g-index, m-index, total citations (TC), and start-year of publications (PY_start) in this field.

From the figure, it can be inferred that the maximum articles have been published in the Journal of Cleaner Production (68), followed by Sustainability (Switzerland) (25), Resources, Conservation & Recycling (24), Waste Management (10), and Science of the Total Environment (9), respectively. The h-index, i.e., productivity and citation impact of publications, is maximum for the Journal of Cleaner Production (17), followed by Resources, Conservation and Recycling (13), Sustainability (Switzerland) (6), and Waste Management (5), respectively. Journal of Cleaner Production and Resources, Conservation, and Recycling has the highest g-index of 30 and 23, indicating the higher distribution of citations in these journals. In the case of the total citations, the Journal of Cleaner Production tops the list with 986 citations, followed by Resources Conservation and Recycling (532) and Journal of Industrial Ecology (139), respectively.

3.2. Authors

The total of 1262 authors have published on this topic. The authors (top 20) with the highest number of publications and their corresponding impact is illustrated in Table 3.

Haas C is the author with maximum impact with five publications, h-index = 2, g-index = 5, and total citations being 48. The research focus of this author has been on the adaptive reuse of buildings for facilitating CE. The second most popular author in this field is Jimnez JR, who has researched majorly on the reuse of construction materials. Sanchez B, the third most relevant author, has also researched on the adaptive reuse of buildings with Haas C. The author's impact table helps to understand and analyze the authors' impact in the field and also points to the fact that this impact is directly dependent on the number of publications of the authors.

3.3. Documents

This section discusses the most cited documents (20), which are listed in Table 4. The table also lists the year of publication of these articles as well as the local and global citations of the articles.

The most cited article by Pomponi and Moncaster, (2017) gives the framework for implementing CE in the built-environment at the micro, meso, and macro-level along with six critical factors of consideration [18]. gives the environmental and economic benefits of adopting CE in construction projects. The third most cited paper by Refs. [19] brings about the importance of stakeholder collaboration for enabling CE in the construction sector. The focus of the remaining research papers

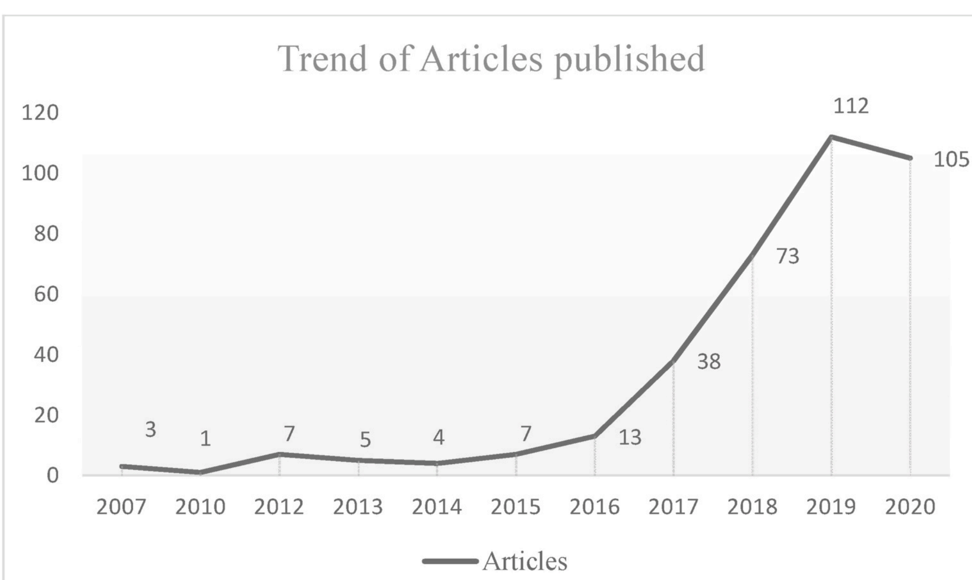

Fig. 4. Trend of articles published until June 2020.

Table 2
Quantitative and qualitative data on top 10 Sources with maximum publications.

Source	Number of publications	h_index	g_index	TC	PY_start
Journal of Cleaner Production	68	17	30	986	2015
Sustainability (Switzerland)	25	6	10	134	2015
Resources, Conservation and Recycling	24	13	23	532	2016
Waste Management	10	5	8	78	2017
Science of the Total Environment	9	2	3	12	2019
Materials	8	3	4	26	2017
Construction & Building Materials	6	3	4	21	2018
Procedia Environmental Science, Engineering and Management	6	1	1	1	2017
Waste Management & Research	6	1	4	17	2016
Journal of Industrial Ecology	5	5	5	139	2007

Table 3
Authors with maximum publications.

