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Review

Selection Criteria for Building Materials and Components in Line with the Circular Economy Principles in the Built Environment—A Review of Current Trends

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Abstract: A growing concern is given to the environmental impacts caused by the construction industry. Waste generation, resource consumption, and greenhouse gas emissions are the main drawbacks of the rapid urbanization that the world is witnessing. As a response to these pressing issues, policymakers and academia are exploring the concept of Circular Economy (CE) to manage resources better and achieve resource efficiency while eliminating waste. One of the strategies to implement CE in the built environment is to select the appropriate building materials and components from the early stages to carry out the concept's principles along the value chain and create a closed-loop system. Therefore, this study aims at identifying selection criteria for building elements according to CE principles through a review of the latest research. Results have shown that little has been concretely achieved in terms of a paradigm shift to CE since the main focus of the literature is still the use of recycled products and the recyclability of building materials and components at their end-of-life. Although the present study is solely focused on the technical aspect of building materials and components, it outlines current adopted criteria to bring about a circular built environment and highlights the need for a more innovative approach to attain higher circularity levels.

Keywords Circular Economy; circular buildings; built environment; materials selection; recycle and reuse

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1. Introduction

The construction industry has been an essential sector for humans as it provides the necessary infrastructures, buildings, jobs and economic prosperity [1]. Nevertheless, with the rapid urbanization that the world is facing, the building sector is imposing severe environmental impacts on the planet [2]. This accounts for more than a third of the waste generated, emissions, and materials consumption [3]. In the long run, this would create a global issue of materials scarcity as the consumption rates would exceed the regeneration rates of resources [4,5].

In this context, the concept of Circular Economy (CE) came into broad recognition by policymakers in Europe, to urge the industry to shift its linear consumption pattern to a circular one wherein the economic progress does not threaten the ecosystems [6,7]. The concept encourages more proper and efficient use of renewable resources while considering waste as a resource that could be put back into the economy in a closed-loop system.

Although the built environment represents a significant opportunity to embrace the CE, the literature regarding the topic is still emerging and mainly theoretical [8]. The challenge lies in the fact that the industry has been following the same economic model with little to no consideration of the end-of-life stage of consumed materials. Several studies have already tackled the topic of selecting adequate construction materials from a triple bottom line perspective to ensure a balance between the environment, economy, and

society [9]. However, so far, not a single study has undertaken the critical factor of materials selection from a technical perspective according to the CE principles. As such, this study will review the current literature regarding CE practices related to construction materials to identify and analyze the materials selection criteria that are being followed to support the adoption of CE principles in the construction sector. In this article, the term built environment describes all the elements of our surroundings that are human-made, such as buildings and infrastructures [10], whilst the terms "material" and "components" refer to all the building elements which constitutes the built environment, taking into account the concept of Buildings As Material Banks, which is a framework that aims at implementing the CE in buildings by reducing the virgin materials input, increasing buildings flexibility and adaptability, and designing out waste [11].

Given that the article's objective is to discern materials criteria from literature, it is structured in five sections. Section 2 reviews the origins and the idea behind the CE, the adoption of the concept's principles in the built environment, and answers why and how materials selection is important for implementing circularity in the built environment. Section 3 describes the methodology of the study. Section 4 presents the literature review results, while Section 5 discusses the outcomes, and explains the trends of materials selection encountered in literature. Finally, Section 6 presents the conclusion of the study, provides further recommendations, and outlines the limitations of this study.

2. Background and Context

2.1. The Concept of CE

In response to the current predominant pattern of the linear economy, which consists in an "extract, make, use, dispose" model, the concept of CE was elaborated to provide a durable and sustainable resolution to distinguish economic prosperity from environmental damage [12]. Scholars, practitioners, and policymakers have demonstrated, mainly throughout the last decade, a great interest in applying the concept's principles into sectors that imposed heavy impacts on the environment. Nonetheless, originally the work of Kenneth Boulding entitled "The Economics of the Coming Spaceship Earth" [13], initiated the idea of closed systems with finite resources. From thereon, numerous studies tackled the pressing issue of adverse environmental impacts resulting from economic welfare. In 1990, the environmental economists, Pearce and Turner introduced the term "Circular Economy" to describe a pattern wherein materials are kept in use and waste is designed out [14]. In recent years, the CE gained more attention with the creation of the Ellen MacArthur Foundation (EMF). The latter stated that the CE is rooted in several schools of thought such as: Regenerative Design, Performance Economy, Industrial Ecology, and Cradle to Cradle [15].

Up to now, there is no global consensus when it comes to defining the CE concept accurately. Kirchherr et al. [16] analyzed 114 definitions of the CE to provide transparency to its current comprehension. The authors concluded that the CE concept might face incoherence and eventually breakdown or "remain in a deadlock" as many conflicts were found in those definitions. The authors ultimately defined the studied paradigm as "*An economic system that replaces the 'end-of-life' concept with reducing, alternatively reusing, recycling and recovering materials in production/distribution and consumption processes. It operates at the micro-level (products, companies, consumers), meso-level (eco-industrial parks) and macro-level (city, region, nation and beyond), to accomplish sustainable development, thus simultaneously creating environmental quality, economic prosperity and social equity, to the benefit of current and future generations. It is enabled by novel business models and responsible consumers*" [16]. Preston [17] argued that a lack of an acknowledged definition might challenge future international cooperation. Currently, the most used and well-known definition of the CE is stipulated by EMF as:

"*An industrial system that is restorative or regenerative by intention and design. It replaces the 'end-of-life' concept with restoration, shifts towards the use of renewable energy, eliminates the*

use of toxic chemicals, which impair reuse, and aims for the elimination of waste through the superior design of materials, products, systems, and, within this, business models" [18].

Nevertheless, a recent study regarding CE indicators for cultural heritage buildings, defined CE in a more comprehensive manner as: "*…a production and consumption process that requires the minimum overall natural resource extraction and environmental impact by extending the use of materials and reducing the consumption and waste of materials and energy. The useful life of materials is extended through trans formation into new products, design for longevity, waste minimization, and recovery/reuse, and redefining consumption to include sharing and services provision instead of individual ownership. A CE emphasizes the use of renewable, non-toxic, and biodegradable materials with the lowest possible life-cycle impacts. As a sustainability concept, a CE must be embedded in a social structure that pro- motes human well-being for all within the biophysical limits of the planet Earth*" [19].

2.2. CE Principles in the Built Environment

As previously mentioned, the CE concept entails several schools of thought and ideas which complicates the application of its core principles. In literature, the CE principles mainly arise as the 3Rs principle, especially from a Chinese perspective, commonly summarized in its principles to Reduce; Reuse, and Recycle. "Reduce" point out to the action of decreasing the inputs (primary energy and raw materials) and outputs (wastes) to achieve eco-efficiency, while minimizing the consumption rates. "Reuse" means "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" [20]. In contrast, Su et al. [21] referred to "reuse" as an act of using by-products and wastes generated by industries as inputs to other industries as well as extending the life-use of products by maintenance or remanufacture. "Recycle" implies "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for the original or other purposes. It includes the reprocessing of organic material but does not include energy recovery and the reprocessing into materials that are to be used as fuels or for backfilling operations [20]. It incites the industries to process wastes while manufacturing new products to reduce the dependence on virgin materials and minimizing the quantity of materials disposed or landfilled which will, consequently, decrease the environmental burdens [9,21–24]. The 3Rs principle follows a "hierarchical importance", as the action of "reducing" comes first as the main principle when adopting CE [21]. It is commonly perceived that CE is linked to "Recycle", but the proper approach to reach material efficiency and generate benefits in both economic and environmental is to give priority to the "Reduction" and "Reuse" of waste [9].

The 3Rs approach was recently expanded to include more actions to transit from a linear economy to a circular one (Table 1). The "R-list" shows the circularity strategies that are more suitable to embrace CE by a priority order [25].

Table 1. R-list strategies to ensure a shift towards a Circular Economy (CE) (adapted from [22]).

R-List Approach	Action
R0 Refuse	Depreciate a product with harmful impacts and proposing a different one with identical or better functions and fewer impacts.
R1 Rethink	Intensify the product use and adopt smarter strategies as sharing economy or products with multiple functions.
R2 Reduce	Decrease virgin materials and energy consumption while enhancing efficiency.
R3 Reuse	Reuse an abandoned product that keeps the same functions by another user.
R4 Repair	Fix a defective product to give back its initial performance.
R5 Refurbish	Renovate an outdated product to make it as a new one.
R6 Remanufacture	Make a product using parts from a damaged product that had the same functions.

R7 Repurpose	Make a product using parts from a damaged product that had different functions.
R8 Recycle	Include, into the manufacturing process of a product, materials that reached their end-of-life use to make materials with same, higher (upcycle), or lower (downcycle) qualities.
R9 Recover	A process of retrieving heat, electricity, or fuel from non-recyclable materials by incineration.

The EMF highlighted three principles for the CE, first, to keep materials in use and at their highest value for as long as possible by relying on the technical and biological cycles, second, to maintain and improve the natural capital by using renewable resources, and third, to adopt a holistic perspective by designing out waste. Similarly, the European commission has released a report entitled "Circular Economy principles for buildings design" [26] which is a document aligned with the assessment methodology Level(s) to identify relevant aspects to be considered to reach the aim of resource-efficiency and CE implementation at the material level. Three approaches have been highlighted and addressed according to the target audience, which are adaptability and service-life extension, waste reduction, and durability. The latter aspect has also been substantiated by several studies as a crucial factor by stressing the need for high-quality and durable materials to transition towards a circular built environment [27–31].These principles can be translated into practice as a better and wiser use of construction materials that are sustainably sourced or recovered, implementing collaboration across the built environment's value chain, and planning the end-of-life scenario of buildings and materials.

Merging the CE principles with the construction sector offers significant opportunities for reductions in energy use, greenhouse gas emissions, and waste production and improves the global construction industry productivity [8]. Cheshire [32] claimed that circular thinking means redefining waste as a resource to keep materials in use and their value retained. This approach can reduce costs to protect companies against unstable prices related to raw materials while providing more supply security. Gálvez-Martos et al. [33] argued that implementing the core principles of CE in the management of construction demolition waste could drastically minimize the environmental impact and improve resource efficiency by: reducing waste generation, minimizing transport impacts, maximizing reuse and recycling by enhancing the quality of secondary materials and optimizing the environmental performance of treatment methods. The EU action plan on closing the loops to transit towards CE [34] prioritized five sectors, and one of them is the "construction and demolition" waste. At this level, the priorities rely on setting recycling protocols for construction and demolition waste and adopting eco-design to boost competitiveness and minimizing waste generation.

