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MDPI

Review

Circular Material Usage Strategies and Principles in Buildings: A Review

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Abstract: Building construction accounts for a significant proportion of global greenhouse gas emissions, raw material extraction, and waste production. Applying circular economy (CE) principles in the building construction industry would considerably reduce these values. However, uptake by the industry is relatively slow, which is largely attributed to sectoral barriers, including limitations in knowledge and experience. This review paper aims to assess and contribute to diminishing these obstacles by offering a comprehensive review of circular material usage principles and strategies within the construction sector. Opportunities and facilitators of change are also presented, including innovations and emerging technologies in recycling, digitization, robotic systems, novel materials, and processing. Finally, four case studies demonstrate the application of circular theory via a novel block system, recycled aggregate, modular kitchen reuse, and an energy efficiency retrofit. The conclusions show that future efforts should prioritize the development of strong regulatory frameworks, awareness initiatives, and international cooperation. In this regard, the integration of technological advancements, such as AI, robotics, and blockchain, is essential for optimizing waste management efficiency. Furthermore, education on circular practices plays a critical role. Through global collaboration, standardizing circular construction approaches can promote a more sustainable and resilient building construction industry.

Keywords: circular economy; buildings; circular materials; strategies; principles; review

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1. Introduction

The EU has agreed to reduce greenhouse gas emissions by 55% (of 1990 levels) by 2030 and to become carbon neutral by 2050 [1]. The construction industry is a critical sector because it accounts for 5–12% of total greenhouse gas emissions through material extraction, construction product manufacture, and building work. This includes the production of cement, aluminum, steel, brick, and glass, which contributes approximately 9% of global energy related CO_2 emissions [2].

Furthermore, the sector is a lead consumer of raw materials, accounting for approximately 50% of global extracted material [3], including finite resources such as cement and metals. Mineral aggregates, such as sand and gravel, which are extensively used in buildings and construction as concrete, asphalt, and glass, are the largest extracted material group in the world [4]. Scarcity of supply, high demand, and resulting increasing prices have led to illegal extraction activities, including that of river sand [5]. Natural alluvial sand is essentially a nonrenewable resource consumed in the making of materials such as concrete and plaster, leading to a global sand crisis and research into alternative substitutes [6,7]. In addition to this, the European Commission (EC) has defined a list of "Critical Raw Materials". These materials and minerals are crucial to Europe's economy and need to be maintained to meet growing demands in expanding sectors such as renewable energy and digital technologies [8]. Examples include coking coal, which is used in steelmaking [9], and bauxite used in aluminum production [10]. The European Commission (EC) proposed the Critical Raw Materials Act [11] in 2023, intending to make the European Union (EU) more competitive and sovereign by boosting the research and development of alternative materials and more sustainable mining and production. This is a consideration in building design and also for demolition and waste management because many of these materials are already locked inside existing buildings.

Not only does the construction sector contribute significantly to emissions and material extraction but it also represents a major source of waste in the European Union. This is commonly called construction and demolition waste (CDW), which accounts for 36% of total waste generated, according to 2018 figures [12]. A total of 10–15% of building material is wasted during the construction phase [13]. Recycling rates for CDW vary greatly across Europe, from 10% to 90% [14]. Although soil represents the largest portion of CDW, this is closely followed by concrete, brick, gypsum, wood, glass, metal, plastic, and solvents in EU-27 countries [15]. This waste stream has a high resource value, but it also a high potential for reuse and recycling [12].

Despite stringent financial penalties, illegal disposal practices, such as fly-tipping of CDW, persist (Figure 1). The EU has, therefore, made the management of CDW a priority [14]. The Waste Framework Directive (WFD) 2008/98/EC [16] set a mandatory recovery target of 70% recovery rate by weight for CDW by 2020. These recovery efforts encompass various activities, including the preparation of nonhazardous CDW for reuse, recycling, and other material recovery operations, inclusive of backfilling [12].

Figure 1. Illegal dumping of construction and demolition waste (CDW) in Romania (Source: Mihai [17]).

The adoption of circular building materials and practices has been gaining momentum as a means of curtailing energy consumption, emissions, raw material extraction, and waste generation from the sector. A circular economy (CE) has the potential to reduce global CO_2 emissions from building materials by 38% by 2050 [18,19], which would contribute significantly to achieving a net zero EU. The CE is a production and consumption model that aims to retain the value of existing materials and resources for as long as possible, while minimizing waste [20]. It is a departure from the traditional linear economy model of "take-make-dispose", in which materials are extracted, manufactured into products, and ultimately discarded. Instead, it focuses on creating a closed-loop system in which materials are continuously reused, recycled, or regenerated. Although there is no universally accepted definition of a circular built environment [21], it is increasingly recognized that a circular approach to the sector could provide a sustainable solution to meet growing demands without exacerbating environmental degradation.

This paper presents a review of circular material usage principles and strategies within the construction sector. First, the methodological approach is outlined. This is followed by an explanation of key circular economy and material usage concepts. The main principles for circular material usage at the design stage and for construction activities are then outlined. Finally, examples of these concepts in practice are illustrated using selected case studies. It is expected that the research findings can contribute to the development of future research and provide valuable content for the academic and professional community interested in the circular economy and its application in various sectors, including the construction industry.

2. Methodology

In this chapter, the VOSviewer software (https://www.vosviewer.com/) for bibliometric analysis was utilized to examine the knowledge domains and trends related to the circular economy in the construction sector. The analysis aimed to identify patterns, relationships, and clusters of research articles, providing valuable insights into the field.

2.1. Bibliometrics Search

Considering the aim of this paper to review circular material usage principles and strategies within the construction sector, a literature review was conducted, followed by a scientometric analysis. Scopus was the selected database for the review, and a first search was conducted using the keywords “circular economy”, resulting in a total of 3.973 review articles on the topic. The search revealed that the concept of the circular economy began to emerge in 2004. Since then, there has been a significant increase in the number of published articles, with potential growth in the following years, particularly in 2019.

This growth has had a greater impact, both academically and in the development of concepts related to the circular economy. Over the years, new keywords have been developed for this circular economy concept, demonstrating its increasing importance in the construction of knowledge in this field. Figure 2 shows the results of the impact analysis using different keywords such as sustainability, renewable energy, sustainable development, and climate change. This bibliometric analysis allowed us to identify the most used and relevant keywords in the field of study.

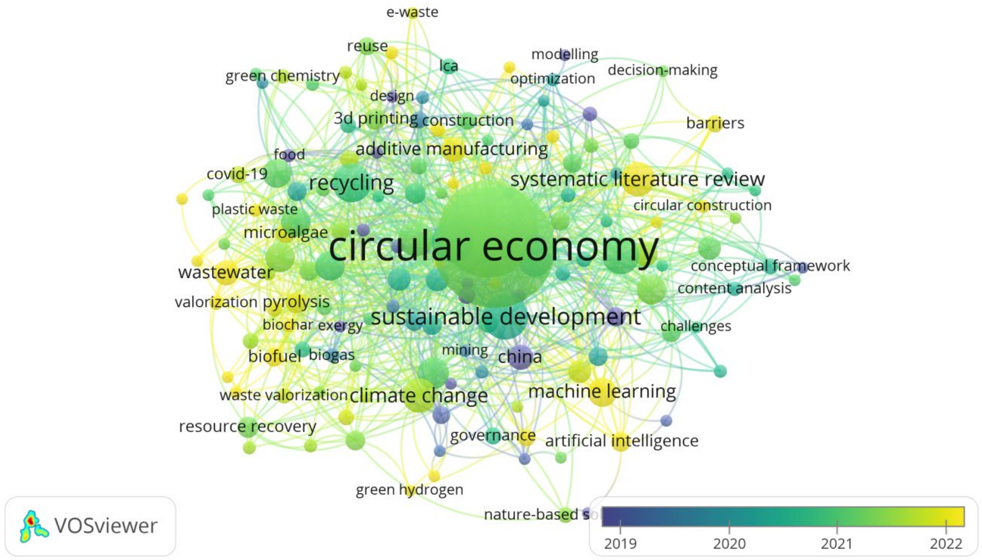


Figure 2. Keyword network between publications on the circular economy (Source: VOSviewer—Visualizing scientific landscapes).

Based on the results of this first search, we selected the keywords circular economy, buildings, circular materials, strategies, principles, and review for this research paper. These keywords were chosen based on their alignment with the existing literature in the field of circular economy, which provides confidence in the relevance and pertinence of the research. By focusing on these keywords, we aim to explore the advances, trends, and perspectives related to the circular economy in the specific areas of buildings, circular materials, policies, principles, and review.

The approach chosen for this paper involves a critical analysis and synthesis of selected articles, identification of patterns and gaps in the existing literature, and generation of valuable insights into the field of study. Figure 3 outlines the connection between the research results with the keywords mentioned.

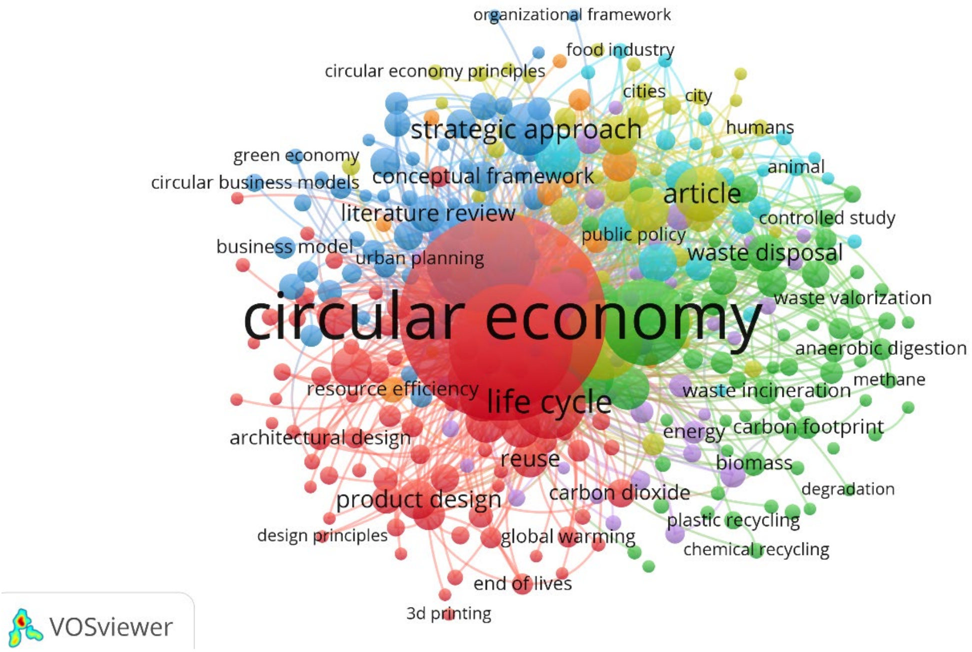


Figure 3. This article's keyword network in circular economy publications (Source: VOSviewer—Visualizing scientific landscapes).

In collecting this information, an analysis was made of the number of countries that have made efforts to research and publish material on the circular economy over the years. Significant growth has been observed in this area, particularly in countries with a global impact, as can be seen in Figure 4.

Countries that stand out in terms of research and development on the circular economy include Italy, China, Canada, the United Kingdom, and France. These countries have shown a remarkable commitment to investing in education and developing initiatives related to the circular economy. Italy was recognized for its leadership in implementing circular strategies, such as waste management, and promoting circularity in different sectors. China, on the other hand, has made significant efforts to transition to a more sustainable economy, with a focus on resource efficiency and emissions reduction. Canada focuses on the circular economy in areas such as waste management, renewable energy, and sustainable production. The UK has put in place strong legislation and support programs to promote the circular economy, particularly in sectors such as construction and manufacturing. France has implemented ambitious policies and strategies to promote the circular economy, with a focus on reducing waste and promoting sustainable production and consumption.