Authors	Articles	h_index	g_index	TC	PY_start
Haas C	5	3	5	48	2018
Jimnez JR	5	3	4	18	2018
Sanchez B	5	3	5	48	2018
Fernndez J M	4	2	3	15	2018
Li H	4	3	4	93	2017
Liu G	4	2	4	33	2012
Ortlepp R	4	4	4	79	2016
Schiller G	4	4	4	79	2016
Wang Y	4	3	4	43	2015
Zhao H	4	2	2	64	2017
Akinade O O	3	3	3	42	2018
Bilal M	3	2	3	38	2018
Bleischwitz R	3	3	3	130	2018
De Brito J	3	3	3	21	2018
Garca-Navarro J	3	2	2	38	2015
Geng Y	3	3	3	178	2017
Grecki J	3	2	3	25	2018
Gruhler K	3	3	3	48	2016
Guo S	3	2	3	66	2012
Hu Y	3	3	3	24	2015

spreads across circular building materials, the use of building information modeling (BIM) tools for circular building designs, and reuse/recycle of construction materials.

3.4. Geographic origin

Fig. 5 shows the country-wise publishing of the research papers. It can be inferred that China has the highest number of publications (123), followed by Spain (91), United Kingdom (86), Italy (67), Netherlands (56), and so on. The highest number of publications in China can be credited to the government policies well as the urgent need to loop resources in the country owing to population growth and business expansion. The impact of adopting the CE policy by the European Union (EU) in 2015 and its inclination towards sustainability resonates the high number of publications, as can be seen in Fig. 5, in the EU member states.

3.5. Keywords

The keywords are an indicator of the trend of research. As can be observed from Table 5, the most frequently used keyword is 'recycling'

Table 4
Most cited documents.

Document	Year	Local Citations	Global Citations
[17]; J Clean Prod	2017	27	117
[18]; J Clean Prod	2018	12	50
[19]; J Clean Prod	2018	12	42
[20]; Build Environ	2017	10	46
[11]; Resour Conserv Recycl	2018	10	72
[12]; Resour Conserv Recycl	2018	10	81
[21]; Build Res Inf	2016	9	31
[22]; Resour Conserv Recycl	2018	9	34
[23]; J Clean Prod	2018	8	27
[24]; J Mater Cycles Waste Manage	2017	7	24
[25]; Int J Prod Econ	2017	7	73
[26]; Resour Conserv Recycl	2018	6	18
[27]; Resour Conserv Recycl	2019	6	20
[28]; J Clean Prod	2017	5	19
[29]; J Clean Prod	2017	5	33
[30]; Sustainability	2018	5	23
[31]; Constr Manage Econ	2018	5	13
[32]; Waste Biomass Valoris	2016	4	15
[32]; Resour Conserv Recycl	2016	4	32
[33]; J Clean Prod	2018	4	18

with a frequency of 150, followed by the circular economy (139), sustainable development (114), waste management (96), and construction industry (82), respectively. The highest frequency of 'recycling' indicates the research inclination towards recycling of construction materials and the ways to facilitate it. Recycling is also the most commonly used circular strategy in construction industry. The next frequent keywords – 'circular economy' and 'sustainable development' – are simultaneously used in many cases, as CE is an enabler of sustainable development. The keywords' occurrences also indicate the use of popular tools (such as material flow analysis or life cycle assessment) and strategies used for circular construction practices.

4. Literature review

The legislation on CE in built-environment draws its roots to regulatory organizations of China, like the State Environmental Protection Administration and National Development and Reform Commission. These organizations have implemented policies and regulations for the application of CE practices in urban infrastructure owing to the resource consumption pattern in China [34]. Following the model, Germany, Japan, and Europe have drawn policies promoting CE [35]. The research on CE in the context of built-environment collates a broad spectrum of business models, end-of-life (EoL) management, reuse/recycle of construction materials, urban stocks, and the impact of CE adoption on the environment and GHGs emissions. Also, the adoption of CE in built-environment by slowing, closing, and narrowing the loop by reusing materials, designing for disassembly, material substitution, and resource optimization can reduce the GHGs emissions by 30%–50% [36]. The research papers which have been employed for the purpose of literature review along with their classification, are listed in Table 6 below.

4.1. Interpretation of CE built-environment

Pomponi and Moncaster, (2017) determined the drivers and barriers in economic, societal, governmental, environmental, behavioral, and technological dimensions for the adoption of CE by conceptualizing the built-environment at the micro (building components), meso (buildings as a unit), and macro levels (cities and regions). For instance, in the case of meso level constructions, such as bridges, highways, power distribution lines, and grids, a holistic approach is required which can encompass technical solutions, user behavior & ownership, bio-based construction, and circularity assessment [73]. Decisions for the degree of