2.3. The Relevance of Materials Selection for Embedding CE in the Built Environment

At the core of the built environment, construction materials play an essential role in defining the built environment's vision. In some cases, selecting the best suitable construction materials from a CE perspective would attain higher sustainability levels by reducing the environmental impacts, lowering the costs of materials, and increasing collaboration across the value chain among other benefits [35,36]. Still, overall sustainability performances of construction materials, that match the CE thinking, require meticulous research to designate the perfect balance between circularity and sustainability [37].

Pomponi and Moncaster [8] outlined the CE in the built environment in three levels where they positioned materials as the micro level due to their ability to introduce the concept from its roots whilst involving less complexity in the process of embedding the CE principles.

The current attempts to reduce the impacts of buildings during the use phase has emphasized the embodied impacts carried by materials as they account for more than half of the total life cycle impacts [38], which evince that construction materials hold the potential of lowering overall embodied impacts of buildings right from the early stages. Designers, project managers, and different construction actors can decide CE applications

[39]. In sustainable construction, the selection of materials has been established as a crucial step to integrate the sustainability principles into buildings projects [40]. Nassar et al. [41] stated that during the design stage, selecting the proper building materials will influence the building's performance depending on the design criteria that has been chosen. Milani et al. [42] relied on the multiple criteria decision making and life cycle assessment to provide a comparative study and select the most favorable composite material according to its environmental, economic and technical performances.

As CE and sustainability concepts may overlap in some aspects, previous studies have partially examined which CE principles are already embodied in sustainability criteria. Akadiri and Olomolaiye [43] highlighted the need for a framework that identifies sustainable building materials and developed an assessment criteria to select the best materials based on sustainability principles. Among the prioritized criteria, the authors relied on recyclable and reusable materials, used waste, durability, and safe disposal scenarios. Simultaneously, maintainability stood out as one of the most significant indicators that must be considered while selecting building materials along the design process [43]. Jeanjean et al. [44] argued that the improvement of the building envelops by materials selection according to their thermal performances will tackle potential environmental issues at a lower cost. The experimental research concluded that using a building material with recycled content presented the best results according to the selected criteria. Likewise, Govindan et al. [45] proposed a set of indicators for materials selection from a sustainability perspective in the United Arab Emirates (UAE) context using a multicriteria decision-making method. They established that, according to the experts' opinion, the most significant criterion for the study was "Potential for recycling and reuse". In the same context, Mahmoudkelaye et al. [46] presented a model of materials selection that went beyond the triple bottom line and included the cultural and technical aspects to provide a holistic approach to the process. Still with little regard for the material's end-of-life, since the only relevant indicator for this aspect was "reuse and recycling". Pedersen Zari [47] used an ecosystem services approach to underline the best suitable materials to decrease the construction industry's harmful environmental impacts. One of the adopted strategies was the "Nutrient cycling" which emphasizes the reuse and recycling of finite earth elements. Reddy et al. [48] investigated the challenge of selecting proper sustainable construction materials by developing the "Sustainable Material Performance Index" based on three construction stages. One of the indicators that the authors relied on was recyclability, which can define the material's end-of-life scenario.

Therefore, to ensure an optimal CE implementation in the built environment, a wise materials selection is crucial for the construction project. Eberhardt et al. [49] claim that the second most popular strategy to implement CE in buildings is materials selection. Despite the comprehensive studies that explored Circular construction materials, a lack of criteria identification linked to CE principles remains overlooked.

In this context, the following research will attempt to classify the CE technical aspects of building materials that have been studied by academia to identify critical trends linked to the CE. Based on the background knowledge described in this section, the technical criteria that will be considered in this study are recycled or recovered content, recyclability, reusability, ease of deconstruction, durability, maintainability, upcycling potential, energy recoverability, and biodegradability.

3. Materials and Methods

To ascertain the trends of current studies which related construction materials and components practices, a review was carried out between November and December 2020 using the keywords "Circular", "economy", "Construction", "Building", "Materials", in two different databases, namely Scopus and Web of Science. The reason for considering these two is that they are considered the most exhaustive databases [50] (Figure 1). The language selected was English, and only papers published during the last six years are considered. Due to the number of publications that have been found, the review will only

consider journal articles. Preliminary results were 159 articles in Scopus and 120 in Web of Science. After that, duplicates have been disregarded, and screening has been performed for titles, abstracts, and keywords to determine relevant journal articles concerning this study's scope. Finally, 131 selected journal articles were eligible for full-text read, and the results are presented in the next section.

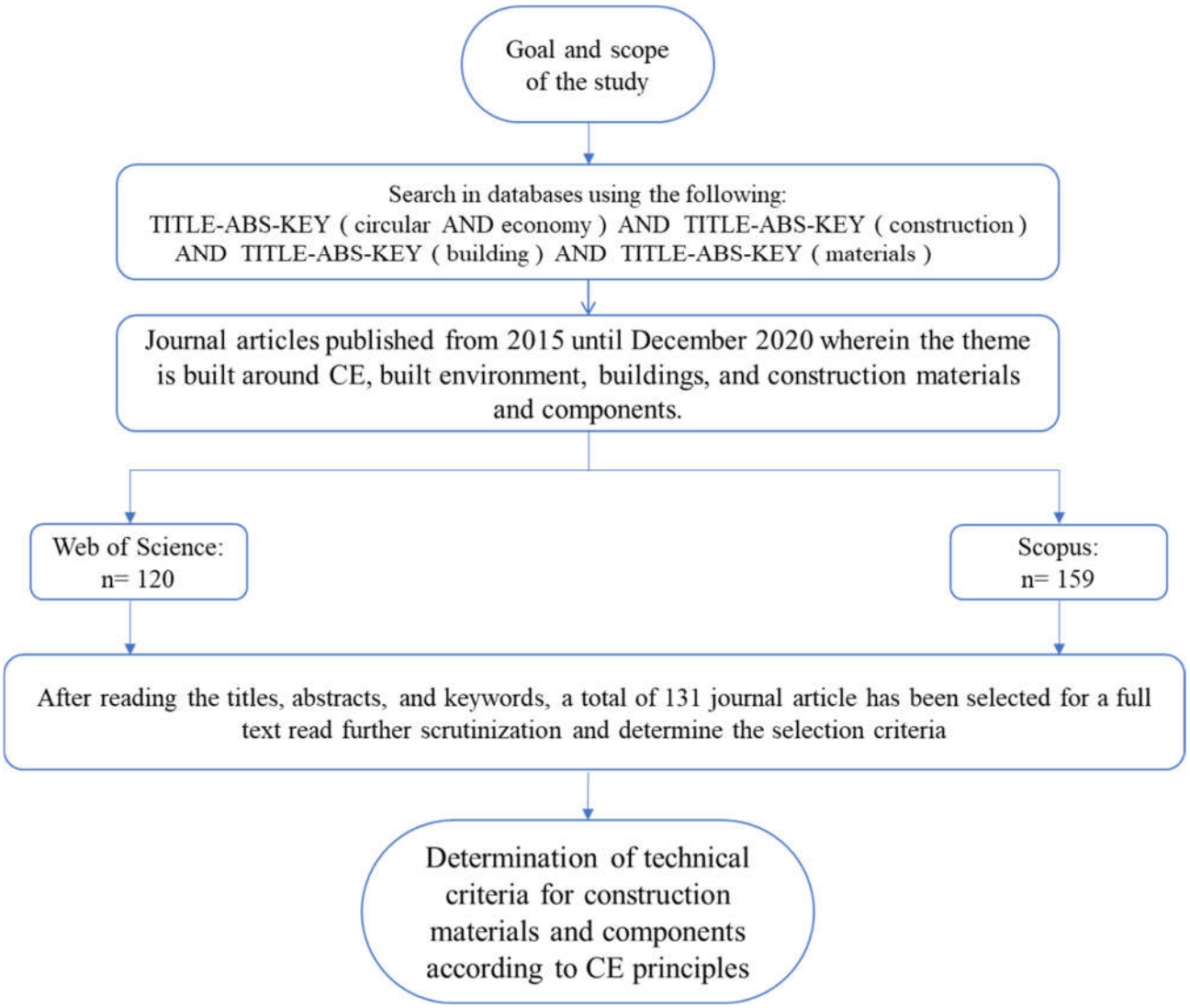

Figure 1. The methodology of the study.

4. Results

4.1. Temporal Analysis

Apart from the current year, the amount of publication has substantially increased since 2015 (Figure 2), which implies a growing interest from academia in the CE topic. This phenomenon can be explained by the fact that several governmental and non-governmental agencies are releasing reports and action plans (e.g., [51–53]) which has enabled a more significant concern to translate the circular thinking into the construction sector to support the sustainable development further.

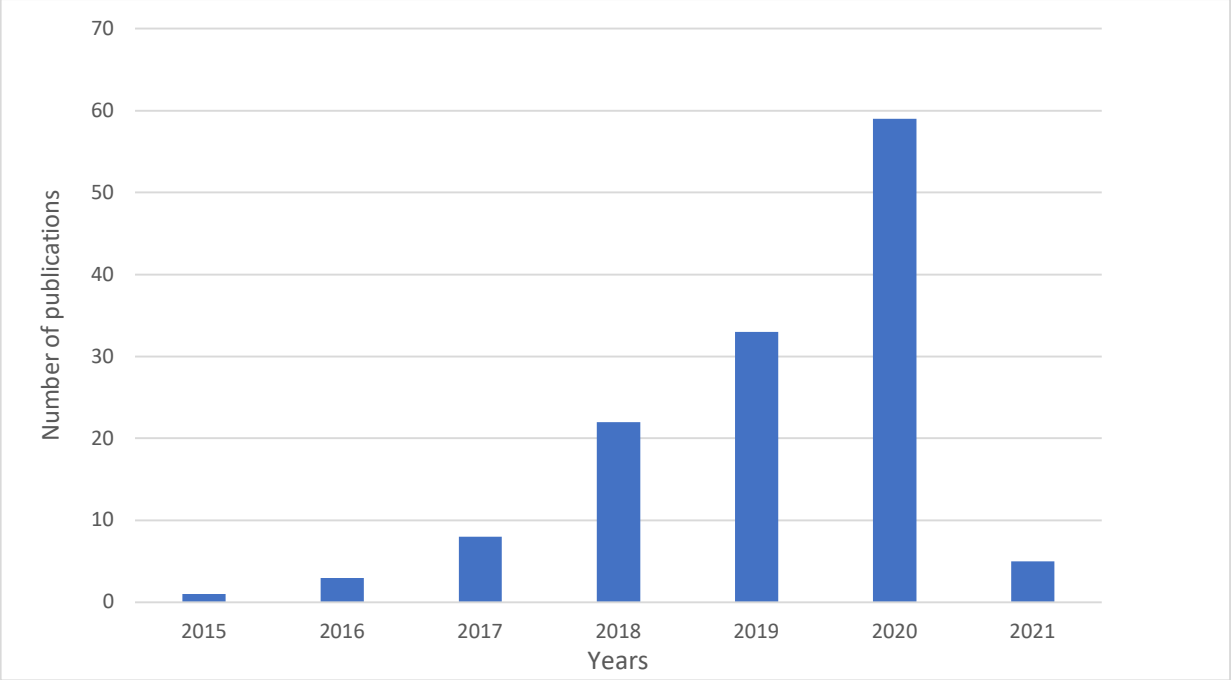

Figure 2. Temporal analysis of the selected papers.