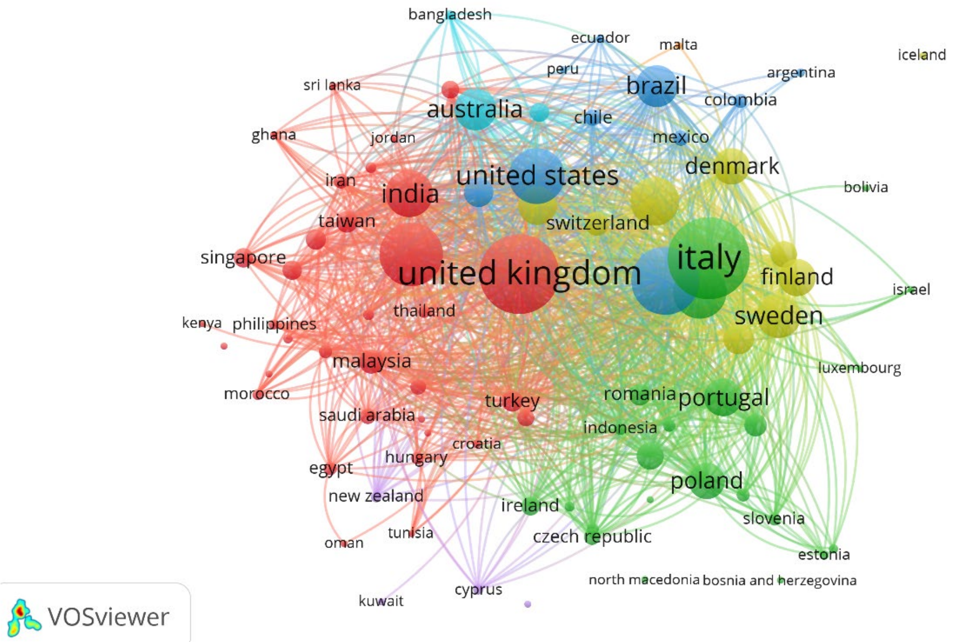


Figure 4. Network between countries whose authors have published at least two papers on the circular economy that match the keywords in this article (Source: VOSviewer—Visualizing scientific landscapes).

These countries have demonstrated a strong commitment to promoting the circular economy, and their investment in education and the development of related initiatives has led to a greater impact on the sustainable development of their respective countries.

It is important to note that this analysis only mentions some of the countries that have shown a greater focus on the circular economy, but many other countries are also making significant efforts in this area. The global drive toward a circular economy reflects a growing global awareness of the importance of sustainability and the efficient use of resources.

2.2. Scientometric Analysis

A review of available English-language open access (OA) articles was then conducted. As a result of this process, a total of 4515 articles that met the established criteria were selected.

By this approach, it was possible to have a more comprehensive and up-to-date understanding of the existing literature on the circular economy, including articles from European countries, as well as other emerging countries in the field. Thus, we were able to conduct a more accurate and informed bibliometric review based on the relevant information available.

After this analysis, we decided to select 162 articles that confirmed the information obtained in the first analysis, as illustrated in Figure 5.

The specific analysis of the 162 selected articles allowed us to identify the keywords that highlight the interest of our research. These keywords include sustainability, reuse, and the construction industry.

It is interesting to note that these keywords are in line with and complementary to the previous analysis of the existing literature in the circular economy field. This alignment provides greater confidence in the relevance and pertinence of our research because these keywords are consistent with the themes and approaches addressed in the existing literature.

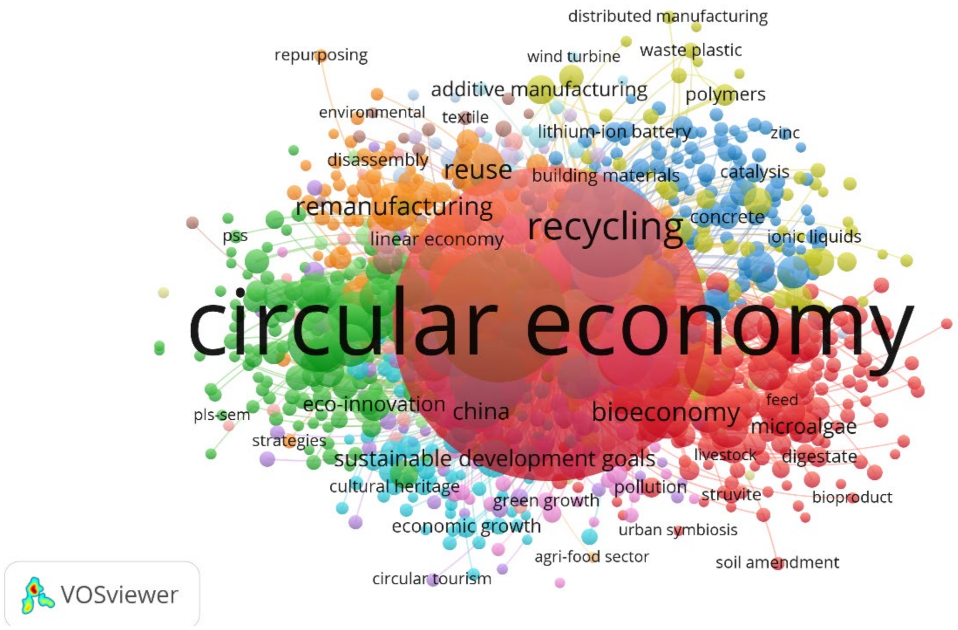


Figure 5. Keyword network between chosen publications to this review (Source: VOSviewer—Visualizing scientific landscapes).

Moreover, these keywords provide a solid foundation for article selection and generate an appropriate bibliometric review for the content that will be developed in the following sections of this paper. By focusing on sustainability, reuse, and the construction industry, it becomes possible to explore the advances, trends and perspectives related to the circular economy in these specific areas in depth.

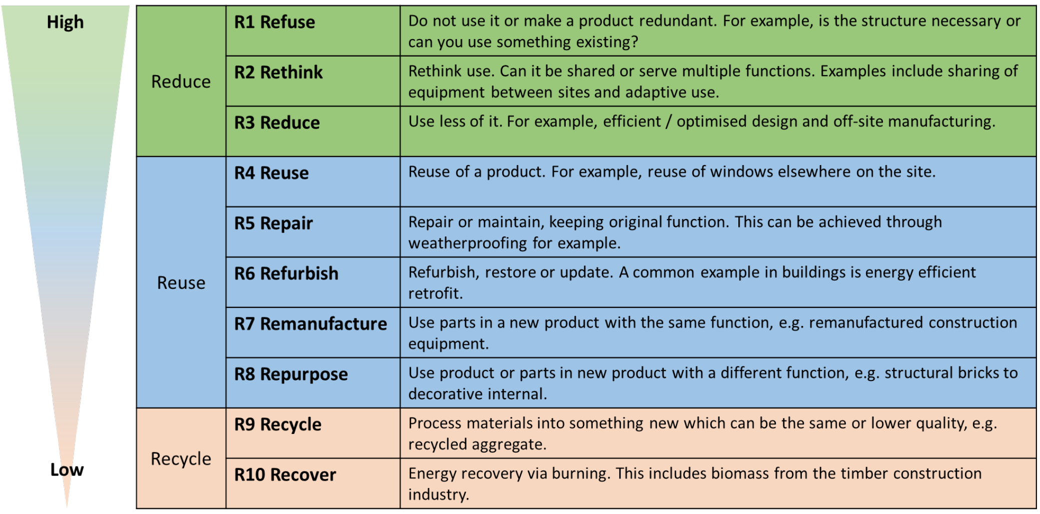
This critical approach analyzes and synthesizes the selected articles, identifying patterns and gaps in the existing literature and generating relevant and novel insights into the field of study. It also provides a solid basis for the development of future research and the generation of valuable content for the academic and professional community interested in the circular economy and its application in the construction industry.

3. Understanding the Circular Economy and Material Usage

According to the Ellen MacArthur Foundation [22], the three principles of a circular economy are the elimination of waste and pollution, the use of circular products and materials, and the regeneration of nature. Within these principles, there are several subcategories and concepts that will be discussed in terms of buildings and the construction industry in this section.

3.1. Eliminating Waste and Pollution

In circular building practice, materials can be designed to remain in use for multiple cycles by following the 3R principles: reduce, reuse, recycle. "Reduce" refers to the reduction of consumption and waste generated, "reuse" includes the reuse of building products or material at the end of life, and "recycle" involves processing to break down and reproduce materials and new products [23]. There have been many iterations of the R principles that subdivide the 3Rs into 14, 22, and even up to 38 Rs [24,25]. The 38 identified by Reike et al. [26] are listed here in alphabetic order: "re-assembly, recapture, reconditioning, recollect, recover, recreate, rectify, recycle, redesign, redistribute, reduce, re-envision, refit, refurbish, refuse, remarket, remanufacture, renovate, repair, replacement, reprocess, reproduce, repurpose, resale, resell, re-service, restoration, resynthesize, rethink, retrieve, retrofit, retrograde, return, reuse, reutilize, revenue, reverse and revitalize". However, the most commonly encountered principle is the 10 Rs included in Figure 6, which also indicates their hierarchy from 1 to 10 based on maximizing resource efficiency, minimizing waste generation, and highest value creation and retention. Recycling and recovery are ranked lowest because of the loss of complex state and the need for higher energy inputs and higher polluting potential [27].



High → Low			
High	Reduce	**R1 Refuse**	Do not use it or make a product redundant. For example, is the structure necessary or can you use something existing?
		R2 Rethink	Rethink use. Can it be shared or serve multiple functions. Examples include sharing of equipment between sites and adaptive use.
		R3 Reduce	Use less of it. For example, efficient / optimised design and off-site manufacturing.
	Reuse	**R4 Reuse**	Reuse of a product. For example, reuse of windows elsewhere on the site.
		R5 Repair	Repair or maintain, keeping original function. This can be achieved through weatherproofing for example.
		R6 Refurbish	Refurbish, restore or update. A common example in buildings is energy efficient retrofit.
		R7 Remanufacture	Use parts in a new product with the same function, e.g. remanufactured construction equipment.
		R8 Repurpose	Use product or parts in new product with a different function, e.g. structural bricks to decorative internal.
	Recycle	**R9 Recycle**	Process materials into something new which can be the same or lower quality, e.g. recycled aggregate.
Low		**R10 Recover**	Energy recovery via burning. This includes biomass from the timber construction industry.

Figure 6. Circularity hierarchy in the product chain (Source: adapted from Potting et al. [28], with examples added).

3.2. Use of Circular Products and Materials

Circular materials usage within construction can be largely divided into two groups: 1. bio-based or renewable low materials, such as wood, and 2. materials that are already in use and can be reused, repaired, or recycled using low-energy and -emissions processes [29]. Bio-based building materials can follow the biological cycle of concentric loops, whereas all building systems, products, and materials have the potential to follow the technical cycle as illustrated in Figure 7.

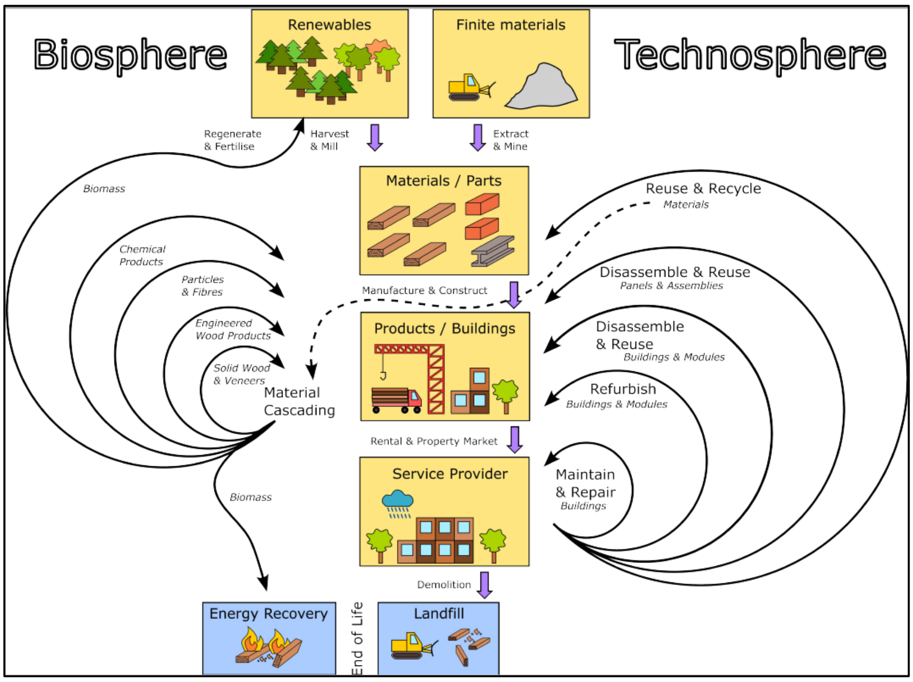


Figure 7. Circular economy butterfly diagram applied to the construction industry (Source: Ottenhaus [30]).