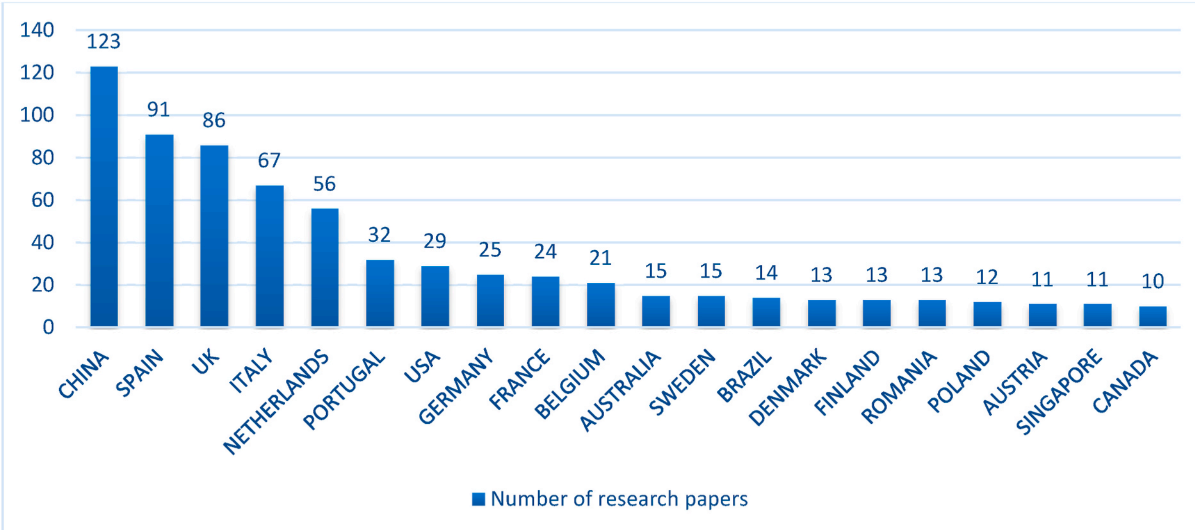

Fig. 5. Research publications with geographic origin.

Table 5
Keyword occurrence.

Words	Occurrences	Words	Occurrences
Recycling	150	economics	41
circular economy	139	sustainability	38
sustainable development	114	construction and demolition waste	34
waste management	96	construction	32
construction industry	82	material flow analysis	31
Environmental impact	67	climate change	28
Article	58	compressive strength	28
China	56	fly ash	27
Demolition	44	industrial economics	26
life cycle	43	life cycle assessment (lca)	25

adoption of CE in a project can be determined by the indicators for measurement. A scale for the measurement of CE, given by Ref. [30] has based efficient construction management on seven indicators – 3Rs (reduce, reuse and recycle), material efficiency, energy usage, water usage, emissions, waste, and CE principles. Another approach to implementing CE is by focusing on each of the stages of construction separately and adopting suitable CE strategies for each stage [81]. To add to this, government policies, economic instruments, prefabrication, design for disassembly, and waste prevention are CE strategies for the pre-construction stage. Efficient site waste-management plans – collection, segregation & distribution – have been proven beneficial in the construction and renovation stage. Selective deconstruction and demolition audits can aid in the maximum recovery of secondary materials. Also, the practice of reuse, recycling, and energy recovery at the production or material recovery enables resource optimization.

4.2. CE business models

The building of social institutions and circular business models precedes a practical implementation of CE in any sector [95]. Businesses tend to adopt CE depending on the potential of supply-chain collaborations, technical know-how, networking among various stakeholders, innovation in process designs, and sustainability policies of the firms [19]. These factors facilitate the efficient exchange of information on materials and components that can be shared, reused, or recycled. Construction firms that are drawn towards research and technological innovations for practicing a closed-loop economy have higher chances of succeeding in implementing CE [55]. The practice of interface management, i.e., establishing hard/soft contact between various stakeholders in a construction project, can facilitate in sharing of data on secondary materials and other resources, thus enabling a resource-efficient built-environment [52,96]. According to Ref. [68]; public-private partnerships can also prove an efficient approach for bridging CE with CDWM. Also, government policies and legal frameworks play an important role in facilitating circular business models [63]. Thus, we can infer that for the creation of circular business models, a holistic approach encompassing businesses, society, and government is essential.

4.3. CE enablers

In this section, the authors bring about the tools, strategies, or actions which promote or facilitate CE, thus grouping them together as CE enablers. CE in the construction sector can be enabled at various stages of construction, from designing, planning, construction, operation, and maintenance to EoL and demolition. The use of sequential disassembly for deconstruction facilitates adaptive reuse and thus promotes the idea of sustainable buildings [23]. BIM platform can be used for planning disassembly and deconstruction of a structure and is one of the most commonly used techniques at the design stage of buildings [62]. The BIM can also be used to integrate supply-chains with construction waste management, facilitating the sharing of materials and components for reuse/recycle [97]. To add to this, in the construction stage, prefabrication and modularization are the most efficient approaches that facilitate CE as prefabricated or modular building components can be easily disassembled and reused [45]. Relocatable modular buildings also present an innovative solution for growing cities and municipalities with growing and fluctuating space demands [57]. Material passports are known to efficiently determine material stocks [60]. A material components bank of building materials can aid in the reuse and recycling of construction wastes paving the way for sustainable construction [70]. Further, a model for the ‘Circular building components’ generator, developed by Stijn and Gruis, (2019) combined technical inputs, building designs, and business models, and aids in predicting the volume of resources that can be recovered, reused, or recycled from a structure. The estimation of material stocks enables the government and policymakers to determine the reuse and/or recycling rates of resource recovery and implement suitable economic instruments like taxation or subsidies [67].

CE strategies for adaptive reuse of buildings have proved to be useful for materials (recycling and energy recovery), extending the lifes-

Table 6
List of research papers classified as per review dimensions considered for this article.

