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Review

Circularity Outlines in the Construction and Demolition Waste Management: A Literature Review

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Abstract: This study provides a comprehensive view of the research field of construction and demolition waste (CDW) management in the circular economy based on a literature review. The increased intensity of interest is due to the need to create frameworks, mechanisms, and tools for the process of mind-shifting towards circularity. Research topics, researched life cycle stages, strategies for CDW management, sustainability assessment, building stock quantification, assessment tools and forecast methods, materials with CDW content, waste treatment solutions, and the barriers and drivers for efficient waste management in the construction industry are identified as the main concerns in the analyzed research field. The results show that a major concern in the academic field directs research to the path of innovative strategy elaboration, identifying the enablers and barriers in CDW management, computational tool creation for design and assessment, building stock modeling, and circular building material development. The environmental approach prevails, leaving economic and social assessments in CDW management uncovered. Although stakeholders' involvement is stressed in most cases, strategies for awareness-raising and education for a sustainable circular activity in the field are lacking. The circularity of CDW management being a multifaceted and multi-disciplinary complex challenge, it is approached on different levels. This study introduces the novelty of structuring the trends of existing knowledge in a holistic view, identifying the research directions, dimensions, specific aspects, and instruments.

Keywords: circular economy; construction and demolition waste; recycling; recycled materials; sustainability

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Citation: Gherman, I.-E.; Lakatos, E.-S.; Clinci, S.D.; Lungu, F.; Constandoiu, V.V.; Cioca, L.I.; Rada, E.C. Circularity Outlines in the Construction and Demolition Waste Management: A Literature Review. *Recycling* **2023**, *8*, 69. https://doi.org/10.3390/recycling8050069

Academic Editor: Lucía Fernández-Carrasco

Received: 29 July 2023
Revised: 4 September 2023
Accepted: 5 September 2023
Published: 11 September 2023

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1. Introduction

Significant global challenges such as depletion of natural resources, pollution, climate change, and the loss of biodiversity due to intensive raw material extraction, population explosion, and rapid urbanization have heightened the urgency for a transition towards more sustainable societies [1,2]. The accelerated economic growth and rise in consumption patterns have led to a scarcity of resources and an unmanageable accumulation of waste, posing threats to human health and the environment. Recent instances like the COVID-19 pandemic, the Suez Canal crisis, and the war in Ukraine have underscored the drawbacks of our excessive reliance on primary natural resources.

The construction sector is the principal consumer of resources and generator of waste in Europe, making a substantial impact on the economy, local employment, and the standard of living. It uses large quantities of resources and is accountable for about half of all extracted material. The sector contributes about 9% to the EU's GDP, and more than 35% of

the total waste generation in the EU is attributed to this sector. The processes of extracting materials, producing construction materials, and building and renovating structures are estimated to contribute to 5–12% of the total national emissions [3]. The principal element of total waste production in contemporary society is waste from construction and demolition (CDW). The three most prominent economies, China, the United States, and the European Union, are also the leading producers of CDW [4].

CD materials comprise concrete, stone, brick, gypsum, glass, various metals, wood, asphalt, plastic, asbestos, gravel, and dug-up soil. Approximately 90% of the CDW volume in the EU is concrete waste [5]. The construction sector produces the largest and heaviest waste streams [6] and accounts for 25–30% of the total global waste [5]. Thus, the construction sector presents an enormous opportunity to reduce climate change impacts and enhance material efficiency through a shift towards a circular model.

The traditional linear economy model based on the concept of 'take-make-use-dispose' must be replaced with an innovative framework that preserves the value of natural resources within a closed loop. The circular economy (CE) offers a promising alternative by turning waste into resources and uncoupling economic growth from finite resource consumption. The concept of a circular economy is characterized as an industrial system that is intended to be restorative or regenerative, eliminating the 'end-of-life' concept and toxic chemical use, and striving for waste elimination through improved material, product, and system designs [7,8]. This system operates at various levels, from the micro (products, companies, and consumers) to the macro (cities, regions, and nations), with the goal of achieving sustainable development while maintaining environmental quality, economic prosperity, and social equity for current and future generations.