The technical cycle on the right includes construction materials such as metals, concrete, plastics, glass, or synthetic composites. At the end of a building's life, or building products' life, these materials are recovered from the demolition or deconstruction process, sorted, and processed before being reprocessed or reused in construction or other applications. The inner loops in Figure 7 retain most value in the material or product. This is based on the more general circular economy butterfly diagram [31] in which the innermost loop, "Maintenance", prolongs the life of the material or product. This is followed by "Reusing" and "Redistributing", which keeps materials in their original form and displaces the need to manufacture new items or extract new materials. "Refurbishing" and "Remanufacturing" then include some processing, and the outermost loop, "Recycling", is the least favored option according to the hierarchy.

The biological cycle only includes materials that can be safely regenerated in the biosphere via composting or anaerobic digestion, such as timber, bamboo, or straw. Materials from the technical cycle can end up in the biological cycle once they can no longer make a product. The inner loops of the left side of the butterfly diagram show the "cascading principle", which is the cascading use of renewable resources, with several reuse and recycling cycles [32]. For the construction industry, this is most applicable to timber, which could begin its first product life as solid timber beams and end its fifth life being incinerated for energy recovery (Figure 8).

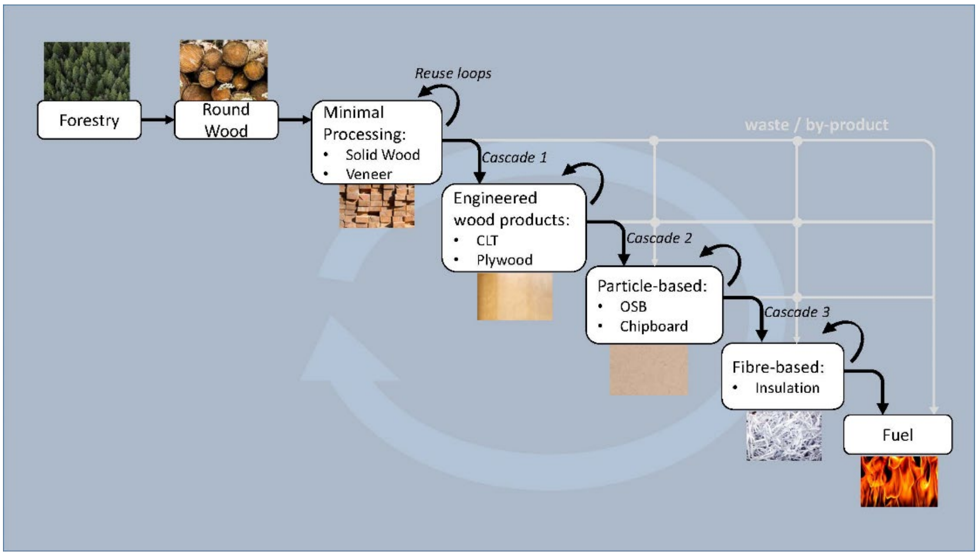


Figure 8. The cascading principle applied to an example of timber in the construction industry (Source: authors).

Cascading ensures that biogenic carbon remains locked in products and materials for longer over multiple lifecycles [33]. Cascading also allows for the sharing of resources across multiple industries so that maximum value is achieved, for example, as a feedstock or soil fertilizer in the farming industry [34].

3.3. Regenerate Nature

This final principle for a circular economy aims to enhance and preserve resources, restoring or renewing materials and energy. In the context of circular construction, biomimicry includes the principles of: nature only using material it needs, prioritizing resilience over performance, simple materials that easily decompose, and the reuse of resources [35]. Urbanization and the loss of natural spaces can have devastating impacts on biodiversity. The use and processing of natural resources is estimated to cause up to 90% of global biodiversity loss [36]. Building construction can contribute to the regeneration of nature by incorporating strategies that support ecological restoration, biodiversity enhancement, and sustainable land management practices [37–39]. The aforementioned biological cycle contributes to biodiversity and ecosystem health by promoting the use of renewable materials that can be regrown and replenished [40]. Maintaining materials in-use also contributes to this principle because less land is required for sourcing virgin raw materials, which allows more land to be returned to nature.

3.4. Challenge Areas

While circular construction materials hold great potential for sustainable and resource-efficient building practices, several challenges need to be addressed to facilitate widespread adoption. These can be broadly grouped as economic, informational, institutional, political, and technical challenges [41], with multiple subcategories identified in the literature (Table 1).

Table 1. Challenges for a circular built environment compiled from review articles (Source: adapted from Adams et al. [21], Munaro and Tavares [41], and Wuni [42]).

Categories	Challenge
Economic	Cost of upfront investment Lack of financial aid, incentives, or short-term benefits Low value of circular materials Lack of grants or unclear financial case
Informational	Lack of awareness, interest, and knowledge Lack of research, education, and information Lack of best practice case studies and leadership
Institutional/ Structural	Fragmented supply chains Lack of strategic vision and collaborative platforms Lack of market mechanisms for recovery
Political/ Governmental	Lack of regulatory instruments or pressure Lack of tax actions Lack of circular vision
Technological	Lack of integrated processes, tools, and practices Lack of an information management system Complexity of buildings Technology and infrastructure readiness

A key challenge in the sector is existing buildings that were not designed for deconstruction, which contain materials that are difficult to reuse or recycle and lack detailed documentation [43]. Reused materials require additional time and more qualified labor, and there is a lack of market mechanisms to aid recovery [21]. A system needs to be developed that supports the use of circular materials, including procedures for quality assurance, standardization, certification, and classification, as well as mechanisms for transport and storage and access to the market [41,44].

Finances, or lack of understood financial benefit, was identified as a leading barrier to CE uptake for stakeholders [13,21,42]. In the context of construction materials, this includes the high availability and low cost of virgin raw material [42], cost of deconstruction, work involved in providing and preparing material for reuse, cost of recycled or reused materials, and lack of reward or penalty [41].

Institutional or informational challenges include a lack of knowledge compounded by a lack of guidance or support tools [41]. Stakeholders throughout construction value chains in Europe are not sufficiently familiar with how CE principles would operate in the built environment, and many were unable to identify the first steps toward a CE transition [13]. Addressing these challenges requires collaborative efforts from multiple agents, including policymakers, professional bodies, and business organizations with input from industry professionals, researchers, and end users.

Overcoming these barriers will pave the way for more widespread adoption of circular construction materials; however, there is a need initially to provide evidence, compile best practice examples, and develop guidance. The following sections act as a first step toward providing this support.

4. Design Principles for Circular Material Usage

This section describes the design principles that enable the development of novel materials produced under circular economy criteria.

4.1. Designing for Circularity

The transition toward the design of new materials that allow for the recirculation of building products is a challenge for the current industry, ranging from organizational changes in the way buildings are conceived to new methods for building design [45]. This, in turn, involves increasing the interest of the technicians involved (including the creation of incentives), as well as their level of knowledge about the potential applications of CDW for the design of new materials [46].

The principles and design criteria for the development of ecofriendly materials in an CE have been schematically outlined in Figure 9.

Materials design: Principles and Criteria

- ➢ Standardised design of products and materials, promoting the use of modular shapes, industrialisation of the sector and waste reduction.
- ➢ Efficient product design, reducing the extraction of virgin raw materials.
- ➢ Design based on the recovery of previous materials, detecting unused materials from extraction or manufacturing flows and incorporating them in the design of new products.
- ➢ Design of materials for extended use and life cycle extension.
- ➢ Design with deconstruction in mind, taking into consideration the recovery phase of the initial product and promoting reuse and recycling.

Figure 9. Criteria and principles for circular materials design (Source: authors; based on Brown et al. [47] and Dumée [48]).

Therefore, although research tends to focus on the recovery of CDW for the development of products with a high content of recycled material and the human factor associated with the management [49], Figure 9 shows that the possibilities are much broader and arise from the study of compatibility between the recycled material and its final application.

In the design phase, the requirements established in the current regulations must be taken into consideration. For example, Del Rio et al. describe the possibility of applying different CDW typologies to produce gypsum composite materials for the design of prefabricated products [50]. Likewise, the aforementioned research shows that recycled materials, such as thermal insulators or plastics, improve the thermal properties of the final products and meet the minimum mechanical strength requirements. This highlights the importance of performing characterization tests beforehand in accordance with the applicable regulations and monitoring the development of the material itself.

These issues bring the focus of the researchers to the final application of the developed products. This is the case for the design of structures using disassembled joints, instead of using glues or binder materials. By analyzing the final application of the product, conclusions can be drawn about the amount of recycled raw material that can be reincorporated [51], its viability for the design of certain construction systems [52], or the possibility of developing economies of scale that allow a competitive cost advantage to be obtained [53]. This combines the need to develop a design to obtain technical characteristics under the requirements of the product during its useful life and analyze the economic viability and profitability of the developed proposal.

Finally, an analysis of suppliers and clients should be conducted, analyzing their level of concentration, the possibility of performing vertical integration actions, the storable or non-stackable nature of the developed product, and the available information channels. In this way, it can be inferred that the analysis of the general and specific environment, as well as the study of the resources and capacities of the construction company, are a starting point to explore potential applications and the development of business models based on a circular design of the product.

4.2. Material Selection and Management

The construction sector, in particular, plays a pivotal role in transitioning toward a less resource-intensive economy by maximizing the use and recovery of resources in building design and construction. Sustainable material sourcing and efficient recycling techniques are crucial for achieving a circular economy [54].

4.2.1. Criteria for Selecting Circular Materials

The European Union (EU) recognizes the importance of implementing circular economy (CE) principles across various economic sectors, giving special attention to water and energy conservation, waste prevention, material recycling, the promotion of reuse and repair, and the utilization of secondary raw materials [55]. According to the Waste Framework Directive [16], end-of-waste (EoW) criteria specify when certain waste ceases to be waste and becomes a product or a secondary raw material. In the construction sector, CE aims to optimize resource use and recovery in buildings, thereby minimizing their environmental impact.

To achieve this, it is crucial to design buildings that prioritize rehabilitation and utilize recyclable materials, as well as incorporate new industrialized long-life materials made from recovered and valued resources. Embracing these practices can contribute to sustainable approaches in the construction sector [54]. By adopting these recommendations, the construction industry can play a pivotal role in transitioning to a more resource-efficient economy and promoting circularity. These efforts are in line with the broader goals of the CE, which include reducing waste generation, conserving resources, and promoting the use of sustainable materials.

4.2.2. Sustainable Material Sourcing

In terms of the availability of raw materials, critical raw materials hold significant economic importance for the EU. The extraction of these materials has a significant impact on the environment, and they are highly sensitive to supply interruption. For instance, lithium, which is a critical raw material, is commonly found in electronic devices. However, the current low recycling rate of these materials results in missed economic opportunities. Therefore, it is essential for the circularity strategy at the European level to prioritize incorporating these materials into reduction, reuse, and recycling practices. The EU aims to achieve autonomy concerning these materials by advocating for diversified and undistorted access to global raw materials markets. Simultaneously, efforts are being made to reduce external dependence on these materials and mitigate the environmental pressures associated with their import [55].

4.2.3. Material Efficiency and Recycling Techniques

The EU places a strong emphasis on the importance of providing incentives for the adoption of resource efficiency measures and promoting increased recycling, eco-innovation, and investments in green products and services [55]. To transition toward an economic model of material efficiency, it is crucial to align economic priorities and lifestyles. The goal is to reduce excessive reliance on materials through the principles of circularity, namely, prioritizing reduction and reuse before recycling [55]. Within the concept of circular economy, key aspects related to recycling include (i) designing with a focus on efficient use of materials and energy, utilizing recyclable and renewable materials, and facilitating easy disassembly and replacement of materials and components; and (ii) promoting the recycling and recovery of nonreusable materials [54].

Despite high recycling rates in some EU member states, waste prevention remains a significant challenge [55]. The use of recycled materials can contribute to partially meeting the overall demand for materials, thereby reducing the need for raw material extraction. Establishing efficient secondary materials markets facilitates higher-value recycling cycles, as most materials are recycled after disassembly.

The principles listed next aim to address the significant challenge of waste prevention and promote sustainable practices:

- Waste prevention;
- Design oriented toward the economy of materials and energy;
- Use of recycled materials;
- Use of recyclable and renewable materials;
- Easy disassembly and replacement of materials and components.

4.2.4. Lifecycle Assessment and Material Management

The efficient use of materials in production systems plays a crucial role in transitioning to a CE. It is essential to prioritize activities that incorporate CE principles from the beginning of the production process, rather than solely focusing on recycling and waste conversion at the end. This approach serves as a recommendation for changing economic models and moving towards a less resource-intensive economy. Innovative and effective methodologies that analyze material flows and specific circularity indicators linked to the lifecycle are fundamental in addressing this transition [55].