Sr. No.	Research	CE framework in built- environment	CE business models in built-environment	CE enablers (tools and strategies)	CE based End-of-line management	Circular building materials	Material and urban stocks	Environmental impact & climate change mitigation
1	[37]						✓	
2	[38]					✓		
3	[32]							✓
4	[32]	✓						
5	[21]						✓	
6	[39]					✓		
7	[40]						✓	
8	[25]							✓
9	[41]						✓	
10	[17]	✓						
11	[20]							✓
12	[29]					✓		
13	[42]	✓						
14	[43]						✓	
15	[24]				✓			
16	[44]				✓			
17	[28]				✓			
18	[45]			✓				
19	[12]				✓			
20	[22]				✓			
21	[46]						✓	
22	[47]					✓		
23	[19]		✓					
24	[18]				✓			
25	[23]			✓				
26	[31]		✓					
27	[26]				✓			
28	[30]	✓						
29	[48]				✓			
30	[11]				✓			
31	[49]				✓			
32	[50]				✓			✓
33	[51]						✓	
34	[33]							✓
35	[52]		✓					
36	[53]			✓				
37	[54]			✓				
38	[55]		✓					
39	[27]					✓		✓
40	[56]							✓
41	[57]			✓				
42	[58]							✓
43	[59]						✓	
44	[60]			✓				
45	[61]							✓
46	[62]			✓				
47	[63]		✓					
48	[64]							✓
49	[65]							✓
50	[54]			✓				
51	[66]				✓			
52	[67]			✓				
53	[68]		✓					
54	[69]			✓				
55	[70]			✓				
56	[71]							✓
57	[72]							
58	[73]	✓						
59	[74]			✓				
60	[75]			✓				
61	[76]						✓	
62	[77]						✓	
63	[78]				✓			
64	[79]						✓	
65	[80]						✓	
66	[81]	✓						
67	[82]						✓	
68	[83]			✓				

(*continued on next page*)

Table 6 (*continued*)

Sr. No.	Research	CE framework in built- environment	CE business models in built-environment	CE enablers (tools and strategies)	CE based End-of-line management	Circular building materials	Material and urban stocks	Environmental impact & climate change mitigation
69	[84]			✓				
70	[85]				✓			
71	[86]					✓		
72	[87]						✓	
73	[88]							✓
74	[89]		✓					
75	[90]				✓			
76	[91]			✓				✓
77	[36]							✓
78	[92]				✓			
79	[93]				✓			
80	[94]							✓

pan of buildings (repair, refurbish and repurpose) and smarter use and manufacture of buildings by sharing and multifunctional uses [74]. Also, the construction of urban mining bases – for collection, segregation, and recycling of wastes – promotes CE [98]. As per Campbell-johnston et al., [99]; stakeholder behavior, capacity to influence value chains, and multi-level policy integration are required to transition towards CE. Finally, it is established that the employment of a CE manager can aid in better implementation and operation, owing to the expertise and broader understanding of circular constructions [75].

4.4. End-of-life management

The management of structures at the EoL is essential to ensure the reuse of sufficient quality resources, segregation of resources for recycling, and minimize deposition of waste to landfills. The practices of EoL management of constructions are different across the globe depending on the policies of different nations, treatment methods, available technology, research, and development as well as sustainability perspective [100]. This also includes variation in CDWM in developed and developing countries, depending on the availability of technologies and existing infrastructure facilitating resource reuse and recycle [85]. Numerous researches have focused on the inclusion of the CE framework for CDWM to facilitate environmental and economic sustainability. However, this is dependent on building materials and structure, transportation distances, and economic & political contexts [18]. For instance, China has based its CDWM policies on the principles of 3R – reduce, reuse, and recycle [12]. The Chinese city of Shenzhen successfully implemented CDWM practices owing to government interventions, availability of market for secondary materials, innovation in recycling technologies and institutional framework for promotion of CE [92,101]. In Europe, the CDWM plans are implemented at the national, regional, and local level with elaborate plans for all the life-cycle stages of construction [11]. On a similar note, research by Ref. [24] has shown that Malaysia can adopt CE in CDWM by categorizing and designing waste management plans at the micro, meso, and macro-level.

At a micro-level, i.e., in the case of a unit structure, a BIM-based whole-life performance estimator can aid in the determination of the building materials or components that are recoverable from a building and also the proportion of reusable/recyclable resources [22]. Favorable market conditions and sufficient support from local communities contribute significantly towards deconstruction projects, thus assisting in resource conservation and environmental protection [50]. The investment decisions for the life cycle of a building can be determined depending on the resource recovery potential based on construction management and the EoL scenario [44]. According to Refs. [49]; the EoL management practices for construction projects across the globe require up-gradation of existing regulations, laws, and policies to enhance sustainability and meet the goals of cleaner production, CE and sustainable construction. A case study from Japan showed that different stakeholders have different motivations – ranging from government policies, economic incentives, material value to cultural beliefs – for deciding on the life-span of a structure [66]. Another research by Ref. [93]; showed that the major drivers towards EoL recycling are personal motivations (which include perceived costs and benefits, attitude and perceived behavioral control), environmental consciousness and regulatory pressures. Critical barriers for CE based EoL management include behavioral, technical, and legal impediments, along with the availability of logistics and infrastructure, cost of secondary materials, and time required for disassembly or selective deconstruction [26,78].