4.2. Spatial Analysis

The spatial analysis of the selected literature was done according to the first author's affiliation (Figure 3). The analysis indicates the dominance of the European research output in CE. Over 70% of the publications were from European countries where Spain, Italy, and the UK came in the top three with 22, 17, and 10 publications, respectively. This is due to the numerous EU funded projects that investigated CE in the built environment (e.g., BAMB) and the collaboration developed across the continent in addition to the release of the CE action plan by the European Commission in 2015 and 2020 [26,52]. Asia came second in terms of publications with over 15% followed by North America (6%), Oceania (5%), South America (2%), and Africa (2%).

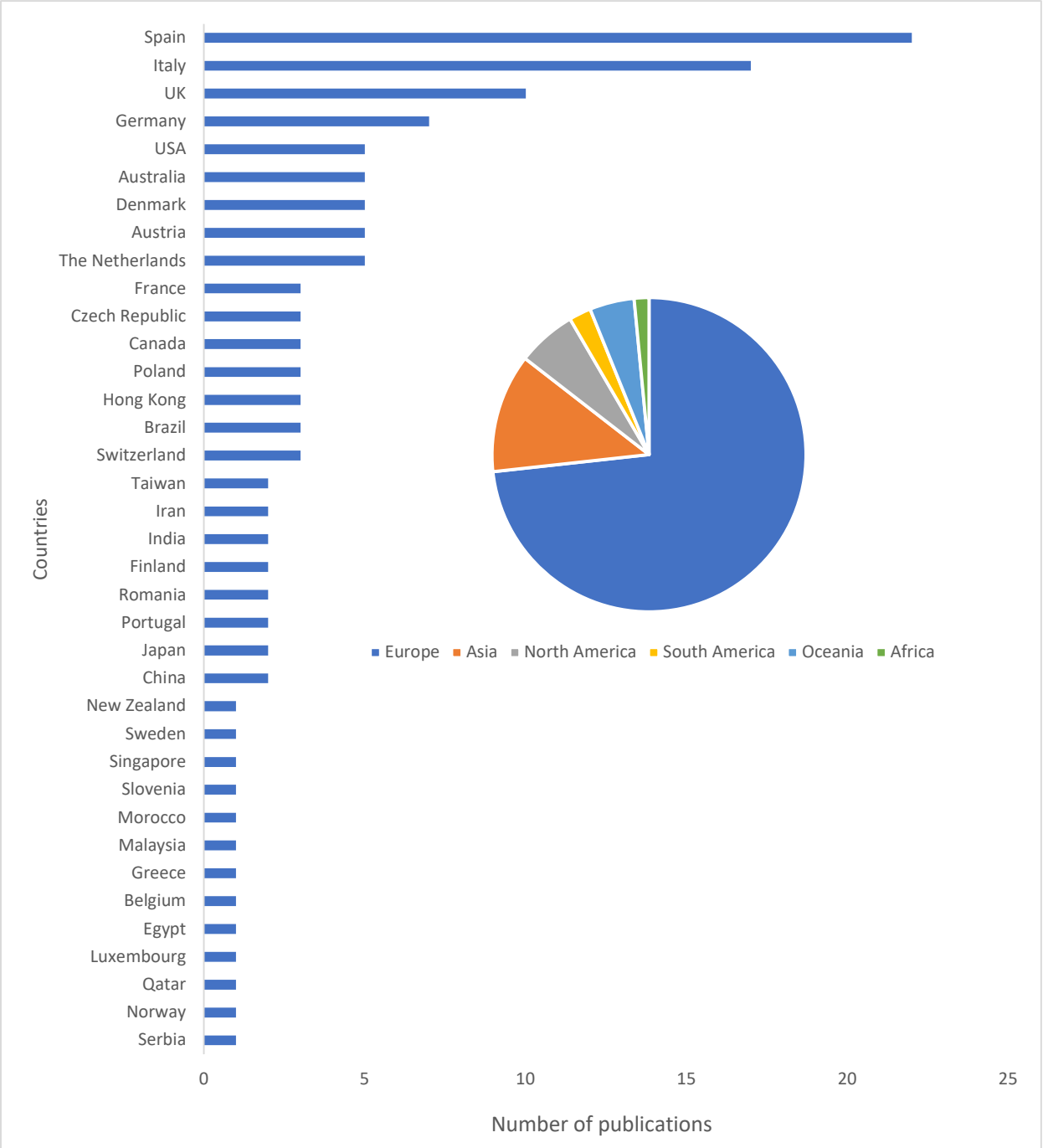

Figure 3. Spatial analysis of the selected papers.

4.3. Source Analysis

Out of the 51 journals where the selected literature has been published (Figure 4), the "Journal of Cleaner Production" came first in terms of publications related to the topic with a total of 32 articles, followed by "Resources, Conservation, and Recycling" with 15 articles, and "Sustainability" with 11 articles. These journals have been publishing considerable scientific research regarding the domain of CE. The other main scopes of the remaining journals are waste, environmental research, structures, architecture, buildings, energy, and materials.

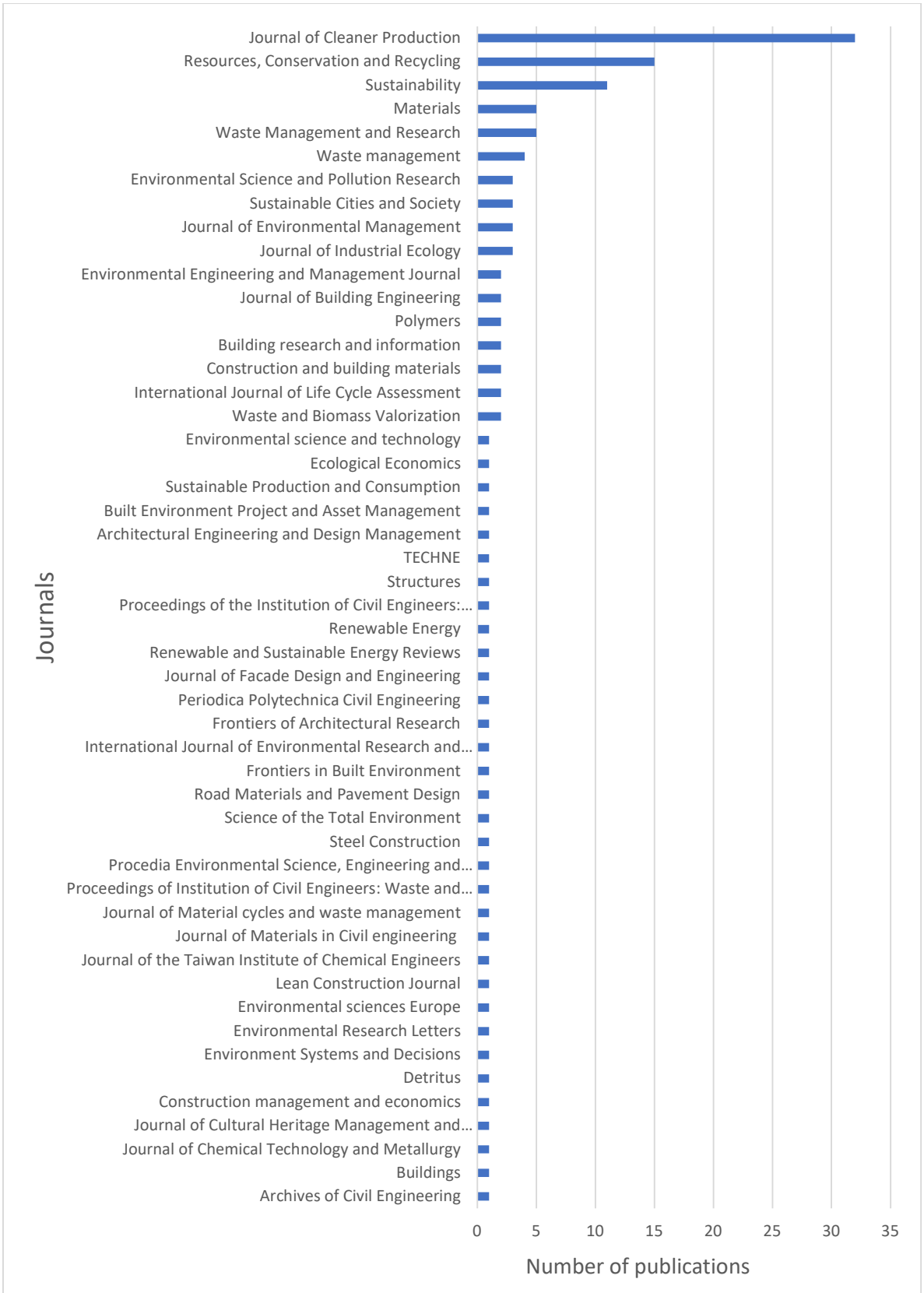

Figure 4. Sources analysis.