By adopting these methodologies, companies can identify areas where material efficiency can be improved and waste can be minimized. They also facilitate optimizing resource allocation by identifying opportunities for reuse, recycling, and material recovery. These practices not only help reduce the environmental impact but also enhance competitiveness and contribute to the development of a sustainable economy. Emphasizing efficient material use from the outset of production processes supports the evolution toward a circular model and enables the realization of a more resource-efficient and sustainable future [55].

5. Principles and Strategies for the Circular Use of Materials in Construction Operations

This section is devoted to examining the principles and strategies related to the circular utilization of materials within the construction industry. It begins by outlining strategies aimed at prolonging the lifespan of materials and addressing end-of-life considerations. Subsequently, collaborative approaches and business models designed to promote a circular economy in the construction sector are discussed. The assessment and illustration of technological innovations for circular material usage follow. A comprehensive review of the primary obstacles and facilitators influencing circular material usage in the building sector is then provided. Finally, exemplars of best practices in circular economy within the construction industry, specifically about material usage, are presented as "case studies".

5.1. Extending Product Lifespan and End-of-Life Strategies

Frequently, the economy is saturated with items that have been created without considering the question: What are the implications for this product at the conclusion of its lifecycle [56]? Hence, it is crucial to establish, during the design phase, the end-of-life strategies that will enhance the circular economy (CE) of construction products and materials.

The construction industry is undergoing a gradual and progressive shift towards CE, as determined and affirmed by Charef et al. [57]. Indeed, the building industry is beginning to adopt circular strategies, as illustrated by the work of Nußholz et al. [58]. In their study, they examined 65 real-world cases of new construction, renovation, and demolition projects in Europe, considering the circular solutions employed, the extent of their application in buildings, and the reported potential for decarbonization.

Several researchers developed and made use of disruptive technologies to foster the circular building industry. Setaki and Timmeren [59] delineated how disruptive, frequently digital technologies have the potential to facilitate a CE in the building industry, particularly during the construction and demolition phases, which are recognized as the two most wasteful stages in the building cycle. Furthermore, in the realm of additive manufacturing, Tavares et al. [60] conducted a comprehensive review outlining the assessment of advantages and obstacles associated with additive manufacturing in the context of the circular economy. They also introduced a proposed framework. Moreover, there is a rising trend in employing artificial intelligence to improve the integration of systemic circular practices within the construction industry, as recently examined by Oluleye et al. [61].

As stated by Marsh et al. [62], the construction CE principles could be congregated as follows:

- Minimization of material usage through design and specification;
- Creation of long-lasting designs to enhance durability;
- Emphasis on maintenance, repair, and refurbishing;
- Adoption of practices for reuse and remanufacturing;
- Incorporation of recycling methods.

A fundamental principle of the circular economy is to maximize the utilization duration of products and materials, as emphasized by Figge et al. [63]. This involves designing for longevity to prolong the time items remain in use [62]. The objective is to maximize the period of use for products and materials, encouraging practices such as reuse, refurbishment, remanufacturing, and recycling. Prolonging the lifespan of products preserves their value and diminishes the necessity for extracting and processing new resources. Nevertheless, Kirchherr et al. [64] stated "that the CE is most frequently depicted as a combination of reduce, reuse and recycle activities". They also observed that the term "recover" is frequently added to the previously mentioned CE activities, thereby establishing a 4Rs framework instead of the traditional 3Rs.

In addition to enhancing the durability of materials and products, it is crucial to promote their repairability. Moreover, there should be the incorporation of a remanufacturing process, with a focus on upgrading the product to its highest value whenever feasible.

Given the numerous available possibilities and potential approaches for addressing the circular economy in existing buildings, it is highly pertinent to assess the recoverable value of in situ building materials. Mollaei et al. [65] established a new computational tool to "choose the optimal combination of reuse, recycling and disposal options for those materials", considering "cost, value, duration, environmental impacts, and building component precedence in demolition and deconstruction activities".

According to Marsh et al. [62], the principles and strategies of CE can be organized into three primary groups, categorized by the lifecycle stage, as outlined in Table 2. It is worth noting that numerous other strategies could be defined and incorporated into this table, such as the recovery of products/materials from a building's end-of-life for subsequent reuse, remanufacturing, or recycling. Another instance could involve the recovery of thermal energy from the combustion of a material (e.g., plastic or rubber). Both examples mentioned above pertain to the end-of-use lifecycle stage.

Table 2. CE strategies/principles organized by lifecycle stage (Source: adapted from Marsh et al. [62]).

Lifecycle Stage	CE Strategies/Principles
Design stage	- Reduction of material usage through design and specification - Design for increased longevity
In-service	- Maintenance - Repair - Refurbishing
End-of-use	- Reuse - Remanufacturing - Recycling

The actual subsection will primarily address strategies aimed at prolonging the lifespan of products and explore the existing end-of-life approaches to promote circular material usage in construction activities.

5.1.1. Extending Product Lifespan

- Increasing durability through maintenance, repair, and refurbishment

Maintenance, repair, and refurbishment represent in-service strategies to decelerate resource flows by prolonging the technical lifespan of products and components [62]. Maintenance entails universal upkeep, and preventive measures aim to prevent damage to building components, such as the application of protective coatings. Repair and refurbishment involve addressing limited damage to a component or replacing a damaged component entirely with a new one [62].

Designers should consider how their product aligns with either technical or biological cycles after use, ensuring that the product is created with the subsequent path in mind. In the case of products intended for technical cycles, it is advantageous for them to be easily repairable and maintainable, simple to disassemble, and constructed with modular components that can be replaced [66]. They should possess sufficient durability to endure the wear and tear caused by numerous users. Additionally, they should be crafted from materials that can be easily recycled.

The optimal solution would involve utilizing self-healing materials to prolong their lifespan and, in the extreme, create “immortal” products or components, as investigated by Haines-Gadd et al. [67].

5.1.2. End-of-Life Strategies

- Remanufacturing and Upgrading

In the processes aimed at enhancing durability mentioned earlier, when the product becomes unusable, its components should, whenever feasible, undergo remanufacturing and upgrading [68]. Upgrading and remanufacturing are strategies employed at the end of a product’s use, aiming to decelerate resource flows by incorporating still-functional components from end-of-use products into new products. In his research work, Atta [68] outlined how digital technologies play a role in facilitating the adoption of circular service-based models centered around remanufacturing in contemporary construction practices.

Plans for upgrading and remanufacturing building components should be anticipated during the design phase. Van Stijn and Gruis [69] established an integral design software for circular buildings components (CBC), named “CBC-generator” 2.0. This software is a parameter-based “three-tiered design tool, consisting of a technical, industrial and business model generator”, in which the designers can choose and compare various design alternatives.

- Reuse, Reverse Logistics, and Take-Back Programs

These are also strategies employed at the end of use. Indeed, the most efficient method for preserving the highest value of products is through maintenance and reuse. Take a window, for instance: its value is greater as a functional window than as a collection of individual components and materials (such as PVC or aluminum from the frame, glass, etc.). Therefore, the initial stages in the technical cycle focus on maintaining products intact to maximize their potential value. This may encompass business models centered on sharing, allowing users access to a product rather than ownership, and facilitating broader usage over time (e.g., renting equipment during the construction phase). It might involve reuse through resale or recurring cycles of maintenance, repair, and refurbishment.

Reverse logistics (RL), defined as a series of activities conducted after the sale of a product to recapture value and conclude the product's lifecycle, plays a crucial role in promoting the circular economy in the construction sector [70]. It usually entails sending a product back to the manufacturer or distributor or redirecting it for servicing, refurbishment, or recycling. In the context of construction, RL is described as "the movement of products and materials from salvaged buildings to a new construction site" [70]. This approach promotes material reuse, as well as the processes of deconstruction and disassembly.

In a more recent study, Ding et al. [71] conducted a review on forward and reverse logistics for the circular economy in construction, concluding that "while similar methods and CE strategies are used in forward logistics (FL) and RL, RL operations require more integration between supply chain actors to close the loop for CE in construction".

A take-back program essentially involves a brand reclaiming or repurchasing its own materials or products. These items are either cleaned, repaired, and subsequently resold by the brand at a discounted rate, dismantled and repurposed in other collections, or recycled through alternative methods. The construction industry is also beginning to adopt this strategy [72,73].

A market for secondhand building products and materials already exists, encompassing items like windows and doors (see Figure 10), lumber, flooring, furniture, masonry, tiles, stones, sheathing boards, appliances, architectural/decorative elements, lighting, heating, and cooling devices, electrical components, plumbing, etc., which are available for commercialization and reuse [74–76].

(**a**) (**b**)

Figure 10. Instances of preowned building products available for reuse that are being exchanged on online platforms: (**a**) window [75]; (**b**) door [76] (Source: reproduced with permissions from seconduse.com [75] and rotordc.com [76]).

- Material Recovery

Material recovery pertains to the process of reclaiming and reutilizing materials from construction and demolition waste (CDW). This involves the identification of valuable materials within the "waste" stream, salvaging them for reuse or resale [77]. The activities involved in material recovery typically include deconstruction, which requires the careful disassembly of structures to preserve valuable components. Recovered materials may encompass lumber [78,79], cross-laminated timber [80], bricks [81], and other items that can be repurposed in upcoming construction projects. The primary aim of material recovery is to decrease waste generation, conserve resources, and minimize the environmental impact associated with the extraction of new raw materials.

It is important to acknowledge that CDW can originate from various sources, whether human-made or natural, as depicted in Figure 11. Concerning the human-made sources of CDW, these authors categorize them into three groups: (1) public works construction and maintenance; (2) building construction works; and (3) building renovation and demolition works. The key constituents of this CDW, encompassing the natural sources, are also outlined in the illustration (Figure 11), including aggregates, concrete, bricks, stone, wood, glass, metals, plastic, etc.

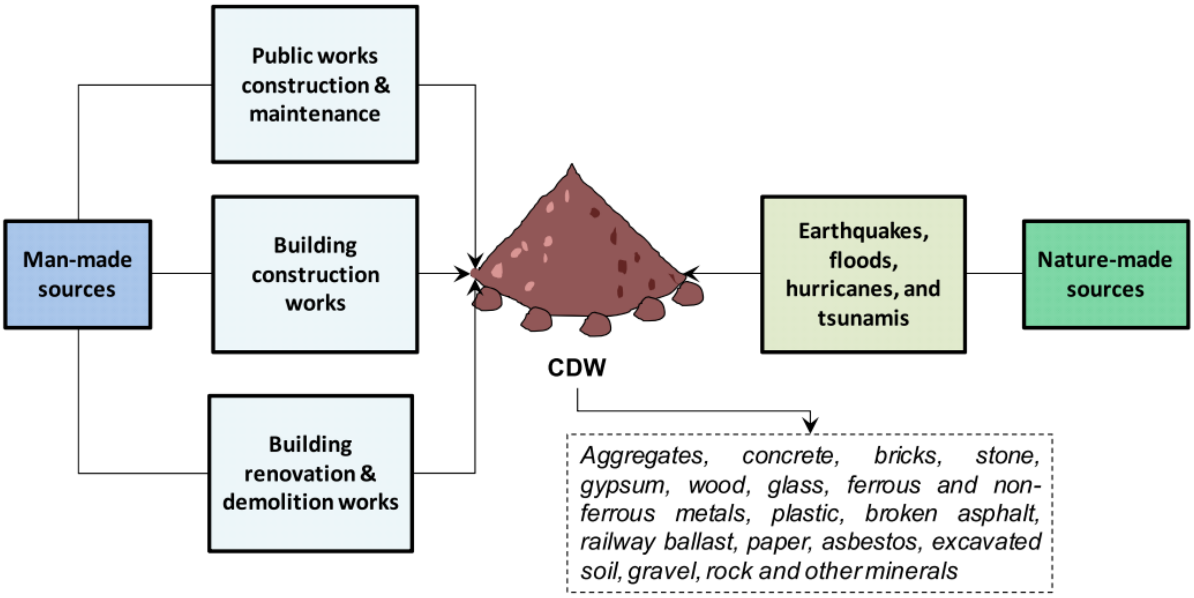


Figure 11. Categorization of construction and demolition waste (CDW) based on its source of origin (Source: dos Reis et al. [82]).