4.5. Circular building materials

The circularity of a project depends on the sourcing of building materials – i.e. if the materials are extracted from virgin sources or recycled/reused – and on what happens to these building materials at the EoL of the structure. The built-environment acts as a material stock that has the potential to contribute resources for new projects after its useful life. The nature and amount of waste recovered from a structure depends on the economic demand for secondary wastes, ease of disassembly, and durability [89]. The recycled construction aggregates have been used in the construction of roads, tunnels, and buildings [102] as well as for backfilling [103]. [38] found that sewage sludge ash can also be used in the construction industry by adding cement, mortar, or manufacture of ceramics and bricks. Another example of CE implementation is the case of a port in Sweden, which was created using contaminated dredged materials [47]. Circular building materials also reduce GHGs emissions and thus have significant carbon savings potential [27].

4.6. Material stocks

Urban infrastructure acts as material stocks for resources to be reused/recycled at the end of the useful life of structures to promote the circulation of resources in the economy and enable intergenerational availability of resources. Material stock maps the structures for resource outflows, construction assembly, and building typologies. It serves as a guide for better management of building stocks in terms of waste processing, urban mining, and CE [20]. Numerous studies have been conducted for the determination of material stocks in the built-environment [43]. mapped the anthropogenic stocks in Germany, and this mapping can aid in developing long term monitoring of urban stocks and also devise policies for closed-loop material flows [79]. determined the global material stocks for six materials – steel, wood, concrete, copper, aluminum, and glass – in residential buildings for the period between 1970 and 2050. Material stock analysis at individual material or component level needs to be combined with building stock at the city or regional level as this can help to determine the urban mining potential and facilitate recycling [59]. Existing material stock can be reused in the construction of affordable houses for underprivileged communities, and this can be achieved by selective deconstruction or soft stripping of structures at the end-of-life [82].

The material stocks database, along with circularity indicators, aid in understanding the degree of CE implementation [77]. In many cases, material composite indicators are used for the calculation of material stocks [46]. Researchers have worked on developing resource cadaster for building material stocks in various regions [87]. developed an urban resource cadaster for the city of Odense, Denmark consisting of 46 different building materials as of 2018. The study of material stocks and the resource inflow-outflow acts as an essential database for the determination of the available pool of resources and thus predict further potential actions for the circular supply of resources.

4.7. Environmental impact

The gradual transition to CE in the built-environment by waste reduction, resource efficiency, and material recovery facilitates the reduction of negative anthropogenic impacts on the environment [58]. Studies have pointed out that a considerable reduction in carbon emissions is achieved by adopting CE strategies in the built-environment [36]. A significant step towards decarbonized buildings is the reuse/recycle materials, which is possible by implementing suitable business models, developing technological know-how on reuse and/or recycling of waste resources, and incentivizing the usage of secondary materials [27]. The majority of researches employ life cycle assessment as a tool to determine the environmental impact of buildings and their components [61]. Buildings designed for disassembly are proven to have reduced environmental impacts – variation depending on the structural components (columns, beams, slabs, etc.) and building materials [65]. Research by Ref. [56] showed that a demountable composite concrete floor system is more environmentally friendly as compared to other conventional structural systems and thus aided in reduced resource consumption and carbon emissions. Also, the use of prefabricated units reduces carbon emissions in the construction of new buildings [91]. Carbon footprint analysis can be used to determine the carbon emissions of materials, and this can be achieved by circularity indicators and carbon footprint indicators [104]. The carbon footprint of built-environment can be reduced by the adoption of low emission approaches, such as the implementation of reuse and recycling of wastes, use of alternative resources – natural materials, local materials, and renewable energy, the innovation of production process, and performance optimization of structural design [72]. Adaptive reuse of building structures decreases the environmental impacts and reduces the economic costs of the buildings [71]. It is also recommended that the reuse and recycle of building materials and components be integrated into the initial design of a building project to align with the concept of CE [88].

5. Theory development

The authors have elaborated the theory development in the area by categorizing the past researches into observation, categorization, and association types of research. The authors have also determined if the researches were original in their form, replicated to a different region, model or unit, or validated. The results obtained were listed in a 3 (original, replication, validation) x 3 (observation, categorization, association) matrix. The purpose of developing this model is to help the readers understand the development of theory and identify the potential research gaps.

5.1. Interpretation of CE in built-environment

The theory for this dimension of interpreting CE in a built-environment bring about indicators, scale development model, and frameworks which can quantify and or aid to establish circularity in a construction project. None of the articles fell in the category of observation, which meant that the research in this dimension focused more on establishing relations or predicting models. In the categorization stage, most of the researchers have worked on developing models and indicators for most efficient built-environment practices along with frameworks for evaluating CE at different levels of implementation. The research for the development of frameworks for CE in constructions is replicated in the context of bridges and the life-cycle stages of constructions. However, none of these frameworks are validated by any of the researchers. The development of scale by Ref. [30] for measurement of CE using seven indicators falls in the association stage as this research can quantify circularity in a project. Table 7 illustrates the theory development in the dimension of interpretation of CE in the built environment.