4.4. Identified CE Criteria for Building Materials and Components

After a thorough analysis of the eligible research articles (see Table A1), a total of nine CE strategies has been identified and categorized as shown in Table 2 and illustrated in Figure 5. The most followed criterion was "Recycled or recovered content" as over 80% of articles have discussed the possibility of incorporating recycled or recovered content into materials and components to cut down the use of virgin materials into new products. The large majority of these articles have studied the use of secondary materials into concrete/mortars as aggregates or cement replacements, at specific ratios, and concluded that the approach met the minimal requirements while reducing the associated environmental impacts [54]. The second and third most adopted strategy are "recyclability" and "reusability", considered by over 60% and 50% of the papers, respectively. The "recyclability" approach requires a process to prepare the waste to be used in new building material or component while "reusability" means extending their service life without a particular treatment. Considering the principles of closed-loop systems, around 25% of literature referred to materials and components that hold the ability to be easily deconstructed, which promotes reversibility in the built environment [55]. Despite being often highlighted in sustainability-related practices, the "durability" criterion was only mentioned in 15% of the articles. Current literature has neglected this important aspect, which directly correlates with the quality and performance of materials and components over time. Following the 9R's hierarchy (Table 1), "Energy recoverability" should be considered the last scenario for building elements before landfill. Over 10% of literature envisaged incineration to building products to recover energy and convert it to fuel, heat, and electricity. The "maintainability" englobes the actions of repairing, maintenance, and refurbishing building components to ensure optimal performances. However, only around 10% of articles have tackled this criterion. The last two criteria, "upcycling potential" and "biodegradability" are covered by very few articles because current construction practices are far from embracing such strategies on a large global scale.

Table 2. Findings of materials and components criteria according to CE in the literature.

CE Strategy	Description	Related Research	∑
Recycled or recovered content	Reduction of the input of virgin materials content and partially rely on recycled or recovered waste.	[2,5,6,19,27–30,36,38,40,49,50,54,56–151]	110
Recyclability	The ability of a material to be recyclable through a particular process at its end-of-life.	[5,6,19,27–30,40,49,57–59,62–64,66–68,71–74,78–80,83–91,95–97,99,100,102–107,109–114,116,117,119–121,123,125–134,136,140,145,147,150,152–167]	85
Reusability	The capability of materials to be reusable at their end-of-life and thus providing the building elements a second life.	[5,6,19,27–30,49,55,58,63,64,66,68,71–74,78–91,95–97,99,100,102,105–107,110,112–114,116,117,119,121,125,127,130–133,136,152–159,161–163,165–169]	71
Ease of deconstruction	The selected materials facilitate different design strategies to adopt reversibility such as: adaptability, disassembly, while undergoing little to no damage.	[27,29,30,49,55,58,66,68,81,83,85,87,91,99,102,105,107,110,113,116,119,125,130,132,133,152,154,157,162,167,168]	31
Maintainability	This feature characterizes materials and components that can be kept in use with	[6,27,40,49,68,71,84,107,127,129,133,167]	12

	through maintenance, repair, and refurbishment.		
Durability	The resistance of materials and components to deterioration over time while meeting the minimal requirements	[6,27–30,49,78,89,90,99,107,112,113,130,137,156,169]	17
Energy recoverability	The potential of converting building materials and components to energy by incineration.	[6,28,49,71,80,83–85,90,110,116,127,131,133,157,165]	16
Upcycling potential	Re-introducing the materials and components in the loop for a higher value	[5,58,63,72,95,102,130,166,169]	9
Biodegradability	The ability of disintegrating the building elements to the natural environment with no ecological damage	[29,90]	2

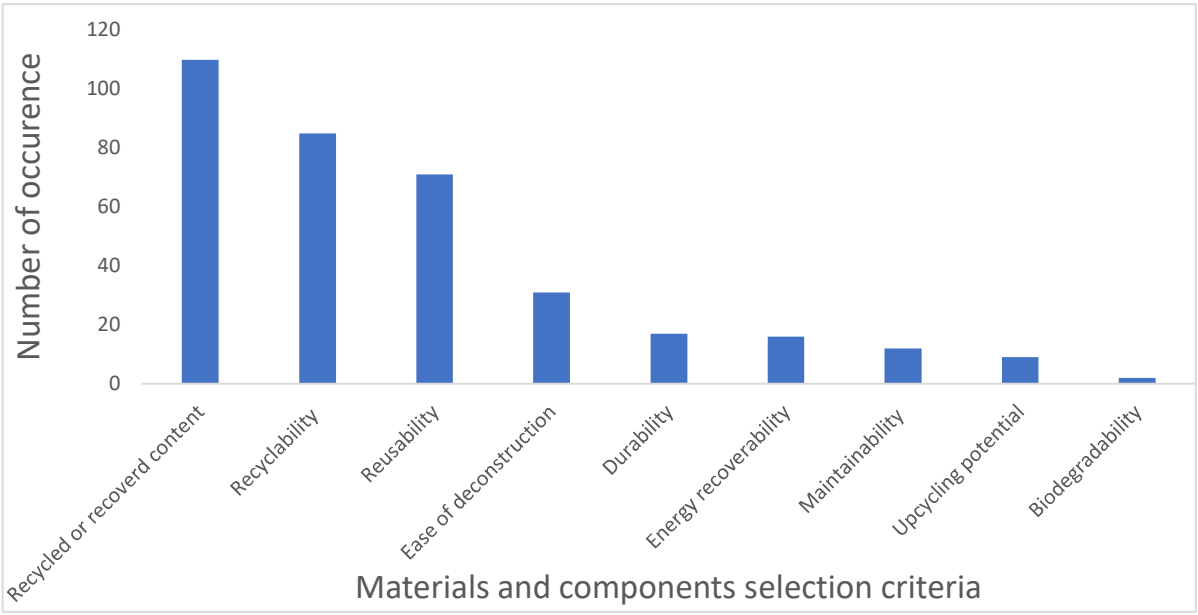

Figure 5. Materials and components selection criteria according to selected literature.

5. Discussion

The objective of this study was to determine the technical criteria of building materials and components adopted by academia under CE principles. Other environmental, economic, social criteria such as embodied carbon, maintenance cost, and aesthetics were not considered to provide a more in-depth focus on technical-related features. The nine identified CE criteria covered three facets: type of input, the use phase, and the end-of-life scenario. The type of input included only one criterion, "recycled or recovered content" which implies using recycled or recovered materials from other sources into the manufacturing of a new construction material. "Durability" and "Maintainability" are two criteria that suggest building materials or components that hold the potential of longer life-service. The end-of-life scenarios include the remaining CE criteria which are: "Recyclability", "Reusability", "Ease of Deconstruction", "Upcycle potential", "biodegradability" and "energy recoverability" as the least favored option to avoid landfill.

The conducted research about incorporating waste or by-product into building materials was already widely accepted within the frameworks of waste management and resource efficiency. With the emergence of CE, these practices have intensified, and several studies have further investigated the use of secondary materials into concrete [139], bricks [70], ceramics [60], steel [61], polymers [118] and road pavements [146].

During the use phase of materials and components, durability and maintainability are considered reliable criteria to distinguish higher longevity [29]. Numerous studies have stressed the significance of durability to implement CE principles that have to be taken into account during the design phase [27,28,132]. Durable and high-quality building elements can endure different use-cycles, ensure repeated assembly/disassembly stages, and enable reversibility [27,51,132]. Whilst maintainability refers to CE actions during the use stage through maintenance, repair, replacement, and refurbishment to preserve the value and performance of materials and components. These operations considerably contribute to overall buildings performance while lowering environmental impacts.

Recyclability and Reusability were the most approved and adopted CE strategies in the literature. From a waste hierarchy standpoint, recyclability is less preferred to reusability but was more privileged than the latter in the analyzed studies. With the intensification of the building stock, urban mining has been increasingly explored and can contribute to retrieving materials and components already in use through recycling and reuse [123,165,170]. Nevertheless, there are multiple barriers to materials reuse in the building sector such as the complexity of building structures and infective waste management, which puts forward recycling as a more feasible scenario [5,35]. Another obstacle to building's deconstruction is the hardship of retrieving materials or components without compromising their value since the buildings themselves were not designed to embrace disassembly in the first place. Envisaging deconstruction during the design phase of a building could prevent the associated environmental impacts by 70% [132]. Still, existing buildings are seldomly considered for deconstruction. The main factor for designers to embrace circularity is a neat selection of building materials that can facilitate such operations. According to literature, steel and timber are well-established materials that can enable reversibility and direct reuse with improved connections [28,57,87,89,154].

The possibility of recovering energy from building materials and components was more mentioned throughout literature than upcycling and biodegradability. A waste-to-energy strategy is a viable option compared to landfill by reintroducing energy to the loop [84]. Materials and components which are not eligible for reuse and recycling can be incinerated as an alternative for value recovery. In specific scenarios where organic materials are involved, biodegradability could be a beneficial strategy for an efficient biological metabolism according to CE principles [90]. Upcycling or creative reuse of materials and components is another strategy to achieve materials efficiency by upgrading their quality and value [166]. Rather than recycling, upcycling contributes to keeping the products in a better closed-loop with cleaner resource flows [5,72].

Most of the experimental studies that have been conducted so far, related to CE in building materials, focused on the following three CE criteria: "recycled or recovered content", "recyclability", and/or "reusability". In contrast, other quantitative and qualitative research, literature reviews, and other software simulations included a wide range of criteria [84]. This different approach evidences the discrepancy between theoretical and experimental research when implementing CE in a rigid sector that lacks innovation and still old-fashioned.

The CE was extensively promoted through the use of secondary materials from other sectors as an approach to enable industrial symbiosis. Smol et al. [56] claimed that the use of sewage sludge ash as a substitute to primary raw materials in construction products can result in better environmental impacts. Díaz-García et al. [60] investigated the use of olive oil production waste as an input for the production of structural ceramic materials and found out that this type of waste decreased the energy consumed during the manufacturing process while delivering a final product good quality. Wong et al. [74] proposed

a framework for using waste generated in the automotive industry as secondary material for the construction sector. Saeli et al. [82] argued that biomass fly ash and effluents from kraft pulp mills can be incorporated into the production of mortars and geopolymeric binders. Ricciardi et al. [98] explored the use of agro-industry wastes resulting from coconut, corn, and cotton industries into the production of thermal and acoustic panels.

The Life-Cycle Assessment (LCA) method was the most used method to quantify environmental benefits of CE strategies in the built environment. Lozano-Miralles et al. [70]assessed the environmental impacts of clay bricks containing organic waste and concluded that the incorporation of vegetable additive to clay bricks might decrease the studied environmental impacts from 15% to 25%. Brambilla et al. [85] compared the environmental impacts of different structural composite floor systems and found out that the structural composite floor system that was designed for disassembly was identified as the most environmentally friendly compared to the typical one. Eberhardt et al. [83] quantified the potential environmental impacts of a building designed in line with CE principles and concluded that there are several factors affecting the overall embodied environmental impacts such as type of materials used, the reuse cycles, and building's service. In the same context, Cruz Rios et al. [87] claimed that reuse rates and transportation greatly influence the environmental impacts of reusing building materials and components.