In their study, [83] assessed the dynamics at a local scale to enhance the sustainable management of CDW. Their findings emphasized the importance of investing in local solutions to optimize logistics and address cost issues, fostering cooperation among stakeholders, and enhancing the market for recycled aggregates. Furthermore, they underscored the necessity of providing support in the form of information, awareness, and training, with a focus on promoting good practices onsite and implementing oversight procedures. While material recovery concentrates on salvaging and reusing intact components or materials, recycling involves breaking down waste materials to generate new products or raw materials, as will be elaborated on next.

- Material Recycling

Recycling serves as an end-of-use strategy aimed at closing resource loops by reprocessing materials for use in another product, thereby preventing both waste generation and the extraction of raw materials [62]. Components that cannot undergo remanufacturing can be disassembled into their constituent materials and recycled. Although recycling is ideally considered as a last resort due to the potential loss of embedded value in products and components, it is crucial as the final step in ensuring that materials remain within the economy and do not become waste [56].

Recycling entails converting waste materials into new products or raw materials, which can subsequently be utilized for diverse purposes. Within the construction sector, recycling typically denotes the transformation of CDW into reusable materials. This process may include activities such as crushing, grinding, or shredding waste materials like concrete, asphalt, metal, and wood to produce recycled aggregates [83], crushed concrete, or other materials capable of substituting virgin materials in construction projects.

Numerous studies have explored the feasibility and effectiveness of new recycled materials derived from CDW, including cement [84];,concrete [85], mortars [86], plasters [87], gypsums [88], plastics [89,90], insulation materials [91], bricks [92,93], soil reinforcement [94], and fire-resistant materials [95].

In addition to CDW, other waste sources are being recycled and investigated for utilization in the construction sector and the building environment, including concrete [96], mortars [97], plasters [87,98], gypsum [88], thermal break strips made of recycled tire rubber [99,100] and rubber–cork composites [99,100], plastics [101], and insulation materials such as silica–aerogel composites and recycled tire rubber [102,103].

5.2. Collaborative Approaches and Business Models

This section includes some of the innovations that are currently affecting business models linked to construction and which promote the integration of circular economy criteria in this industrial sector.

5.2.1. Circular Supply Chains and Networks

The literature addressing CE in the construction sector includes the design of circular supply chains to improve the management of natural resources and reduce the volume of waste generated [104]. Policymakers have referred to these circular supply chains as a key activity to move toward sustainable and environmentally friendly economic growth [105]. In the linear model, construction products at the end of their use are considered waste, and their management becomes a challenge for cities [106]. It is known that in the demolition processes, about 40% of the total mass of raw materials extracted during the execution/production phase is lost, making the construction industry one of the most polluting on a global scale [2]. For this reason, the CE includes as a goal "closing the loop" in the flow of raw materials and resources used in construction throughout the useful life of buildings [64,71] because it is at this point that the supply chain represents a value proposition in the redesign of the execution process [107,108].

To provide an overview, Figure 12 schematically shows the relationship between stakeholders and the different stages included in the supply chain.

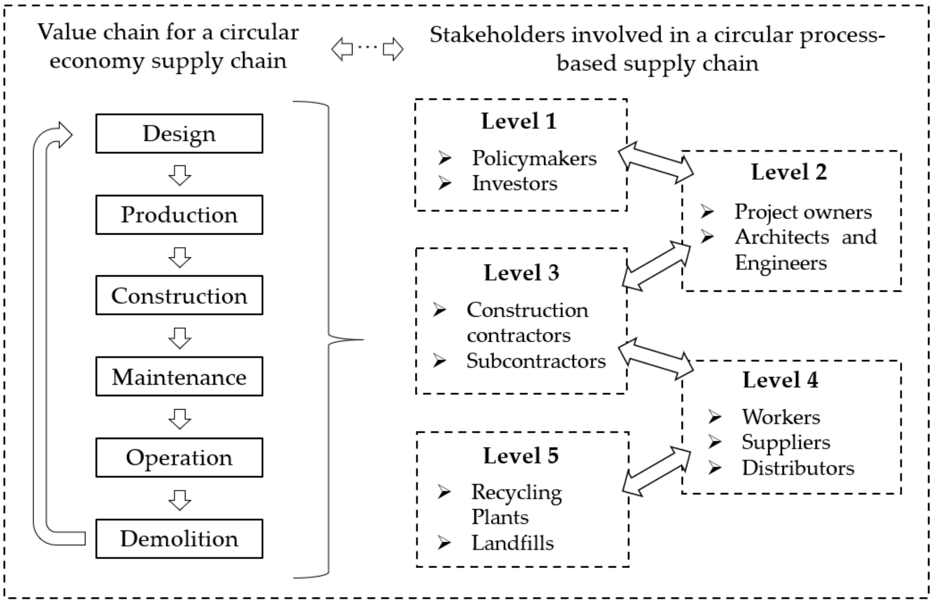


Figure 12. Complete supply chain cycle and stakeholders involved (Source: authors based on Chen et al. [104]).

Therefore, as shown in Figure 12, it is necessary to make a combined effort on the part of all stakeholders included in the network generated in the process of supplying construction materials to advance toward the integration of the CE in the sector [109]. In this regard, the establishment of agile communication channels that enhance transparency in the agreements and allow CDW to be recovered, create value from them, or correctly dispose of them [71,110] is particularly relevant. This is the only way to achieve an eco-industrial symbiosis and incorporate the reverse logistics stage in the manufacture of building products, redesigning current distribution processes and improving warehouse management to increase the level of service [71,111]. In turn, a greater recirculation of construction products would favor the creation of a controlled market for CDW, which, together with strategies that impute the environmental costs derived from the distribution process to the final product, would make it possible to boost its demand [41].

Finally, the importance of separating CDW at the point of origin should be emphasized. A selective sorting of waste at the initial stage of the recycling or reuse process would significantly improve the management process of these secondary raw materials [112]. This would reduce costs by reducing the work of intermediate processing and sorting plants, obtaining more homogeneous products, and improving the traceability of samples [113]. At the same time, this separation at the starting point would mitigate the environmental impact by reducing the number of trips to the landfill and the volume of occupation at the deposit points [86].

5.2.2. Sharing Economy and Product-as-a-Service Models

The strategies used at the industrial level to promote value creation have evolved in recent years as a result of globalization processes and the dizzying technological development that has taken place in recent decades [114]. Sharing economy business models aim to create a service around a product, technology, or equipment in such a way as to enhance its reuse and share it among the different stakeholders [115]. This initiative has also affected the construction sector, which, through the development of new information channels, allows stakeholders to use and share goods to move toward a model based on product–service systems (PSS) [116]. This adds complexity because companies are forced to introduce innovations in their manufacturing process and increase the level of interaction in the development phases to enable these business models [117,118]. By transmitting the value of the product to its use and linking its functionality to its use, manufacturers are forced to understand its complete lifecycle and the needs of the customer in depth, sometimes requiring a redesign of activities [118].

Certain factors (external and internal) have been found to condition the incorporation of these business models in the construction sector (Figure 13), and it is necessary to raise consumer awareness to promote the acceptance of this product or service model.

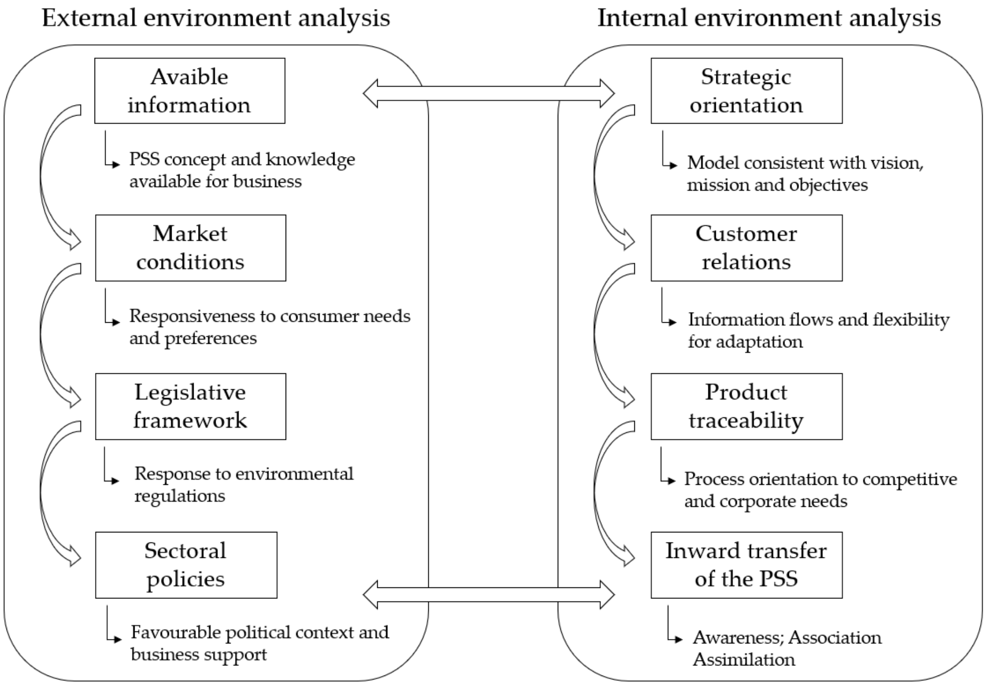


Figure 13. Internal and external determinants of product-as-a-service models (Source: authors based on Cook et al. [117]).

Several authors have worked on the implications of implementing this business model to different products to advance in this “servitization” process. Thus, we find examples linked to construction machinery and construction equipment [114,118], prefabricated building products [119], or building components [120]. In the cases in which it has been implemented added environmental benefit is obtained thanks to the greater ease of product recovery [121]. It is worth noting that the promotion and proliferation of online platforms has made it possible, among other things, to share geographic location, know the demand and available resources in real time, and provide new opportunities for business collaboration [122]. This makes it possible to promote a more democratic organization and reduce information asymmetries between the parties involved [123]. In short, this collaborative economy model allows companies to have high value-added resources available without the need to purchase them with the large initial outlay that this action entails, thus reducing the volume of waste generated as a result of disuse [119].

5.2.3. Extended Product Responsibility

Extended product responsibility (EPR) was first defined at the beginning of the century by Lindhqvist [124] as a strategy to protect the environment and is intended to ensure that any product manufacturer takes responsibility for its entire lifecycle, incorporating the stages of recovery, recycling, collection, and disposal. As a result of this definition, other related actions have arisen, such as the extension of the useful life of products, which goes against the traditional linear model, where the benefit lies in individual mass consumption and preventing products from remaining for long periods of time [125].

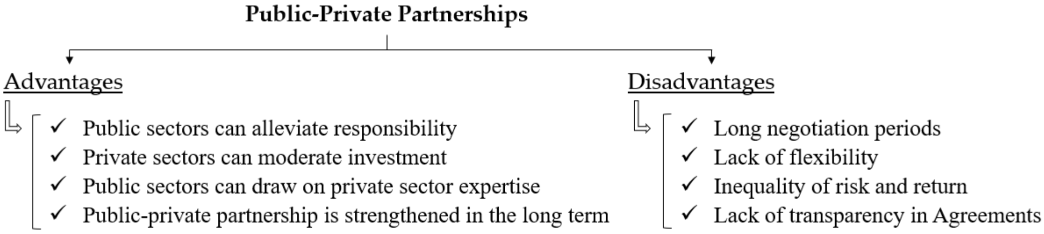
This approach would make it possible to change the current production models related to the construction industry, so that the companies involved should include in their activities a plan for collection and management of the resource once it has been consumed

[12]. Some secondary raw materials, as in the case of plastics, are leading the way in the development of these business models [126], as well as household appliances or air conditioning equipment commonly used in homes [127]. However, complex civil infrastructures or constructed buildings, conceived as unique products made onsite, hinder the implementation of these models. In this sense, it is possible to think of an EPR localized to the main raw materials used in the elaboration of constructive systems; however, the useful life of this is rarely less than 50 years, and it becomes difficult to manage the final management of these products [128].

In this sense, it is necessary to review the current initiatives and regulations in force to address the problems related to CDW generated and implement the "polluter pays" principle as far as possible [129]. Thus, through a solid legislative framework, companies can be encouraged to incorporate CE criteria in their manufacturing process, moving toward eco-efficient design and including the final stages of recycling, recovery, and revaluation of the manufactured product [130,131].