5.2. CE business models

The evolution of theory in the context of business models for the implementation of CE in built-environment commences with the observation that government regulations and policies provide the necessary support to incorporate CE in construction projects. Also, public-private partnership models facilitate circular practices for CDWM. In the categorization stage, the researches have determined frameworks in terms of supply chain collaboration, stakeholder networking, and capital planning for CE. Replication of such research depicts a framework for socio-technical factors that impact the implementation of CE in construction firms. The association stage of theory stresses on the use of interface management systems amongst stakeholders for adaptive reuse of buildings. Also, government regulations and innovation enable CE in built-environment projects. Notably, in this dimension, none of the business models or frameworks have been validated, thus presenting a future scope for the determination of an exhaustive circular business model. The stages of theory development for CE business models are shown in Table 8.

5.3. CE enablers

The acknowledgment by various researchers that prefabricated, modular and relocatable buildings facilitate CE, constitutes the observation stage of the theory development in this dimension. The observation stage also extends to the need for the determination of material stocks for facilitating reuse/recycle of resources at the EoL of structures. The research in this stage also includes the fact that the employment of an expert or a CE manager has more advantages in executing a circular construction project. The categorization stage in the CE en-

Table 7
Stages of theory development for interpretation of CE in the built environment.

Stages of theory	Original	Replication	Validation
Observation	-NA-	-NA-	-NA-
Categorization	- Key performance indicators for construction materials for best EoL practices [105]; - Conceptual model for resource-efficient built environment [42]; - Categorization at micro, meso, and macro-level & framework for economic, societal, governmental, environmental, behavioral, and technological dimensions [17]	- CE framework for meso level construction [73]; - CE framework across life-cycle stages of construction [81];	-NA-
Association	- Scale development for measurement of CE [30]	-NA-	-NA-

Table 8
Stages of theory development for CE business models.

Stages of theory	Original	Replication	Validation
Observation	- CE adoption in businesses requires legal backup [63]; - Public-private partnership enables efficient CDWM [68]	-NA-	-NA-
Categorization	- Supply chain collaboration, technical know-how, networking of stakeholders & process design frameworks for CE implementation [19]; - CE based capital planning for efficient execution [31];	- Framework of socio-technical factors that impact CE implementation in firms [89]	-NA-
Association	- Use of Interface management system for adaptive reuse [52]; - Government regulations and innovations facilitate CE in the construction industry [55]	-NA-	-NA-

ablers' dimensions builds on frameworks for sequential disassembly for deconstruction for adaptive reuse of buildings using BIM tools and development of urban mining centres. Finally, the association stage establishes the need for material passports, sequential disassembly, supply chain integration, and strategic urban planning as enablers of CE. An elaborate framework for the stages of development of theory for CE enablers is shown in Table 9.

5.4. End-of-life management

The evolution of theory in the context of CE for EoL begins with the identification of CE based CDWM practices in different countries along with replication and validation of similar research. The barriers, as well as best practices for CDWM are identified. The observation stage also includes methods for recovery of construction waste and the factors which impact recovery. In the categorization stage, the research builds CE-based frameworks for efficient management of a structure at the EoL. This includes the use of cleaner production techniques, deconstruction models, as well as identification of best practices. In the association stage, the EoL management of circular structures is justified by proving the environmental and economic feasibility of the adoption of CE in a built-environment. Also, the BIM platform facilitates the determination of the salvage performance of a structure at the EoL. The theory development stages are given in Table 10.

5.5. Circular building materials

The understanding of various materials that can be reused or recycled, comprise the observation stage for theory development for circular building materials. The research on the use of construction wastes and recycled aggregates has not only been replicated but also validated for different structures. The dependence of circularity of building materials on economic feasibility and quantity forms the categorization stage of theory building. However, this research proposition has neither being replicated or validated. Finally, in the association stage, the research establishes that circular building materials have carbon saving potential. This research, too has scope for validation. Table 11 illus-

Table 9
Stages of theory development for CE enablers.

Stages of theory	Original	Replication	Validation
Observation	- Prefabricated buildings aid in circular building practices [45]; - Relocatable modular buildings facilitate CE [57]; - Barriers and strategies for the design for deconstruction [54]; - Determination of material stocks in a region aids in the formulation of CE policies [67]; - CE manager fosters CE in construction projects [75].	- Material and components bank for facilitating reuse/recycle [70]; - Modularization promotes CE [84].	-NA-
Categorization	- Urban mining bases for collection, segregation & recycling of waste for CE [98]; - Design for disassembly and deconstruction models for circular constructions [106];	- Comprehensive framework for CE strategies for adaptive reuse buildings [74]; - Selective disassembly facilitates adaptive reuse [83].	- BIM platform for performance assessment of buildings designed for disassembly and deconstruction [62].
Association	- Planning for sequential disassembly aids in the adaptive reuse of buildings [23]; - Use of circular-building-components generator for developing circular designs [53]; - Material passports determine material stocks and flows, thereby promoting circularity [60].	- BIM-based integration of building designs and supply-chain for the determination of construction waste management [97].	- Strategic urban planning as an enabler of CE adoption [69].