Despite that several studies praised environmental benefits of CE approaches, Lederer et al. [59] highlighted the risk of introducing heavy metals into the materials loop, which is the case of using municipal solid waste incineration fly ashes into the production of cement that can hinder future recyclability of the final product. Likewise, some studies suggested economic benefits resulting from CE practices [96,104,163], whereas the lack of financial incentives into using secondary raw materials, labor cost for the deconstruction process, and the lack of governmental support might impede the CE uptake in the built environment [5,57,60].

6. Conclusions

The concept of CE has recently gained prominence among academia and stakeholders in the construction industry to improve resource efficiency and regulate waste management. In this paper, a review was conducted to determine criteria to select building materials and components following CE principles. A total of nine key selection criteria has been identified that cover three aspects: type of input, use stage, and end-of-life scenario. The most covered CE strategy was "recycled and recovered content" which refers to materials and components that include content from other product that reached their end-of-life. The least mentioned CE strategy was "biodegradability", which can be explained because the building industry hardly ever relies on bio-based materials.

Although CE recently gained massive attention from academia, professionals, and policymakers, current practices related to the concept rarely take an innovative approach to ensure resource efficiency. The use of recycled products or forecasting recycling to the existing building stock does not comprehensively promote CE. Cutting-edge technologies are required to move further from recycling and apply more economically viable and environmentally friendly CE strategies.

It is worth mentioning that numerous studies promoted the use of materials passport and other digital means such as web-based platforms and Building Information Modelling (BIM) to keep track of materials and components and assess the level of circularity in buildings. This novel approach can bring about CE by increasing collaboration between stakeholders and introducing automation for CE assessment.

Further research can be developed about the hierarchization of the identified criteria to assign weights to each criterion according to its priority to promote CE in the construction sector. Other sustainability dimensions, such as environmental, economic, and social, should be included to provide a more comprehensive approach under the UN's Sustainability Development Goals.

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Appendix A

The following Table A1 summarizes the main features and the covered CE criteria within each journal article included in the literature review.

Table A1. Summary of the reviewed journal articles.

Reference	Objective of the Study	Research Methods	Main Outcome	Covered CE Criteria
[56]	To explore the use of Sewage Sludge Ash as an input into construction materials to promote CE	Literature Review and exploratory study	The use of Sewage Sludge Ash as a substitute in construction materials can reduce environmental impacts and promote CE in the construction industry	- Recycled or recovered content
[57]	To determine the best practice for gypsum waste	Quantitative KPIs	17 KPIs were selected and applied to 5 European pilot projects and the results suggests that recycling gypsum at its end-of-life is more suitable than landfill from an economic standpoint	- Recycled or recovered content - recyclability
[103]	To quantify energy consumption and GHG emissions of gypsum recycling	LCA and MFA	Three gypsum recycling scenarios were compared and the results shows that recycling gypsum does not impact energy consumption throughout its lifecycle (mainly due to transportation and pre-processing). On the other hand, GHG emissions decreased when recycling rates were higher	- Recycled or recovered content - recyclability
[58]	To investigate the obstacles and motivations of deconstruction and building materials reuse in western Germany.	Survey and energy analysis of the deconstruction process	Despite the environmental benefits of deconstruction, the process still requires economic incentives, a trained construction team, and a special attention to the impacts on human-beings.	- Recycled or recovered content - reusability - recyclability - Ease for deconstruction - upcycling potential
[59]	To determine the applicability of using municipal solid waste incineration fly ashes as a cementitious material at the national level	MFA and case study	The use of municipal solid waste incineration fly ashes as a secondary material at certain rates can increase the content of heavy metals in concrete which will hinder the recyclability of the final product at its end-of-life according to the Austrian technical guideline for recycling construction materials	- Recycled or recovered content - recyclability

[60]	To investigate the use of olive oil production waste as an input to produce structural ceramic materials	Experimental study	Incorporating olive oil production waste in the production of ceramic material will decrease the amount of energy consumed during the manufacturing process while delivering good quality materials depending on the wet pomace content	- Recycled or recovered content
[61]	To study and measure the loss rates of steel while undergoing several products life cycles on a global scale	Global MaTrace which is a model based on input-output analysis, dynamic MFA, and LCA	One of the approaches to alleviate the loss of steel at its end-of-life is to use it as a secondary material in buildings as the latter have prolonged life-spans	- Recycled or recovered content
[55]	To provide insights on the challenges behind the lack of reuse of structural steel in UK	Literature review and semi-structured interviews	The main barriers to steel reuse in UK are cost, wrong client perception of reused steel, availability, traceability, and the time-consuming process of deconstruction	- Reusability - ease of deconstruction
[62]	To develop a new approach to MFA and quantify the recycling potential of construction materials for the German building stock	Extended MFA	There is a lack of use of recycled aggregates as a secondary material due to a loss during the recovery chain and the technical requirements for the replacement ratio in the German context	Recycled or recovered content - recyclability
[152]	To develop a BIM-based assessment methodology to measure the recovery potential of building materials at the design stage	Literature review, software simulation, and a case-study	A tool to estimate the amount of materials that can be recovered at the end-of-life of a building and their potential to be recycled or reused.	- Recyclability - reusability - ease of deconstruction
[63]	To analyze literature regarding the environmental assessment of buildings using LCA and identify the lack of CE integration	Literature review	A comprehensive framework to improve LCA of buildings in way that considers CE principles in the process	- Recycled or recovered content - recyclability - reusability - upcycling potential
[104]	To explore the environmental and economic feasibility of using cork as an insulation material for buildings retrofit	Environmental assessment (LCA) and economic analysis	Despite its environmental benefits, the use of cork as a thermal insulation material revealed to be more expensive than other materials. Still, cork boards can be recycled at their end-of-life and used as an input for new products	- Recycled or recovered content - recyclability
[64]	To identify regional sustainability benefits for bioproducts and highlight opportunities and barriers for the reuse of recovered wood	Survey and interviews for two case-studies	Hurdles might be encountered when attempting to implement CE in the wood industry due to a lack of governmental support and low demand for recovered wood from the construction industry	- Recycled or recovered content - recyclability - reusability
[65]	To develop a bituminous membrane for sound insulation with recycled materials	Experimental study	The new developed membrane can have different recycled materials (e.g., plastics, rubber, membranes), enhance acoustic performance, and be applied in different sectors such as construction and automotive sectors.	- Recycled or recovered content
[66]	To identify best approaches to implement CE principles in prefabricated buildings	Literature review	Seven strategies were developed to apply CE in prefabricated buildings such as design for disassembly, recyclability and reusability,	- Recycled or recovered content

			reduce raw materials input and rely on secondary materials, and design out waste	- recyclability - reusability - ease of deconstruction
[67]	To experimentally measure the release of polluting elements from extensive green roofs containing recycled materials	Experimental study	From an environmental perspective, extensive green roofs with up to 75% content of fine mixed recycled aggregate were acceptable	- Recycled or recovered content
[105]	To analyze literature regarding the Chinese perspective on construction and demolition waste	Literature review	Economic and governmental barriers are impeding the Chinese construction sector to shift towards sustainable practices and minimize waste generation	- Recycled or recovered content - recyclability - reusability - ease of deconstruction
[68]	To explore the level of understanding of CE in the construction sector and outline potential barriers to the concept's implementation	Survey	To enable a nation-wide CE implementation in the construction sectors, several technical and economic barriers needs to be overcome through specific CE guidelines and viable business models	- Recycled or recovered content - reusability - recyclability - ease for deconstruction - maintainability
[170]	To develop an assessment methodology for CE implementation in the construction sector	Literature review, the Delphi technique, and a statistical analysis	A set of indicators was developed to measure the CE implementation. According to the results the most important dimension was "energy" followed by the adoption of the 3Rs principles	- Recycled or recovered content - reusability - maintainability
[5]	To identify and classify potential barriers for CE implementation in managing C&DW	Literature review and MCDM	Twenty-two barriers for C&DW management were identified and classified under three dimensions: technical, behavioral, and legal.	- Recycled or recovered content - recyclability - reusability - upcycling potential
[69]	Environmental assessment of waste treatment following the L'Aquila earthquake	LCA	Local demolition debris treatment will offer various environmental and social benefits by minimizing transport and creating jobs	- Recycled or recovered content
[70]	To assess the environmental impacts of clay bricks containing organic waste	LCA	The incorporation of vegetable additive to clay bricks might decrease the studied environmental impacts from 15% to 25%	- Recycled or recovered content
[71]	To analyze current approaches for capital projects planning and propose a framework and a set of strategies to embed CE in these projects	Analytical research	A framework for capital project planning is proposed which includes adaptive reuse and building stock analysis. The adaptive reuse will offer economic and environmental benefits but it can be hindered by the labor costs and the building's complexity, thus it requires	- Recycled or recovered content – recyclability - reusability

			effective tools to predict the end-of-life scenario and associated impacts	- maintainability - energy recoverability
[72]	To experimentally investigate the mechanical feasibility of reclaimed timber to produce cross-laminated secondary timber	Experimental study	Minor defects on reclaimed timber will have slight impacts on the mechanical properties of cross-laminated timber, however a combination of primary and secondary feedstock will offer suitable mechanical properties for the latter	- Recycled or recovered content - recyclability - reusability - upcycling potential
[73]	To investigate the environmental and economic benefits of implementing CE principles in the C&DW sector	Literature review	Adopting CE in the C&DW sector offers various environmental and economic benefits depending on several factors such as type of buildings and materials involved, location, transport, and local economic and political context	- Recycled or recovered content - Recyclability - reusability
[153]	To evaluate the flows of non-structural building materials in the built environment to assess their replacement	Quantitative research and case-study	To shift towards CE and embrace recyclability and reusability in the built environment, it is crucial to quantify current material stock in the built environment	- Recyclability - reusability
[74]	To investigate the recyclability of vehicles at their end-of-life as a secondary material for the construction industry	Literature review and	The proposal of a framework to reuse and recycle vehicles as an input for the construction industry while taking into account the Malaysian context	- Recycled or recovered content - recyclability - reusability
[28]	To promote the use of timber to embrace CE principles in the construction industry	Analytical research	Design for disassembly is considered as an essential feature to be planned ahead to enable reuse of building elements	- Recycled or recovered content - recyclability - reusability - durability - energy recoverability
[75]	To improve resource efficiency in the construction sector by producing bricks with recycled content	Exploratory research and case-study	The production of bricks with secondary raw materials is technically feasible and requires cross-sectoral collaboration. Moreover, the produced bricks can be entirely recyclable at their end-of-life	- Recycled or recovered content - recyclability
[154]	To grasp the reason behind the short lifespan of residential buildings in Japan	Literature review and interviews	CE measures to extend buildings' lifespan along with governmental and economic support can be adopted to avoid premature demolition of social buildings	- Recyclability - reusability - ease of deconstruction
[36]	To quantify the environmental impacts of mortars with recycled content	LCA	The incorporation of recycled fine aggregates for the manufacturing of masonry mortars can decrease the environmental impacts with special attention to the transport of these secondary raw materials	- Recycled or recovered content
[76]	To test and valorize the use of fine particle product from	Experimental study	The treatment of quarrying waste with hydrocyclones can produce by-products that can	- Recycled or recovered content