5.2.4. Public–Private Partnerships and Policy Implications

Public–private partnerships (PPPs) have become a very useful tool in the construction industry, seeking to leverage the expertise of private companies supported by public resources [132]. These relationships are established with a medium- to long-term temporary objective and with the intention of moving toward a more sustainable design of the sector. These relationships are, therefore, based on mutual trust between the organizations involved, which allows the sharing of resources and capabilities and must, therefore, be coordinated in decision-making [133]. In this sense, there is a shared responsibility and, therefore, these agreements cannot always be considered favorable. Figure 14 shows the advantages and disadvantages of these agreements, as stated by Bao et al. [134].



Public-Private Partnerships

Advantages
- ✓ Public sectors can alleviate responsibility
- ✓ Private sectors can moderate investment
- ✓ Public sectors can draw on private sector expertise
- ✓ Public-private partnership is strengthened in the long term

Disadvantages
- ✓ Long negotiation periods
- ✓ Lack of flexibility
- ✓ Inequality of risk and return
- ✓ Lack of transparency in Agreements

Figure 14. Advantages and disadvantages of public–private partnerships in the construction sector (Source: authors).

However, although PPPs are already established for tasks related to the development of construction infrastructures or the design, execution, and development of facilities [135,136], in the area of waste management, moving toward a circular economy model in the EU is still a pending task, and there is still a long way to go. For this reason, managers and environmental policymakers in the Union are moving toward the development of an international legal framework that will allow for the proliferation of such agreements in the construction sector [137]. Despite this, the changes brought about to date have not been as efficient as could be desired, although it is true that the path has been set by policymakers to create resilient infrastructures that make these collaboration models attractive to companies and serve to maintain solid support from the public administrations that back the agreements [138].

5.3. Technological Innovations for Circular Material Usage

CE aims to enhance productivity in the construction industry through investments in technology and digitalization. In the study by Ferrer et al. [54], the importance of establishing efficient networks for recycling, reusing, and recovering construction materials is highlighted, as illustrated in Figure 15. These networks play a crucial role in achieving several key objectives related to CE [54].

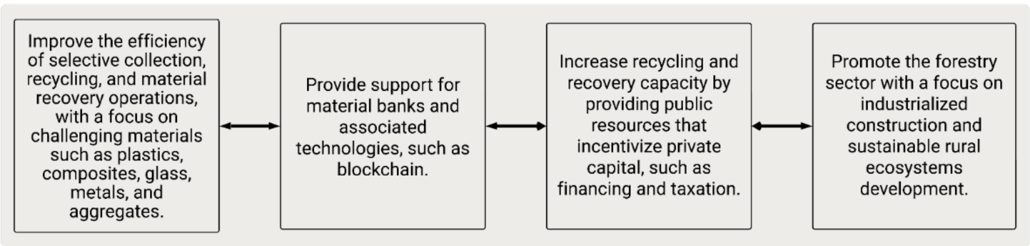


Figure 15. Fundamentals in circular material usage (Source: authors based on Ferrer et al. [54]).

To promote reindustrialization and sustainability in the construction sector, innovation ecosystems advocate for the implementation of research, development, and innovation (R + D + i), as well as knowledge transfer instruments. These instruments focus on various areas, including 4.0 technologies, recycling and recovery of challenging materials and components (such as plastics, composites, and waste), productivity enhancements in component manufacturing and recovery through 3D printing, robotics, artificial intelligence (AI), and internet of things (IoT), as well as the development of new long-lasting materials and material traceability technologies like blockchain [54].

5.3.1. Recycling Technologies

The resource recovery approach, which serves as a business model and a catalyst for the CE, primarily emphasizes the reclamation of materials or energy from waste. Examples include the recycling of steel and fibers, as well as the use of recycled aggregates in construction or other industries. The adoption of CE principles relies on the establishment of industrial and energy symbiosis between complementary sectors [54].

In the construction industry, the adoption of disassembly and recycling best practices is crucial to revalue construction waste, which is often considered as "low value" material. By employing testing methods for disassembly, treatment, and recycling, the recovery and reuse of materials can be optimized, leading to more efficient resource utilization in the production process. Implementing advanced recycling technologies allows the construction industry to reduce waste, decrease the extraction of virgin resources, and promote a more sustainable approach to material management [70]. These technologies enable the transformation of waste into valuable resources, fostering the development of a CE. Recycled steel, fibers, and aggregates find applications in various sectors, including construction, creating a closed-loop system in which materials are continuously reused and recycled [61]. This approach not only reduces the environmental impact of resource extraction but also contributes to the development of a more resource-efficient and less wasteful economy, as highlighted by the European Environment Agency [139].

5.3.2. Revolutionizing Material Sorting and Separation Systems

Intelligent sorting and separation systems play a crucial role in advancing the principles of the CE by improving the efficiency and effectiveness of waste management and resource recovery processes [54]. These systems leverage cutting-edge technologies like AI, machine learning, computer vision, and robotics to accurately identify, sort, and segregate different types of materials. This enables appropriate recycling, reuse, or recovery, promoting sustainable practices.

By automating the sorting process, these systems enhance the purity and quality of recovered materials, increasing their value for subsequent reuse or recycling. They also optimize resource allocation by dynamically adjusting parameters like conveyor speed and sensor settings, maximizing efficiency while minimizing waste [140]. Additionally, these systems detect and eliminate contaminants, improving the quality of recovered materials and reducing the risk of cross-contamination [141].

Moreover, intelligent sorting systems reduce the need for manual labor, increase throughput capacity, and enable the processing of larger volumes of waste due to their exceptional accuracy and speed. Furthermore, they generate valuable data on waste composition, quantity, and quality. This data-driven approach facilitates informed decision-making, process optimization, and the development of innovative recycling technologies.

By integrating into circular supply chains, these systems facilitate the efficient recovery and reintroduction of recycled materials, closing the loop in the CE. As technology continues to advance, intelligent sorting systems are expected to contribute significantly to resource efficiency, waste reduction, and sustainable material utilization.

5.3.3. The Transformational Power of Digitalization and Blockchain Applications

The delivery of a sustainable and circular built environment requires the promotion of a guaranteed system for components and spare parts, along with digital traceability through a European passport and associated documentation. These measures ensure transparency and accountability in the construction industry, as emphasized by Ferrer et al. [54]. Furthermore, financial aid for investments by industrialized and sustainable construction companies is proposed as a complementary measure. This includes support for technologies such as modular design, building information modeling (BIM), internet of things (IoT) digitalization, 3D printing, and cutting-edge robotics. Additionally, the establishment of components' banks and material passports is suggested as a means to promote public–private collaboration and drive innovation in the industry. These initiatives aim to encourage sustainable practices and foster the transition toward a circular economy, as highlighted by Ferrer et al. [54].

In terms of material circularity, the utilization of blockchain technology for material passports addresses the issue of low transparency and traceability in the construction industry. This solution allows for improved tracking of materials such as fiber plates, steels, coatings, and facades [142]. The integration of collaborative design and manufacturing technologies, such as BIM and the internet of things (IoT), benefits from the availability of these new technologies. Thus, by integrating design, production, and delivery systems, including just-in-time (JIT) delivery, construction sites can operate more efficiently and effectively.

5.3.4. Robotic Deconstruction

Technological advancements in deconstruction have brought about innovative tools and techniques that enable the dismantling and repurposing of buildings and structures in a more efficient, sustainable, and profitable manner. These innovations are designed to reduce waste, minimize environmental impact, and enhance safety throughout deconstruction [142].

In this regard, robotic systems have emerged as a promising solution for deconstruction, offering improved efficiency and sustainability in the construction industry. Traditional demolition methods often pose significant risks and have adverse environmental effects, particularly in densely populated urban areas, as highlighted by [143].

In Japan, alternative approaches have been developed to address the legal, economic, and ecological requirements of deconstruction. These include the utilization of single-task construction robots (STCRs) and the establishment of semiautomated onsite factories. These methods aim to streamline the deconstruction process while meeting the specific needs of the project [142]. By implementing these technological innovations, the construction industry can achieve more efficient and environmentally friendly deconstruction practices, contributing to overall sustainability and safety [61].

However, the implementation of traditional industrial robots in a deconstruction environment presents challenges, particularly in terms of human–robot interaction and collaboration. To address these challenges, the efficient collaboration between humans and robots is carefully considered when designing deconstruction STCRs. Moreover, the adoption of the robot-oriented design method can enhance the efficiency of the deconstruction system's operation [143].

To evaluate the effectiveness of robot-assisted, systemized deconstruction, Leder et al. [142] proposed a framework that includes performance indicators that can be adjusted based on the perspectives of stakeholders. Overall, the use of robots in deconstruction provides a scalable and sustainable solution for the industry, offering improved efficiency and environmental outcomes [142].

5.3.5. Emerging Materials and Sustainable Manufacturing Processes

Innovation in materials, sustainable design, and the development of alternative technologies can play a crucial role in mitigating supply risks. These advancements can help reduce the ecological footprint and increase material recovery, ultimately improving the safety and competitiveness of production processes. While solutions to these challenges are within reach, global scenarios continue to present increasing complexity and competition for natural resources, as highlighted by Morató et al. [55]. Industrialized systems exhibit lower durations and footprints of carbon dioxide (CO_2), water, and material consumption. The environmental impact of circular and sustainable industrialized construction can vary depending on different modelling scenarios of recycling percentages, as identified by Ferrer et al. [54]. This suggests that by incorporating circular and sustainable practices, such as increased recycling, the duration and environmental impact of construction processes can be further reduced.

5.4. Barriers and Enablers of Circular Material Usage

It is critical to identify the barriers and enablers to understand the circular material usage strategies and principles in construction activities. This could be achieved by collecting stakeholders' opinions, particularly the ones who are the implementers of CE in the sector. However, this is out of the scope of this review study, so we decided to extend the literature review to investigate the barriers and enablers that others have already identified.

The first and most critical finding during our closer inspection of the existing literature is that the CE concept is multifaceted and that barriers and enablers have a primary focus on the use of materials and products and their technical specifications, including their compositions and origins. Charef et al. [144] identified and classified barriers into six different categories. The first category, economic barriers, refers to those that are related to market constraints, such as lack of financial resources or funding. The second category, sociological barriers, addresses cultural or psychological obstacles that can impede progress. The third category, political barriers, involves obstacles that arise due to government policies or regulations. The fourth category, organizational barriers, includes obstacles that involve stakeholders, such as a lack of support or resistance from key players. The fifth category, technological barriers, pertains to issues related to technology, such as outdated equipment or inadequate infrastructure. Finally, the sixth category, environmental barriers, concerns ecological impact and any obstacles that may arise due to environmental factors. Similarly, Ababio and Lu [145] also identified five distinct categories of barriers in this field. These categories are as follows: social and cultural barriers, political and legislative barriers, financial and economic barriers, technological barriers, and framework- and theory-related barriers.

The second critical general issue identified during the review is that while significant research has been conducted on the barriers, including obstacles and challenges, that hinder the development of circular economy practices, relatively little attention has been given to the factors that, as enablers, facilitate and promote CE initiatives. For instance, Ababio and Lu [145] did not classify enablers but discussed them within selected themes. Therefore, this research addresses the importance of conducting more studies and research on CE enablers to identify the key drivers that can accelerate the transition.

Generally, enablers are related to building design and construction technologies and innovations, internal and external policies and legislations, professional training and education, stakeholders' awareness, financing options, and market creation.

After providing the justifications above, we decided to concentrate this section of the present report on the barriers associated with material usage that the literature addresses. They are discussed in four categories and summarized in Figure 16.