Table 10
Stages of theory development for construction and demolition waste management.

Stages of theory	Original	Replication	Validation
Observation	- Barriers for the adoption of CE in CDWM practices [26]; - Methods for reuse or recovery of structural components at the EoL [48]; - Best practices for CDWM in Europe [11]; - Social perception is a determinant for ending or extending the life of a residential building [66].	- CE based CDWM practices in China [92] and USA [90].	- CE based CDWM for resource recovery [78]; - Factors impacting waste recycling in CDWM [93].
Categorization	- Framework for CDWM based on CE principles [24]; - Best practices for EoL management of construction materials [28]; - Adoption of cleaner production techniques in CDWM in China [49].	- 3R principle-based CDWM framework in China [12].	- Deconstruction of buildings facilitates resource recovery and environmental protection under favorable social and market conditions [50].
Association	- Environmental and economic costs for EoL management decisions of buildings [44] and in case of implementation of CE in CDWM [18]; - BIM-based whole-life performance estimator for salvage performance of structural components of the building [22].	-NA-	-NA-

trates the stages of theory development in the context of circular building materials.

5.6. Material stocks

In the observation stage, the research majorly encompasses material stock analysis for different types of constructions, such as buildings, roads, etc. in different geographical locations. The use of material flow analysis to determine stocks and flows is a common tool and has been replicated and validated. The categorization stage lists material composition indicators and circularity indicators to facilitate the development of the material stock database. In this stage, the research also extends to the development of resource cadaster to determine the potential for resource recovery. The association stage establishes the fact that the determination of material stocks and flows, promotes urban mining and thus enables resource recovery, which can be reused for suitable constructions. Table 12 below gives the stages of development of CE for material stocks.

Table 11
Stages of theory development for reuse/recycle of construction waste.

Stages of theory	Original	Replication	Validation
Observation	-Use of sewage sludge ash in the construction industry [38]; -Use of recycled construction aggregates in roads [39]; -Use of dredged sand for construction of port [47].	-Barriers to the use of structural steel [29]; -Use of recycled aggregates in sustainable construction [103] -Reuse of construction waste [86]	-Use of recycled construction aggregates in roads, tunnels, and buildings [102]
Categorization	The reuse of construction waste depends on economic demand, ease of disassembly, and future controls [89].	-NA-	-NA-
Association	Circular building materials aid in the decarbonization of buildings [27].	-NA-	-NA-

Table 12
Stages of theory development for material stocks.

Stages of theory	Original	Replication	Validation
Observation	- Material flow in highway traffic system in China [37]; - Non-domestic material stock in Germany [21]; - Material stock in residential buildings using secondary data [76].	- Anthropogenic stocks in Germany [43]; - Material stocks in roads in the USA [41]; The material flow of timber in residential buildings [76]; - Material stock in public residential buildings using MFA [59].	- Continuous MFA used to determine the material stock of non-metallic minerals in German buildings [43]; - Global material stock database for residential buildings from 1970 to 2050 [79].
Categorization	- Material composition indicators for multi-family housing in Germany [46]; - Material stock database with circularity indicators promotes CE [77]	- Urban stock cadaster for resource reuse [87]	-NA-
Association	- Urban stocks for determination of CE potential [51].	- Increase in global demand for steel and cement for the building until 2050 [80].	- Urban mining potential using MFA and possible reuse in affordable housing [82].

5.7. Environmental impact

The theory development on the environmental impact of the adoption of CE in built-environment begins with researches that observe the fact that adoption of circular construction practices such as recycling, prefabrication, and use of circular building materials have lesser carbon emissions as compared to the traditional construction practices. The categorization stage builds on disassembly and deconstruction mechanisms for carbon savings potential. In the association stage, life cycle assessment is used as a tool to validate the positive environmental impact of the adoption of CE. This is achieved by circular supply chains, demountable floor systems, and prefabricated units of construction. Research also validates that, in numerous cases, multiple reuse cycles are required to ensure environmental benefits. The stages of theory development for environmental impact for CE adoption are listed in Table 13.

6. Discussion

The implementation of CE in built-environment is beneficial environmentally as well as economically. The research in this field has a broad focus on encompassing business models, tools, and strategies for enabling CE, circular building designs and materials, and the impact of the adoption of CE on the environment. The most common research in this forte is exploration of EoL management techniques for efficient resource recovery practices in construction sector. These EoL techniques include sequential disassembly, deconstruction analytics, best practices for waste management, and frameworks for CDWM. The second most common research has been on the determination of environmental impacts of the adoption of CE. Life cycle assessment is the most commonly used method to determine the impact of switching to circular construction practices. The research compares the impact of reusing construction materials, development of circular supply chains as well as the use of prefabricated components – all of which are considered as circular building strategies. The next commonly performed research focusses on the development of material or urban stock models for predicting resource recovery or urban mining potential. Tools like material passports and material flow analysis have been used for the purpose. The research on circular business models and circular building materials is somewhat scarce and thus has significant scope. Also, research on quantifying the concept of CE in the built environment, in terms of indicators or standard framework, is not very well established.