	quarrying processes as a secondary raw material		replace typical raw materials in concretes and ceramics	
[77]	To experimentally test the technical feasibility of bricks containing waste thermoplastics	Experimental study	The results of compressive strength proved that thermoplastic wastes can be incorporated in bricks for up to 10%. This type of bricks has also high thermal resistance which can improve the energy efficiency of buildings	- Recycled or recovered content
[171]	To promote non-destructive testing as a method to assess the recovery of building materials	Literature review	The non-destructive testing can offer a valuable approach for waste management in the renovation process through technical assessment	- Recyclability - reusability
[78]	To identify material efficiency strategies and trade-offs in order to reduce GHG emissions resulting from the construction, automotive, and electronics sectors	Literature review	The most significant opportunity to reduce GHG emissions lies in the building sector. This can be achieved through material efficiency strategies such as intensifying the building's use, waste recycling, and the reuse of building elements	- Recycled or recovered content - recyclability - reusability - durability
[155]	To understand the relationship between green public procurement, CE, and sustainable development practices in the construction industry	Literature review	Public authorities can rely on green public procurement to support CE and lower environmental impacts of the construction materials by enhancing green awareness and establishing specific guidelines and standards	- Recyclability
[156]	To quantify the material stock of non-residential building and promote urban mining	Quantitative methodology based on Material Composition Indicator (MCI)	The implementation of CE strategies for the building stocks requires a quantitative approach to measure the in-use building materials for an accurate resource recovery	- Recyclability - reusability - durability
[54]	To promote the use of recycled aggregates in the construction industry	Exploratory case-studies	The incorporation of recycled aggregates in construction materials has been extensively studied and several case-studies have proved the feasibility of such practices from technical, economic, and environmental perspectives	- Recycled or recovered content
[38]	To highlight the role of business models and policies to promote the use of secondary materials to decarbonize the construction sector	Qualitative methodology	By relying on innovative business models and policy support, the secondary materials can potentially reduce the carbon footprint of the building sector	- Recycled or recovered content
[79]	To identify CE solutions to embed the concept's principles in the construction sector	Qualitative methodology	To enable CE strategies for an effective C&DW management, there is a need for governmental support and proper promotion and dissemination to raise awareness	- Recycled or recovered content - recyclability - reusability
[80]	To enhance the comprehensiveness and precision of building LCA assessment by including CE-related principles	LCA-based methodology	Adopting a resource recovery principle and waste management in different building life-stages can lead to a 63% reduction in harmful environmental impacts	- Recycled or recovered content - recyclability - reusability - energy recoverability

[81]	To provide a design technique for truss structures using reclaimed components and explore their environmental benefits	Structural optimization and case-study	Designing truss structures using reclaimed elements implies higher complexity and precise techniques. Still, structures made of reused elements resulted in lower embodied energy and carbon	- Recycled or recovered content - reusability - ease of deconstruction
[82]	To investigate the use of waste generated from the pulp mill in geopolymeric binders and mortars	Experimental study	The use of biomass fly ash and an alkaline effluent from the kraft pulp industry in the production of mortars and geopolymeric binders resulted in construction products with decent workability and mechanical properties	- Recycled or recovered content
[50]	To explore the use of recycled materials as fibers in reinforced concrete	Literature review	In spite of an extensive experimental research on the use of recycled materials as fibers in reinforced concrete, there is still a lack of specific research regarding the environmental, economic, and social benefits of these products	- Recycled or recovered content
[83]	To quantify the potential environmental impacts of office building applying CE principles using a simplified allocation method	LCA and case-study	The findings suggest that the type of materials used, the reuse cycles, and building's service life greatly affects the overall embodied environmental impacts	- Recycled or recovered content - recyclability - reusability - ease for deconstruction - energy recoverability
[84]	To identify the main aspects that lead to the adoption of CE in the C&DW sector	Literature review	A theoretical framework to define the relevant CE strategies that can be applied in five lifecycle stages of the construction sector	- Recycled or recovered content - recyclability - reusability - energy recoverability - maintainability
[157]	To provide a tool to assess building's end-of-life performance at the early stage	Software simulation, BIM, and case-study	A platform relying on BIM to ensure that buildings are designed under CE principles when they reach their end-of-life	Recyclability - reusability - energy recoverability - ease for deconstruction
[85]	To assess and compare the environmental impacts of different structural composite floor systems	LCA and case-study	The structural composite floor system that was designed for disassembly was identified as the most environmentally friendly compared to the typical one	- Recyclability - reusability - energy recoverability - ease for deconstruction
[86]	To analyze efficient C&DW management strategies for a Greek island	Mixed methods approach based on dynamic MFA	With only 14% recycling rate of C&DW, Samothraki needs the implementation of effective CE-related strategies in order to reach the EU recycling target of 70%	- Recycled or recovered content - recyclability - reusability

[158]	To develop a BIM platform for the construction supply chain and calculate C&DW generation from the design stage	Software simulation and BIM	Using a collaborative platform to predict the building's end-of-life scenario from the design stage could minimize C&DW generation	- Recyclability - reusability
[87]	To quantify the environmental impacts of the reuse of building components	LCA	Transportation and reuse rates greatly influence the environmental impacts of reusing building materials and components	- Recycled or recovered content - recyclability - reusability - ease for deconstruction - energy recoverability
[88]	To identify practices within the literature regarding the minimization of life cycle energy and carbon emissions using computer simulation	Literature review	The use of BIM to optimize the life-cycle design of buildings revealed to be a key enabler for CE strategies	- Recycled or recovered content - reusability - recyclability
[159]	To highlight the current obstacles to implement CE strategies in 3 Dutch cities	Literature review, desk research, and interviews	One of the identified barriers is the lack of governmental support and CE-related instruments regarding the use of secondary materials	- Recyclability - reusability
[89]	To investigate the technical feasibility of incorporating recycled concrete aggregates in precast concretes and assess their associated impacts	Experimental study and LCA	Despite lower mechanical and durability properties for precast concretes incorporated with different ratios of recycled concrete aggregates, the final products still met the technical requirements	- Recycled or recovered content - recyclability - reusability - durability
[90]	To explore the process of using materials passport platform (Madaster) to assess building products used in a circular building	Documentation, quantitative study, and case-study	Using the Madaster platform, the results revealed that 96% of the assessed building is circular with a ratio of 92% of recoverable elements	- Recycled or recovered content - recyclability - reusability - durability - energy recoverability -
[91]	To develop a methodology to analyze and measure environmental and economic benefits of adaptive reuse for existing buildings' structure	LCA, BIM, LCC, and a case-study	From an environmental perspective, avoiding the use of new construction materials resulted in lower impacts, whereas economic profitability was noted when structural subsystems undergo an adaptive reuse	- Recycled or recovered content - recyclability - reusability - ease for deconstruction
[92]	To investigate the incorporation of electric arc furnace dust in self-compacting mortars at different ratios, and promote their harmless impacts	Experimental study	The results showed, that from a mechanical perspective, it is possible to incorporate up to 25% of electric arc furnace dust as cement replacement in self-compacting mortars	- Recycled or recovered content

[93]	To develop and test a binder based on biomass ash, lime hydrate, and metakaolin to produce lightweight mortars	Experimental study	The lightweight mortars with biomass ash presented good technical performances, which can promote its use as a secondary raw material and avoid ash disposal	- Recycled or recovered content
[94]	To investigate the use of plastic wastes as additives in the production of unfired clay bricks	Experimental study	Higher ratios of clay replacement by polymeric waste with smaller grain size resulted in low-cost lightweight clay bricks as the bulk density was lower	- Recycled or recovered content
[95]	To analyze the literature and identify key CE strategies for low-carbon construction materials	Literature review	One of the identified approaches to reduce the GHG emissions from 30% to 65% is to rely on recycled or reused materials as secondary resources	- Recycled or recovered content - recyclability - reusability - upcycling potential
[96]	To highlight the issues of C&DW activities in Romania and provide future pathways towards more sustainable management.	Literature review and theoretical framework	One of the proposed solutions to overcome poor C&DW management is to support the use of recycled aggregates and create economic incentives	- Recycled or recovered content - recyclability - reusability
[97]	To verify whether the use of materials passports can improve the recyclability of buildings at their end-of-life	BIM, material passports, case-study	Using material passport helped to assess and optimize the recyclability of buildings. The findings suggest that buildings with high recycling potential do not necessary lead to low environmental impacts due to several factors such as the total mass of waste generation	- Recycled or recovered content - recyclability - reusability
[98]	To explore the use of agro-industry waste in the building sector as insulation panels	Literature review	Thermal and acoustic panels produced from the waste of coconut, corn, or cotton presents good performances compared to common ones	Recycled or recovered content
[99]	To review current research regarding CE in the built environment and highlight the gaps to support the concept's implementation	Literature review	The main investigated topic within the CE studies is the reuse of C&DW. Still, one of the identified obstacles to implementing CE in the built environment is the lack of incentives regarding such practices.	- Recycled or recovered content - recyclability - reusability - ease for deconstruction - durability
[100]	To understand and compare C&DW management between China and the USA	Literature review	Among the recommendations to tackle C&DW issues is to ensure a governmental support and setup economic incentives	- Recycled or recovered content - reusability - recyclability
[101]	To investigate the use and feasibility of cellulose fibers recovered from wastewater into non-structural mortars	Experimental research	The use of recovered cellulose fibers in mortars proved economic and technical feasibility as the additions of these fibers enhanced some physical and mechanical aspects of the final product	- Recycled or recovered content
[106]	To study the recent progress in literature regarding the implementation of CE	Literature review	The implementation of CE requires an early consideration right from the design stage to	- Recycled or recovered content