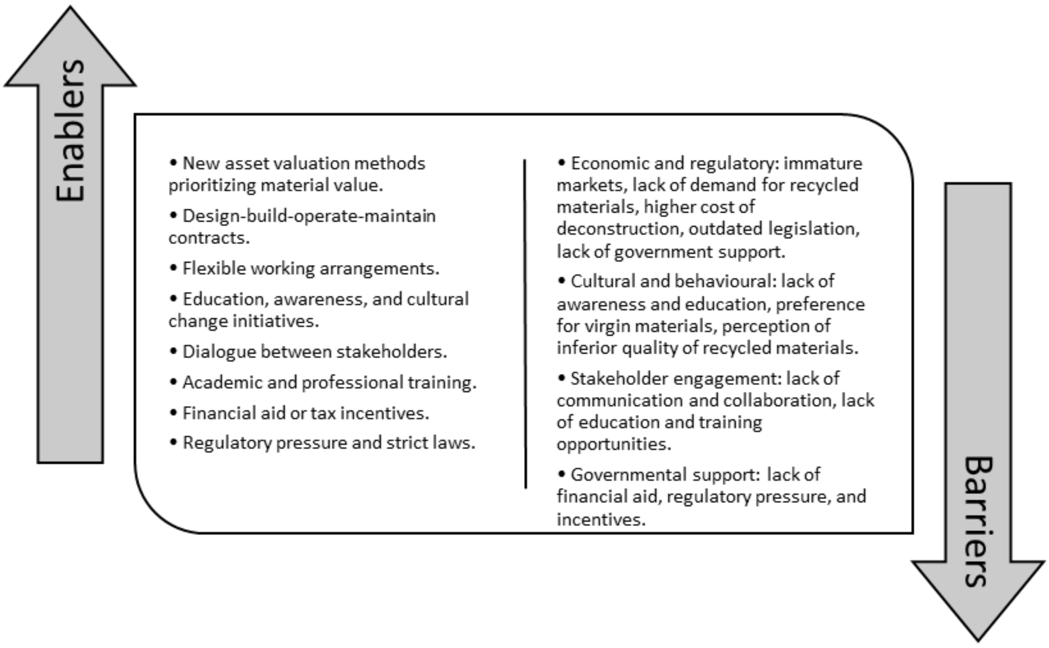


Figure 16. Summary of barriers and enablers of circular material usage (Source: authors).

5.4.1. Legislative and Economic Barriers

Insufficient and immature markets are the most common economic barriers to the implementation of circular economy practices in the construction sector, and they are mostly associated with the low demand for reused and recycled materials [146–148]. The construction industry is often criticized for its inflexibility in adopting innovative practices due to the perceived risk of losing profits [144,147].

The construction industry faces a major challenge in adopting CE practices: the higher cost of resources associated with deconstruction compared to demolition. Virgin materials are less expensive than recycled ones, and recycling costs more than CDW disposal. Unfortunately, the COVID-19 pandemic has further worsened these challenges by halting economic development and increasing the use of single-use materials. Implementing CE practices in construction requires significant investments, such as renewing equipment [148]. Moreover, outdated legislation and the lack of standardized guides related to design and procurement procedures are other leading major regulatory barriers to CE development [144,149]. The lack of government and public institutional support are critical barriers to CE adoption [144,150].

The construction industry can benefit greatly from the integration of CE practices. To achieve this, it is important to adopt new business models and methods of evaluating assets that prioritize the material value. One way to do this is by making long-term investments that support the CE business case through the use of whole-life costing. This involves considering all the costs of a product or service over its entire lifespan, from design and production to disposal or recycling. By implementing CE practices, businesses can also transform their existing business models into product-as-a-service contracts (PSS). This approach involves providing a product or service to customers as a subscription or on a pay-per-use basis rather than selling it outright. This can help to reduce waste and improve resource efficiency because the manufacturer retains ownership of the product and is responsible for its maintenance and repair [151]. The adoption of CE practices can also lead to the development of new revenue streams. For example, businesses can recover and sell valuable materials from waste streams, creating a new source of income. Ababio and Lu [145] highlighted that enablers have been commonly identified, including design-build-operate-maintain contracts and their variations. Furthermore, Torgautov et al. [149] suggested to stakeholders that implementing circular economy practices can offer more flexible working arrangements.

5.4.2. Cultural and Behavioral Challenges

The construction industry faces many obstacles when adopting innovative practices, particularly those related to CE and sustainability. The industry is known for conservatism and reluctance to embrace new ideas that challenge established attitudes, customs, and beliefs. These cultural and behavioral issues pose significant challenges to adopting sustainable practices. One primary cultural challenge is the need for more awareness among construction stakeholders regarding CE and sustainability practices. Many stakeholders are unfamiliar with these concepts and, therefore, need to understand their potential benefits. This lack of awareness can lead to a reluctance to invest in sustainable practices. Another cultural challenge is the inherent risk aversion in the construction industry. This risk aversion can make it difficult to adopt innovative practices, particularly when there is a perceived risk that they may not work as intended. As a result, many stakeholders may be hesitant to invest in new technologies or processes that are not proven. There is also a preference for virgin construction materials over reused and recycled products. This preference is often reinforced by ingrained beliefs that circular economy practices are not feasible. Many construction stakeholders believe that using recycled materials may compromise the quality and safety of construction projects [144,150].

The literature highlights that the perceptions of various stakeholders toward incorporating CE practices in construction significantly impact their adoption. The reluctance of contractors to use recycled or refurbished materials in their projects stems from concerns about the potential decline in the quality of their work. They fear that using such materials may adversely impact the durability and reliability of the structures they construct [42,144,150].

Similarly, customers may not prefer buildings made using old materials due to the perception that they may not be aesthetically pleasing or may lack modern features. Furthermore, the quality of reclaimed materials is often viewed as inferior to virgin materials, which further fuels skepticism about the feasibility of CE practices [149].

5.4.3. Stakeholder Engagement and Awareness

Addressing existing cultural and behavioral barriers is essential to facilitating the widespread adoption of CE practices in the construction industry. This can be achieved through various initiatives, including training, education, awareness-raising activities, and cultural change through work culture. By doing so, stakeholders can work toward creating a CE, which would benefit the industry and the environment.

Open and honest communication between different groups of stakeholders can increase awareness of important issues, challenge assumptions and biases, and ultimately lead to a shift in attitudes and behaviors. It allows people to share their perspectives, experiences, and concerns and encourages active listening and empathy. Through dialogue, individuals can gain a deeper understanding of complex issues, build trust and respect, and work towards finding common ground. Dialogue is a powerful enabler for promoting CE [145]. This can involve open and honest communication between stakeholders, including industry professionals, academics, and government officials. Through dialogue, stakeholders can better understand each other's perspectives and work collaboratively toward finding solutions to industry challenges.

Academic engagement and professional workshops are also essential enablers for promoting CE [145]. These educational opportunities give stakeholders ideas and knowledge to address industry challenges and help them to be equipped with the skills and expertise needed to implement CE practices.

5.4.4. Governmental Support and Incentives

The global construction industry needs more adequate policies, laws, and frameworks to adopt circular practices and business models. Government support, such as financial aid or tax incentives, is needed to make it more economically feasible to invest in circular models. This, in turn, discourages their adoption. The absence of regulatory pressure and strict laws fails to establish the necessary urgency for circularity. As a result, the required behavioral changes in the construction industry are not taking place. This pressing issue needs to be addressed so that the construction industry can move towards a more sustainable and circular future [42].

Circular buildings are gaining popularity as we move towards a more sustainable future due to their environmental benefits. Circular buildings are designed to promote the idea of "building as a material bank" [147], which means that the materials used in the construction of the building can be stored and reused when the building is no longer needed. This approach minimizes waste and reduces the construction industry's carbon footprint. However, designing circular buildings requires careful planning because they need to be easily deconstructed and reconstructed. This is because circular buildings are designed to be disassembled, and all materials are recycled or reused at the end of their useful life. Therefore, the design of circular buildings should prioritize using modular components and materials that can be easily separated and recycled. While the benefits of circular buildings are clear, some challenges need to be addressed. One of the main challenges is the cost, as circular buildings are generally more expensive to construct than traditional buildings. However, governmental support and incentives for circular buildings' long-term economic and environmental benefits can offset this cost.

The circular economy in the construction industry is a complex issue requiring all stakeholders' involvement, including governments, investors, designers, constructors, and users. The transition towards circular practices requires a significant change in mindset and approach and the adoption of new technologies and systems. Nonetheless, the benefits of circularity in the construction industry are far-reaching, including reduced waste and carbon emissions, increased resource efficiency, and improved social and economic outcomes. Therefore, all stakeholders must collaborate and work toward a more sustainable future for the construction industry.

6. Case Studies and Best Practices

This section presents a series of case studies where principles and criteria based on the circular economy have been successfully applied in the building sector. Different elements have been considered within all stages of the construction process, such as materials, construction systems, furniture, and complete buildings.

6.1. Polyblock System (Germany), [49]

The Polyblock has emerged as a prefabricated block-type construction component (Figure 17) that is intended to be used as an alternative to conventional concrete. Its design is based on the reuse of waste materials together with the rational and responsible use of local materials. These blocks are composed of two distinct parts, the cover or shell and the inner filling based on EPS or mineral wool. The shell is made from polymer concrete, a material composed of 12% unsaturated terephthalic polyester resin, which contains up to 38% recycled PET as a binder and up to 88% filler material, such as local sand or secondary raw materials recovered from industry or the construction sector, such as slag, tailings, or construction and demolition waste.

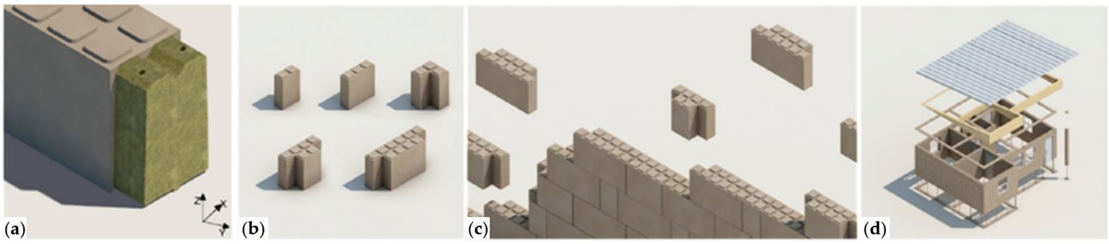


Figure 17. Polyblock construction component: (**a**) composition of the block; (**b**) different block configurations; (**c**) wall assembly process; (**d**) final result (Source: Kouvara et al. [49]).

Mechanically, the block demonstrates very good strength, both in compression (90–13 MPa) and bending (MPa), exceeding those obtained for cement concrete. Likewise, due to the significant amount of thermal insulation contained in the block, its thermal behavior is also improved, obtaining wall thermal transmittance values of 0.4–0.55 W/m^2·K. In addition, it has a low specific weight.

The design of the block allows the materials of which it is composed to be recovered again at the end of its useful life. Firstly, the insulating filler can be easily extracted, with little or no contamination with other materials, and then crushed and sieved to obtain different particle sizes. Secondly, the additions contained in the resin shell can be recovered through electrodynamic fragmentation, so that they can be reintroduced into the production of new Polyblocks. The process of building a wall with these blocks, which is rather similar to an assembly, is performed by stacking the blocks and connecting them with threaded rods. This facilitates the assembly and disassembly of the parts as required for the repair of individual components or the complete disassembly of the construction element at the end-of-life stage.

6.2. Concrete Structure with Recycled Aggregates (Korbach, Germany), [152]

In this project, the concept of urban mining (Figure 18) is put into practice, applying circular economy criteria from the design phase of the building. Nowadays, recycled concrete aggregate is widely known in the construction sector; however, its main use is as filler in road construction. In this case study, the old concrete structure of the Korbach town hall was demolished and reconstructed using concrete with recycled aggregate from the old structure, resulting in a total floor area of 4373 m² built.

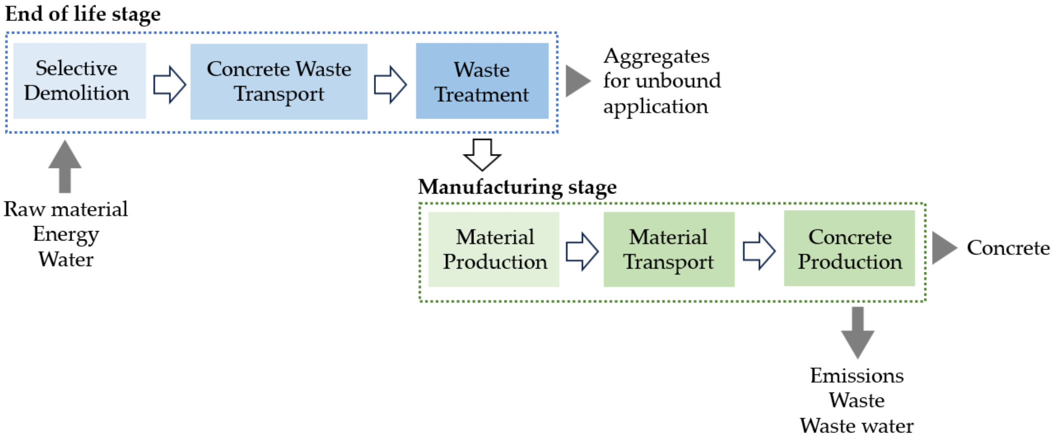


Figure 18. Stages, income, and outcomes of recycled aggregate concrete production (Source: authors based on Mostert et al. [152]).