Table 13
Stages of theory development for environmental impact.

Stages of theory	Original	Replication	Validation
Observation	- Recycling of gypsum gives lesser GHGs emissions [105]; - Mapping and quantifying embodied energy requirements of buildings stocks [20]; - Environmental impacts of adopting CE [33]	- Circular building materials reduce carbon emissions [27];	- Adoption of CE has positive environmental impacts [58]; - CE reduces carbon emissions [36]
Categorization	- Environmental impacts of a building designed for disassembly (or subsequent reuse) [65]; - CE enables low carbon emission approaches in built-environment [72]	- Environmental impacts of adaptive reuse in building structures [71];	- NA-
Association	- Circular supply-chains reduce environmental impacts [25]; - Demountable floor systems are more environmentally friendly owing to lesser emissions [56]; - Prefabrication reduces carbon emissions by 30–50% [91].	- Reusable wall assemblies have a lesser environmental impact than demountable ones [61]; - Aggressive reuse needed to ensure low life cycle impact for high embodied energy materials [64];	- Reuse has more environmental savings as compared to recycling [88]; - Design for reuse can offset GHG emissions by 88% as compared to recycling [94];

This research article hints that the implementation of CE in a built-environment requires a holistic approach encompassing government policies, technological and infrastructure availability, social perception, and business innovation. For an efficient implementation of CE, the practice cannot be limited to a structure but needs to be incorporated at a macro level through strategic urban planning. The theoretical implication of the reserach is that the trend of research in the field of CE in built-environment is advancing, thus incorporating different dimensions in its gambit. Implementation of CE essentially has its benefits, but its approach and feasibility for optimized results and maximum profitability need to be quantified by rigorous research on numerous circular construction models. Further, the future research scope for CE in the context of the built-environment is elaborated in the succeeding texts.

In the case of *interpretation of CE in the built environment,* the future scope can include the study of case studies on CE implementation in different types of construction projects, and construction practices in countries wherein CE is adopted as a government policy. Future studies can further focus on the validation of existing models and frameworks for implementation of CE, determination of a standard set of indicators to quantify CE, and developing a universal model for circular constructions for easier replication. Future research on *CE business models* can include the validation of existing business models in different economies and geographic locations. The development of circular business models specific to different types of structures based on their utility can be an exciting research area. The research on *CE enablers* can be extended to determine the strategies (economic, legal, social, and technological) for establishing circularity in a construction project. The research on modular and prefabricated buildings needs to be validated for economic feasibility and environmental impacts. Also, research on supply-chain integration for construction waste management can be more elaborate, determining methods for integration of supply-chains, application of artificial intelligence for resource recovery, and stakeholder collaboration platforms for the facilitation of exchange of construction materials.

In the case of research on *EoL management,* the future scope of research can focus on establishing models for EoL deconstruction mechanisms at the management level. Another research proposition would be to establish economic and environmental feasibility based on available technology and infrastructure. The future scope of research on *circular building materials* can include the development of models and designs for subsequent reuse of different construction materials, which can set a standard possible reuse option. Also, many construction materials need to be brought under the purview of research, as the current research is limited to steel, aggregates, timber, and concrete. In the dimension of *material/urban stocks,* the future scope for research includes determination of reusability of building materials or components at the end-of-life of a structure, development of the region or countrywide material stock database to facilitate determination of stock outflow, and extending the research on material stocks from roads and buildings to other structures like power grids, railways, etc. Another potential research scope includes modeling the frequency of different types of material outflows in different countries based on population, economy & socio-economic parameters. In the forte of *environmental impact* owing to CE adoption, the future scope includes validation of this impact by comparing ecological & carbon footprint indicators – for linear and circular buildings, usage of cost-benefit analysis for justifying investment for the development of infrastructure for the implementation CE. Also, the reduction of carbon emissions by adopting CE at each stage of construction can be studied to determine the efficient CE path for different types of constructions.

7. Conclusion

This research article was envisioned to build an understanding of literature and stages of theory development on CE in a built-environment. The adoption of CE in built-environment presents a challenge as buildings and infrastructure are complex composite structures that usually are designed to last for a longer time span as compared to other products. Countries like China, Japan, Germany, and the USA have started moving towards the adoption of CE, and a strong technical & research back-up that is essential for this transition. This research article focusses on seven broad dimensions of CE in the built-environment as envisioned by the authors. However, the research on CE in the built-environment is not limited to these, as it can also extend to include other dimensions such as economics of CE adoption, countries practicing CE in built-environment, circular structures, etc. This research article is also limited in terms of not including conference papers that are informative and comprise emerging research trends. Another limitation of the research is the selection of keywords, which could have been expanded to include construction and demolition waste, reuse, recycle, repair, maintenance, and recycle. However, the authors limited the keywords to avoid ambiguities and confusion.

The primary aim of this article has been to present an elaborate analysis of the research done on CE in built-environment. Literature review and theory development on the topic have achieved this aim. This research has enabled the authors to understand the trend of evolution of research in the field and also to draw practical and theoretical implications as well as future research scope in the identified dimensions of CE in the built-environment.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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