			allow a projected reuse of materials and components at the building's end-of-life	- recyclability - reusability
[102]	To develop a methodology for urban mining at the city level and assess the recovery and reuse potential of construction components in residential buildings	An extended dynamic MFA and case-study	The developed urban mining assessment methodology provided insights on the potential of reintroducing the recoverable and reusable materials as low-cost secondary materials into the built environment	- Recycled or recovered content - recyclability - reusability - ease for deconstruction - upcycling potential
[2]	To calculate the inflows and outflows of residential and service buildings stock in 26 regions between 1970 and 2050	A modelling methodology for buildings stocks	A growth of 50% of the residential building stock is expected by 2050. The findings also suggest that by that time, only 55% of the demand for construction materials such as steel and wood will be achieved by recycled building materials.	- Recycled or recovered content - Recyclability
[107]	To support CE by proposing a database acting as a material and component bank to enable their recycling and reuse at buildings' end-of-life stage	Literature review and theoretical framework	The database can be linked to a BIM model to optimize the recycling and reuse of building materials and components throughout different stages of the construction process	- Recycled or recovered content - recyclability - reusability - durability - ease of deconstruction - maintainability
[168]	To experimentally test and validate the mechanical performance of demountable shear connectors in steel-concrete beams	Experimental study and software simulation	The results showed that using bolts with nuts on both ends of the steel flange can be used as shear connectors that will be able to be disassembled	- Reusability - ease of deconstruction
[30]	To understand the drivers and incentives for recovering building materials and components for reuse	Literature review, semi-structured interviews, and analytical research	The demolition contractor will consider reuse if three requirements are met: identifying financial incentives, proper knowledge for disassembly, and manage future performance	- Recycled or recovered content - Recyclability - Reusability - ease of deconstruction - durability
[108]	To study the feasibility of incorporating electric arc furnace dust as a cement replacement in mortar	Experimental study	The use of electric arc furnace improved the mechanical properties of mortars compared to the reference. However, due to the presence of lead (Pb), these mortars were classified as hazardous	Recycled or recovered content
[109]	To compare carbon emissions and CE indicators of two production processes based on different system boundaries	Quantitative research and case-study	The use of recycled content in the production of stonewool and extruded polystyrene resulted in lower carbon footprints in two different system boundaries (cradle-to-gate and cradle-to-site)	- Recycled or recovered content - recyclability

[110]	To propose a methodology to optimize the reuse of building elements and quantify the environmental impacts of this practice	Literature review, software simulation, BIM, LCA, and case study	The developed methodology was used on a case-study and the authors concluded that for an effective reuse of load-bearing elements, concepts such standardization and design for reuse should be generalized	- Recycled or recovered content - reusability - ease for deconstruction - energy recoverability
[111]	To compare the C&DW management in Brazil, USA, and European Union (EU), and outline the differences and similarities	Data collection and analysis	The study concluded that the C&DW management in Brazil, in comparison to the EU and USA is confronted to several hurdles such as lack of economic incentives, lack of governmental support, and low quality of recycled materials.	Recycled or recovered content - recyclability
[112]	To explore the C&DW management in Qatar and report on the benefits of using recycled aggregates	Literature review, SWOT analysis and case study	Seven strategies were identified to increase the use of recycled aggregates in the construction industry, to list a few: raising awareness among construction stakeholders, relying on LCA to highlight the environmental benefits, and establishing a market for secondary materials	- Recycled or recovered content - recyclability - reusability - durability
[113]	To develop a BIM-based platform to store information regarding materials and components to manage their recycling and reuse	Software simulation and BIM	The developed web-based tool can store all the relevant characteristics of materials and components to provide building stakeholders insights regarding waste management	- Recycled or recovered content - recyclability - reusability - durability - ease for deconstruction
[114]	To analyze the inflows and outflows of construction materials in a Chinese district	MFA	The study revealed that while considering the inflows and outflows of construction materials, the amount of reused or recycled materials has been comparatively low due to technical and economic factors	- Recycled or recovered content - recyclability - reusability
[115]	To introduce a special issue regarding solutions to lower the carbon footprint of the built environment through CE principles and resource efficiency	N/A	N/A	- Recycled or recovered content - durability
[116]	To analyze and compare current approaches to quantify environmental impacts related to the reuse and recycling of building elements through a case-study	Literature review, LCA, and case-study	The current LCA methodologies do not take into account the environmental benefits of reusing building elements at their end-of-life due to several factors such as the disassembly of the components and their degradation when undergoing a use/reuse cycle	- Recycled or recovered content - recyclability - reusability - ease of deconstruction - energy recoverability

[117]	To analyze the type and flow of materials resulting from C&DW and determine their potential of reuse and recycling	MFA and case-study	Recycling C&DW as secondary raw materials to produce concrete, bricks, asphalt can reduce the reliance on virgin raw materials and support waste minimization	- Recycled or recovered content - recyclability - reusability
[118]	To experimentally test the technical feasibility of using cooking oil to produce bio-foams as an insulating material	Experimental study	The production of bio-foams using cooking oil exhibited good technical performances which offers a promising approach to waste oil	- Recycled or recovered content
[29]	To highlight the complexity of applying CE principles in buildings to extend their service-life and close materials-loop	Literature review	Reversibility and durability are two potential indicators to improve the building's design in line with CE principles. However, there is a lack of addressing these two indicators in CE assessment at the building level	- Recycled or recovered content - recyclability - reusability - durability - ease of deconstruction - biodegradability
[27]	To analyze CE-related literature and identify barriers and opportunities to apply the concept in the construction industry	Literature review	A framework to implement CE in the building industry was developed and several strategies, such as durability of construction materials, governmental support, and adequate CE design approaches have been judged critical for CE adoptions.	- Recycled or recovered content - recyclability - reusability - durability - ease of deconstruction - maintainability
[119]	To study and analyze the design approach as well as the thermal performance of a bio-based ventilated façade	Experimental study	The façade is made from recyclable and bio-based materials which ensure low environmental impacts with indoor air quality. Moreover, the ventilated façade can be disassembled at its end-of-life to be reassembled in another location	- Recycled or recovered content - recyclability - reusability - ease of deconstruction
[120]	To test and validate the feasibility of the heating-air classification system as a process to treat ultrafine recycled concrete	Experimental study and LCA	The optimal replacement ratio of cement by ultrafine recycled concrete was 5%. Additionally, all the assessed environmental impacts of concrete with this ratio were reduced by 5%	- Recycled or recovered content - recyclability
[121]	To assess and compare the environmental benefits of CE practices and conventional ones at a country level	LCA and case-study	Applying CE principles in residential buildings can at least reduce the environmental impacts by 16%. Likewise, at the country level, adopting reuse and recycling resulted in environmental benefits	- Recycled or recovered content - recyclability - reusability
[122]	To assess the environmental impacts of using shipping	LCA	Using shipping containers as structural elements showed environmental benefits in comparison to a typical steel structure. However,	- Recycled or recovered content

	containers as building components		these environmental benefits are tightly dependent of the waste transportation from depot to manufacturing	
[123]	To develop a framework for measuring and enhancing the sustainability of technologies integrating thermal energy storage as an approach to shift towards CE	LCA and case-study	Recycling the materials involved in the studied building-like cubicle at its end-of-life decreased the environmental impacts by 5%. While including recycled content in the early stage resulted in 30% less environmental impacts.	- Recycled or recovered content - recyclability
[124]	To and analyze the technical feasibility of reinforced cement mortars designed for coating which incorporate recycled fibers	Experimental study	The study showed that recycled fibers have similar physical and mechanical behaviors to commercialized fibers when used to reinforce cement mortars for external coating, which confirms their technical feasibility	- Recycled or recovered content
[125]	To investigate and categorize hurdles and drivers for building elements reuse and outline possible actions to overcome these barriers	Literature review	The most influential barrier to building component reuse is the economic aspect considering the time and labor needed to deconstruct a building in addition to a lack of demand for reused items.	- Recycled or recovered content - recyclability - reusability - ease of deconstruction
[126]	To shed the light on new and existing C&DW and outline a framework to aid decision-making regarding their future use in construction projects	Multi-criteria analysis	According to the selected criteria, the most adequate C&DW and by-product is fly ash followed by recycled concrete.	- Recycled or recovered content - recyclability
[49]	To review current literature regarding CE-related practices in buildings and quantify their feasibility in this sector	Literature review	The CE strategy that was the most covered by the selected literature was building disassembly, followed by materials selection. The authors identified the lack of measuring the environmental benefits of CE as a potential obstacle for implementing the concept	- Recycled or recovered content - recyclability - reusability - ease of deconstruction - durability - maintainability - energy recoverability
[127]	To study the relationship between building conservation and CE practices	Literature review	Merging building conservation and CE can support the preservation of the built environment. However, both approaches are confronted to the same obstacles such as low-cost virgin materials and high-cost labor.	- Recycled or recovered content - recyclability - reusability - maintainability - energy recoverability
[40]	To assess and compare the environmental impacts of indoor flooring systems from cradle-to-cradle	LCA and sensitivity analysis	Despite having heavier impact factors in the manufacturing process, inorganic floors showed better environmental performance due to their low need for maintenance	- Recycled or recovered content - recyclability