First, a selective demolition of the structure was conducted, thus facilitating the subsequent separation of the different materials in accordance with German regulations [153] and European guidelines [154]. A total of 7060 tonnes of concrete was demolished and transported to a mobile treatment plant 41 km from the construction site. At the treatment plant, the rubble was crushed, screened, and separated from the steel waste through magnetic separation. The plastic and wood waste were then removed using an air sifter and manual sorting.

For the construction of the new structure, two different dosages were used, the first with 43% recycled aggregate for elements exposed to nonaggressive environments (XC1 class), such as interiors, and another dosage with 35% recycled aggregate designed for exposure to humid environments (XC2 class) for the foundations. In all cases, the cement used in the mixes was CEM II/A-LL.

To determine the total environmental impact of this case, a lifecycle analysis of the structure was conducted considering the product footprint, i.e., taking into account energy, water, and environmental factors of the materials and services required for its manufacture. The following factors were analyzed at all stages of the material production: the selective process in the demolition, the transformation in the mobile plant, and obtaining the final concrete. The results show that the use of recycled aggregate reduced the use of raw materials by 37% for the XC1 dosage compared to conventional concrete, although it should be noted that in the case of using 100% recycled aggregate, the savings in original raw materials could reach up to 50%. It is worth noting that the use of these aggregates may increase water consumption, depending on the process of obtaining the aggregate, thus increasing the environmental impact of the final product.

6.3. The Circular Kitchen (Delft, The Netherlands), [155]

This project approaches the development of a housing component in a holistic way, from the design of the component itself to the supply chain and the business model, to achieve a solution as sustainable and circular as possible. To this end, collaborative work has been conducted between housing associations, companies involved, such as manufacturers, material and appliance suppliers, and contractors. The opinions of all these stakeholders have been recorded and evaluated throughout the development process.

This research had a two-fold approach: to extend the useful life of a component for social housing, which is usually around 20 years, and to make it easily dismountable and reusable or adaptable at the end of its useful life. These products are usually made up of pieces of chipboard with a honeycomb finish, joined together using glue. This, together with their low price and low adaptability, makes them elements with great potential to achieve significant reductions in the use of resources and waste generation.

The main difference between the circular kitchen (CIK) and a conventional kitchen is based on its design, considering first of all the demountability and durability of the materials. These strategies allow for the generation of a closed cycle, as well as the deceleration of the renovation process within the same unit. Based on a modular system (Figure 19), the structure of the CIK is formed by a base or docking frame, where the different modules are connected and disconnected without the use of tools, thus allowing a great variety of possibilities within the system itself. The material chosen for the construction of the system was primarily highly durable plywood. The result is a product that can be adapted to the user's needs at any time, avoiding the need for full replacement in an easy and convenient way and saving tons of waste in landfills while preventing the use of natural resources.

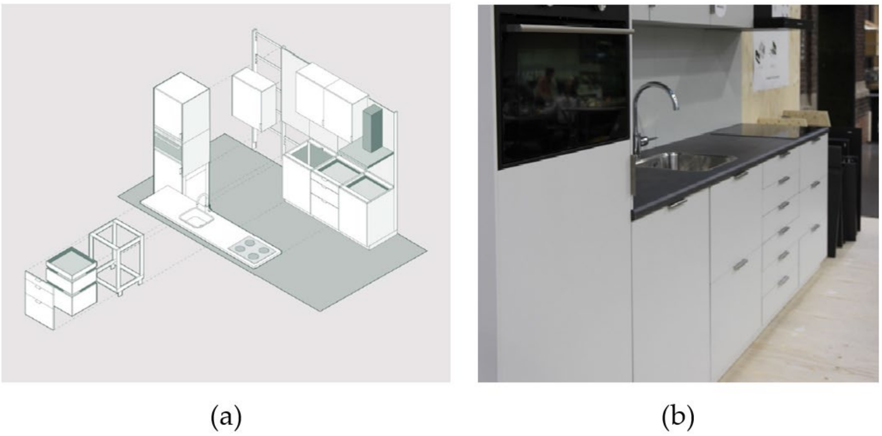

(a) (b)

Figure 19. (**a**) CIK demonstrator technical design concept; (**b**) CIK prototype 1 (Source: Wouterszoon Jansen et al. [155]).

CIK not only applies circular economy strategies to product design but also encompasses the development of a business system based on these same principles. The prototype was tested in a series of social housing units; therefore, CIK was sold to housing associations, which installed the cookstoves in eight housing units. The CIKs had a subscription scheme, whereby the supplier provided assistance in the case of changing, extending, or returning any of the modules at the user's request.

After the construction of the first prototype, the CIK has undergone several changes according to the requirements of the producers, always trying to remain faithful to the concepts of circularity that gave rise to it. The main change took place in the basic structure of the kitchen, which is now made up of removable panels of sustainable chipboard, contributing to the greater repairability of the system. In addition, the modules were redesigned so that the side panels could be installed without any type of exterior coating (saving on the use of materials and resources), with this coating only being necessary on the horizontal shelves, as these suffer greater wear and tear during the useful life of the product.

The CIK as an alternative to conventional kitchens has proven to generate a lower impact on the environment through a design that encompasses all stages of the product lifecycle, prioritizing the durability, adaptability, ease of disassembly, and reusability of each component.

6.4. VELUXlab (Milano, Italy), [156]

This case study focuses on the energy renovation of a building in Southern Europe, designed by ACTX/IDOM studio, which was a modular housing building that was transported and assembled onsite. The project approaches the concept of circular economy from several perspectives: the reuse of previously built structures for reuse, the application of recycled and recyclable materials, and the concept of design for disassembly.

In the new design, a change in use from housing to offices and research centers has been conducted, where maximum efficiency has been prioritized with the use of minimum resources. The design process of the refurbishment was based on the active house methodology, which evaluates indoor comfort, energy efficiency, and environment impact while prioritizing sustainability and the well-being of the occupants. All project decisions were based on a continuous analysis of the lifecycle of the materials and solutions used in the renovation, taking into account aspects related to the environmental impact of the production of the materials, the service life of the building, and its end of life.

The external deterioration of the old facade led to the proposal of a new envelope reusing the old enclosure as a base, which was used to modify the construction system and reduce its thermal transmittance. In the new solution, both recycled and recyclable materials were used. In this sense, recycled glass panels with a plaster finish were used as the exterior cladding, leaving a 3 cm-thick ventilated air gap, thus improving the performance of the façade, especially in summer. For the next layer of the envelope, prefabricated rigid polyurethane panels were used, which had ledges to support the exterior finish while allowing natural air movement in the cavity. These panels were placed on a steel substructure to ensure a good connection. Figure 20 shows a schematic diagram of the construction solution implemented in this rehabilitation.

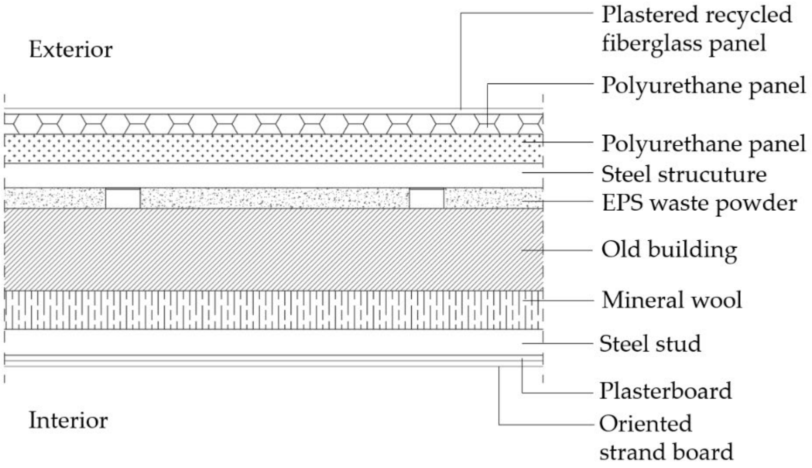


Figure 20. Schematic cross-section ofaçadefacade wall (Source: authors based on Brambilla et al. [156]).

On the other hand, the poor uniformity of the old facade resulted in some gaps between the old building envelope and the new one, which compromised the maximum efficiency of the solution. To solve this, it was decided to fill these gaps with powdered polystyrene waste from the construction site disposal. This solution proved to be the most suitable as, due to the transport of other elements, there was a large amount of EPS packaging waste available onsite. In addition, the insulating power of this material was found to be similar to other insulators, such as rock wool or polystyrene, with the advantage that it reduced the global warming potential (GWP) by up to 60% compared with commercial XPS.

Ultimately, the new solution has allowed the energy performance of the refurbished building to be optimized by using more sustainable recycled materials and employing dry systems that enable future disassembly at the end of the building's useful life. Overall, the aim has been to reduce the energy embodied in the construction while minimizing energy use during the use phase of the building, resulting in an environmentally and energetically sustainable building.

7. Discussion and Conclusions

This paper reviews the main challenges in circular construction material usage and proposes collaborative solutions. Circular construction materials can revolutionize sustainable building practices by adopting circular principles. By embracing this approach, the construction industry can substantially reduce its environmental impact, conserve natural resources, and build a more resilient environment. However, many challenges must be addressed to facilitate the widespread adoption of circular construction materials.

Based on the conducted state-of-the-art review, specific recommendations for addressing the challenges of the widespread adoption of circular construction materials are highlighted, and future directions are addressed. This interdisciplinary review study also explored the circular material usage strategies and principles in buildings; several barriers, critical success factors, and enablers are also identified within the scope of this research niche.

The construction sector is a significant contributor to waste generation and a major consumer of resources. However, it also has the potential to play a leading role in the transition to a circular economy. The construction sector can reduce its environmental impact by implementing design principles for circular material usage, conserving resources, and promoting sustainable material use. The key design principles for circular material usage in the construction sector include designing for circularity and material selection and management. Buildings should be designed to be durable, adaptable, and easy to disassemble. This will facilitate the reuse, recycling, and upcycling of materials at the end of the building's lifecycle. Construction materials should be selected based on their environmental impact, recyclability, and durability. And construction waste should be minimized and managed to maximize the recovery of materials. The implementation of these design principles will require collaboration between all stakeholders in the construction sector, including architects, engineers, contractors, and material suppliers. However, the benefits are clear: a more circular construction sector will be more sustainable, more resilient, and more competitive. Implementing design principles for circular material usage in the construction sector can lead to reduced costs, increased innovation, and improved job creation, in addition to the benefits mentioned above.

Additionally, this review addresses the importance of the shift toward a circular economy (CE) in buildings that involves collaborative business models and technological innovations. Circular supply chains, product-as-a-service models, and extended product responsibility are pivotal for sustainability. Public–private partnerships offer promise but need careful management. Future efforts should focus on robust regulatory frameworks, awareness programs, and international collaboration. Technological advancements, including AI, robotics, and blockchain, must be integrated for efficient waste management. Education on circular practices is crucial. Global collaboration can standardize circular construction approaches, fostering a more sustainable and resilient industry that, according to the perspective of this review paper, prioritizes resource efficiency, circular practices, innovation, stakeholder collaboration, and adaptive strategies to minimize environmental impact and maximize sustainable practices throughout its operations

Considering the above conclusions drawn from our study, there are significant and far-reaching implications for applying CE principles within the construction industry. This review recommends actionable steps to integrate these principles into practical applications, including design principles for circular material usage, collaboration among stakeholders, technological integration, and the need for robust regulatory frameworks. These recommendations present a roadmap for future implementations and provide a tangible framework for policymakers, practitioners, and stakeholders to adopt and implement these principles. By embracing these conclusions, the construction industry can successfully transition towards a more sustainable and resilient future, reducing environmental impact, conserving resources, and fostering innovation. Additionally, the integration of these principles aligns with the broader global agenda of sustainability, contributing significantly to the advancement of CE practices beyond the confines of the construction sector.

The review of the implementation of CE principles in the construction industry has revealed some vital lessons to improve sustainability and reduce environmental impact. However, the slow adoption of these principles can be attributed to some industry-specific barriers, such as limited knowledge and experience. Therefore, there is a need for a collective effort toward educating and disseminating information to overcome these barriers. Embracing innovation presents a promising way to drive circularity. Successful case studies of circular practices can provide valuable insights for broader industry adoption. Developing robust regulatory frameworks can incentivize sustainable practices, while integrating advanced technologies can optimize waste management processes. Education on circular practices is essential, and global collaboration is critical for standardizing universally accepted approaches.

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