				- maintainability
[128]	To integrate MFA with stakeholders' objective and regional policies as an approach to model materials stock and predict future inflows and outflows	Literature review, MFA, survey, and case-study	The results show that most influential policy measure is increasing taxes and costs on virgin resources, followed by increasing disposal fees and raising awareness among stakeholders. These measures combined can lower the material flows between 2018 and 2030.	- Recycled or recovered content - recyclability
[160]	To study the leaching behavior of concrete containing lead slag as a partial replacement of fine aggregates, in real and laboratory conditions	Experimental study and software simulation	The mechanical and leaching characteristics of solidified products with 25% of slag can be considered as satisfying. However, the release of Arsenic from these products hinders the use of alkaline lead slag in concrete as fine aggregate replacement	- Recycled or recovered content
[161]	To identify the benefits and opportunities of green buildings compared to traditional ones	Cost-benefit analysis	Despite their high initial cost, timber and hemp, can ensure better insulation which will lead to economic and environmental benefits as they can be reused or recycled at their end-of-life	- Recyclability - reusability
[129]	To quantify and estimate the amount of construction materials stocked in buildings, roads, and sidewalks in two Canadian cities	Bottom-up quantitative analysis and case-study	The results indicate an increase in the material stock by 2041 with higher waste generation in both cities. The author also highlighted the need for better C&DW management as recycled materials are being underused	- Recycled or recovered content - recyclability - maintainability
[130]	To identify and evaluate current practices and barriers to apply CE principles for buildings envelope layers	Literature review and analytical study	The authors identified twenty key circular performance criteria to assess the feasibility of embedding CE in current timber wall construction. Among the identified hurdles for CE adoption, the authors referred to chemical connections which impede reversible design and a lack of standardized geometry.	- Recycled or recovered content - recyclability - reusability - durability - ease of deconstruction - upcycling potential
[6]	To review and analyze the implementation of CE across European countries in various sectors based on several frameworks	Literature review	The construction industry is one of the most prioritized sectors to shift towards CE practices. Among the analyzed frameworks, the authors concluded that "recycling" is the most adopted CE strategy to keep materials in closed-loops	- Recycled or recovered content - recyclability - reusability - maintainability - durability - energy recoverability
[131]	To assess environmental impacts of buildings and identify the source of largest GHG and propose a CE approach to tackle this issue	LCA and case-study	Adopting CE strategies in buildings such as reuse of materials and components, adequate materials selection according to their technical and environmental performances, and forecasting reuse and recycling for building	- Recycled or recovered content - recyclability - reusability - durability

			materials, can reduce the overall embodied GHG of buildings.	- energy recoverability
[132]	To propose a CE assessment methodology for the building materials and components in accordance to design for disassembly criteria and embodied environmental impacts	Mixed-methods approach and case-studies	The inclusion of design for disassembly criteria such as accessibility and types of connections, can have a better assessment for the end-of-life scenario of building materials and components.	- Recycled or recovered content - recyclability - reusability - ease of deconstruction
[133]	To review and organize current knowledge regarding CE approaches in European and Chinese cities	Literature review	The authors identified a research gap regarding CE implementation in the construction sector which is the lack of buildings LCA studies to highlight the benefits of CE strategies	- Recycled or recovered content - recyclability - reusability - maintainability - ease for deconstruction - energy recoverability
[19]	To bridge the gap of the lack of CE indicators regarding the adaptive reuse of cultural heritage buildings by developing a comprehensive framework	Analytical research	The developed framework comprises 20 CE-related environmental indictors. The proposed indicators tackle aim at reducing the energy and water use and promote the reuse and recycling of building materials and components in and off-site.	- Recycled or recovered content - recyclability - reusability
[134]	To assess the environmental performances of using recycled brick waste as aggregate replacement, cement replacement, or as a precursor for alkaline activation	LCA	From an environmental perspective, the best scenario for using recycled brick waste was to partially replace cement, while using brick waste as recycled aggregate did not provide considerable environmental benefits.	- Recycled or recovered content - recyclability
[169]	To propose a new strategy to reuse metal waste from the automotive industry as building facades and quantify the environmental impacts of such practice	Experimental study and LCA	One of the design strategies for building facades proposed by the authors showed less environmental impacts and more economic profitability. The authors concluded that the environmental and economic impacts of the design approach depend on the aesthetics and functionalities	- Reusability - durability - upcycling potential
[135]	To study the mechanical, physical, and durability performances of façade panels produced with C&DW in both laboratory and real conditions	Experimental study	The findings confirmed the technical feasibility of façade panels produced with C&DW aggregates as they demonstrated satisfactory results.	- Recycled or recovered content - durability
[136]	To assess the quantity of bricks used in external walls of residential and office buildings to predict their further reuse as an approach to enable urban mining	LCA, quantitative research, and case-study	The developed model comprises four critical features, spatial and temporal dimensions, embodied carbon, and building typologies, which can accurately provide an estimation of in-use bricks to outline future pathways for their reuse and recycling	- Recycled or recovered content - recyclability - reusability

[137]	To investigate the physical, mechanical, and environmental properties of concretes containing alternative fine and coarse aggregates derived from different sectors	Literature review	The substitution of fine aggregates by ground granulated blast furnace slag, electric arc furnace dust, and ceramic powder, improved some of the properties of concretes such as durability and workability.	- Recycled or recovered content - durability
[138]	To investigate and evaluate the performances of lightweight aggregates by using waste glass, slag, and waste sediment	Experimental study	The lightweight aggregates that were produced with waste glass, basic-oxygen-furnace slag, and dredged harbor sediment showed good mechanical and physical properties in addition to offering economic benefits compared to typical lightweight aggregates	- Recycled or recovered content
[139]	To study the mechanical and physical properties of concretes produced with silica stone waste as a cement replacement	Experimental study	The results showed that the optimum replacement ratio was 5% as it improved the mechanical properties and the microstructure of the final product	- Recycled or recovered content
[162]	To quantify and compare the environmental benefits of recycling and reuse at building level	Literature review, LCA, and case-study	The circular building, which is designed and built for disassembly, allows a reuse of 62% of the mass of the building and reduces GHG emissions by 88% along with other environmental benefits	- Recyclability - reusability - ease of deconstruction
[140]	To use the date from LEED and waste reclamation facilities to quantify C&DW flows	MFA and case-study	Between the period of 2007 and 2017, 81% of the total of C&DW generated in Philadelphia was diverted and used into the production of secondary raw materials	- Recycled or recovered content - recyclability
[141]	To investigate the mechanical properties of composite lightweight slab made of wooden joist and mortar produced with recycled aggregates	Software simulation and Experimental and analytical study	The mortars produced with expanded clay aggregates and recycled fines showed satisfactory mechanical behaviors. Similarly, the incorporation of this type of mortars in the studied slab increased the mechanical strength	- Recycled or recovered content
[142]	To study the effects of sodium salts on the production of lightweight aggregates synthetized from sludge marine clay	Experimental study	The authors concluded that adding the Sodium Carbonate is beneficial for the production of ultra-lightweight aggregates from sludge marine clay	- Recycled or recovered content
[143]	To study the feasibility of producing mortar blocks incorporating Polyurethane Foam and electric arc furnace and test their thermal and mechanical behaviors	Experimental study, software simulation, and case-study	The produced mortar blocks from recovered materials exhibited similar thermo-mechanical properties to conventional mortar blocks which validates their usability	- Recycled or recovered content
[163]	To quantify the amount of construction materials stored in buildings and infrastructures and inform about their spatial distribution	Quantitative research and case-study	The significant amount of construction materials stocked in the built environment can inform key-stakeholders about the next steps towards urban mining and CE as an approach for better C&DW management	- Recyclability - reusability
[164]	To explore the end-of-life scenarios of external thermal insulation composite systems	Analytical research	Using specific treatment, the expanded polystyrene can be recovered from the external thermal insulation composite systems and	- Recyclability - energy recoverability

	made with expanded polystyrene		separated from other impurities to be further recycled	
[144]	To quantify the environmental impacts of rammed earth materials containing crushed bricks and concrete and other by-products	Experimental study and LCA	Results suggest that using recycled feedstock in rammed earth materials reduced GHG emissions by up to 73% when compared to a typical cavity brick. Additionally, transportation remains a crucial factor that needs to be considered to reduce GHG emissions	- Recycled or recovered content - durability
[145]	To quantify the material stock in French residential buildings to predict their further reuse as recycled aggregates and highlight the barriers set ahead for such practice	MFA and case-study	The results show that a reduction of 15% to 19% in natural aggregate extraction can be achieved through the recycling of current materials stocked in French residential buildings into aggregates	- Recycled or recovered content - recyclability
[146]	To investigate the effectiveness of rejuvenators to retrieve the desirable properties in aged asphalts	Experimental study and software simulation	The use of certain rejuvenators restored chemical, mechanical, and physical properties of aged asphalts which made them eligible for recycling	- Recycled or recovered content - recyclability
[165]	To promote the use of the indicator waste diversion rate as a means to better improve the C&DW management	Desk research and case-study	The average waste diversion rate in residential projects in Australia is 64%. The findings suggest that this rate will further increase by 2025 to reach 78%. However, several barriers can hinder the recycling of C&DW such as the lack of economic incentives and governmental support	- Recyclability - reusability - energy recoverability
[166]	To quantify the material flows and their associated GHG in a neighborhood over a period of 60 years to better understand the potential of material efficiency strategies	Dynamic MFA, LCA, and case-study	Adopting the following material efficiency strategies; extending the lifetime of buildings, intensifying their use, and improving material productivity, can reduce the embodied GHG by 44%	- Recyclability - reusability - upcycling potential
[147]	To present a platform for construction project management that includes technical standards and specifications, assessment tool for CE, and a database, among other features	Analytical research	The developed platforms incite stakeholders into using secondary materials and will promote green public procurement through an assessment tool for circularity and sustainability and ensuring the compliance to technical and environmental criteria	- Recycled or recovered content - recyclability
[148]	To investigate the use of Waelz slag as a clay replacement into the production of ceramic bricks	Experimental study	The maximum replacement ratio of clay by Waelz slag in the production of ceramic bricks was found to be 10%. Further replacement ratio can compromise the technical properties of the final product	- Recycled or recovered content
[149]	To study the technical feasibility of incorporating glass waste in gypsum composites	Experimental study	Adding glass waste in gypsum composites significantly improved mechanical and physical properties of the final product when compared to the reference	- Recycled or recovered content
[167]	To understand the relationship between BIM and Lean construction to enhance the deconstruction process	Analytical research	The BIM-Lean matrix revealed seventy-three interactions, which suggests that BIM functionalities and Lean principles have high compliance ratio in deconstruction projects	- Recyclability - reusability - maintainability

				- ease of deconstruction
[150]	To highlight the need for a virtual marketplace as a platform for creating economic profitability out of wastes and by-products	Analytical research	The proposed platform can act as a network of users interested in collaboration and increasing the value of recycled materials and by-products	- Recycled or recovered content - recyclability
[151]	To study the development of ceramic tiles incorporating waste glass and fly ash that have new smart functionalities	Experimental study	The developed glass-ceramic tiles can be used as smart coating with different functionalities such as self-cleaning, anti-slip in wet surfaces, and in the automation of a building	- Recycled or recovered content

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