Initially, CE used the 3R strategy (reduce, reuse, recycle), but recent shifts have emphasized the 10R strategy (R0-refuse, R1-rethink, R2-reduce, R3 reuse, R4-repair, R5-refurbish, R6-remanufacture, R7-repurpose, R8-recycle, R9-recover, and R10-regenerate), prioritizing strategies based on their level of circularity [9,10]. The waste management hierarchy indicates a preference list of actions to manage waste in accordance with CE concepts [4,11,12]. The Waste Framework Directive 2008/98/EC (WFD) played a crucial role in modern waste management by prioritizing prevention and setting a minimum target for EU member states of achieving 70% by weight by 2020 for the purposes of reuse, recycling, and backfilling.

The text could be restated as follows: The European Commission suggested guidelines for the enhancement of waste identification, source separation, collection, logistics, processing, and quality management as a part of The Construction and Demolition Waste Protocol in 2018. The European Green Deal framework aspires to position Europe as the premier continent to achieve climate neutrality. The EU Action Plan's objective of achieving zero pollution for air, water, and soil identifies the CDW stream as crucial for executing circularity, while the Renovation Wave initiative is geared towards doubling renovation rates in the upcoming decade to boost energy and resource efficiency [13]. The increasing awareness and financial support from various funding agencies have prompted the development of innovative management strategies such as the VEEP, InnoWEE, RE4, HISER, IRCOW, and C2CA projects to support the transition to a circular economy.

Implementing CE principles in the construction sector entails preserving the maximum value of building components and resources for an extended duration through continuous use, reutilization, mending, and recycling. Essential tactics for advancing the industry's shift towards a circular economy involve the use of sustainable and long-lasting materials, embracing designs intended for disassembly, employing modular and prefabricated components, and devising recovery plans [1]. Achieving circularity in managing CDW calls for a collaborative effort from public authorities, academia, stakeholders, and society, as well as a shift in thinking from linear to circular. This study aims to contribute to the body of knowledge by offering a structured holistic view of the findings, referring to research trends, development directions, pivotal interest points, reference frames, and the evolution and improvement of instruments and circular construction materials up until 2021. As a multi-disciplinary emerging field, CDW management and its research have a large variety

of perspectives, focusing on very specifically delineated technical aspects, universally manageable visions, and integrated strategies and solutions. Specific to CDW sustainable management is also the necessity to create clear-cut, locally applicable circular projects based on national and international directives and regulations, raising the complexity of the circular transition challenge. Although reviews in this field have intensified recently, most of them approach specific aspects of CDW management. This study structures and integrates in a comprehensive manner the existing major concerns, their approaches, and assessment methods, highlighting the directive lines of the existing academic research of the CDW.

Efficient handling of CDW is crucial in concurrently striving for environmental sustainability, economic progress, and social fairness, not only for the present but also for future generations. As a field in development, it focuses on standardizing innovative procedures while adapting to specific local and contextual conditions. The objective of this study is to offer an in-depth perspective on the domain of construction and demolition waste management within the context of a circular economy by conducting a thorough review of the literature. It explores the main research topics and approaches, creating a framework that captures the state of the art in relation to strategies, methods, assessment tools, circular materials, and the drivers and barriers to implementing circularity principles. Thus, the key objectives are to analyze the research field's context, identify focal points of interest, and characterize the current leading-edge developments in the field of construction and demolition waste management research, considered within the framework of the circular economy, for a comprehensive method.

2. Materials and Methods

In order to deeply understand the transition from a linear to a circular economy in handling construction and demolition waste and achieve the set objectives, an extensive literature review was carried out. As a starting point (refer to Figure 1), the terms "circular economy" and "construction and demolition waste management" were used to explore the Web of Science's electronic database for relevant literature. The Boolean operator "AND" was applied in the "topic" field to study how the pressing issue of waste management in the construction industry is being tackled from the comparatively new perspective of the circular economy. This initial search yielded 316 documents. We fine-tuned the search by only including open-access publications and restricting it to peer-reviewed articles. Most of the retrieved publications were in English, with only one being excluded based on language. The search was limited to documents published up until 2021, inclusive. Once articles published in 2022 were excluded, 72 articles remained for a thorough review and analysis.

After the systematic literature review, to present a more comprehensive understanding of the need for a shift towards integrating circularity at the heart of CDW management, the gathered information was organized based on the necessary parameters of a context and content analysis. The context analysis covered temporal, spatial, and source-related examinations to illustrate the escalating interest in the research field of CDW management. The content analysis was structured around variables linked to research topics and explored life cycle stages, strategies for CDW management, sustainability assessment, quantification of building stock, assessment tools and forecasting methods, materials containing CDW, waste treatment solutions, and the recognized obstacles and resolutions for efficient waste management in the construction sector transitioning to a circular economy.

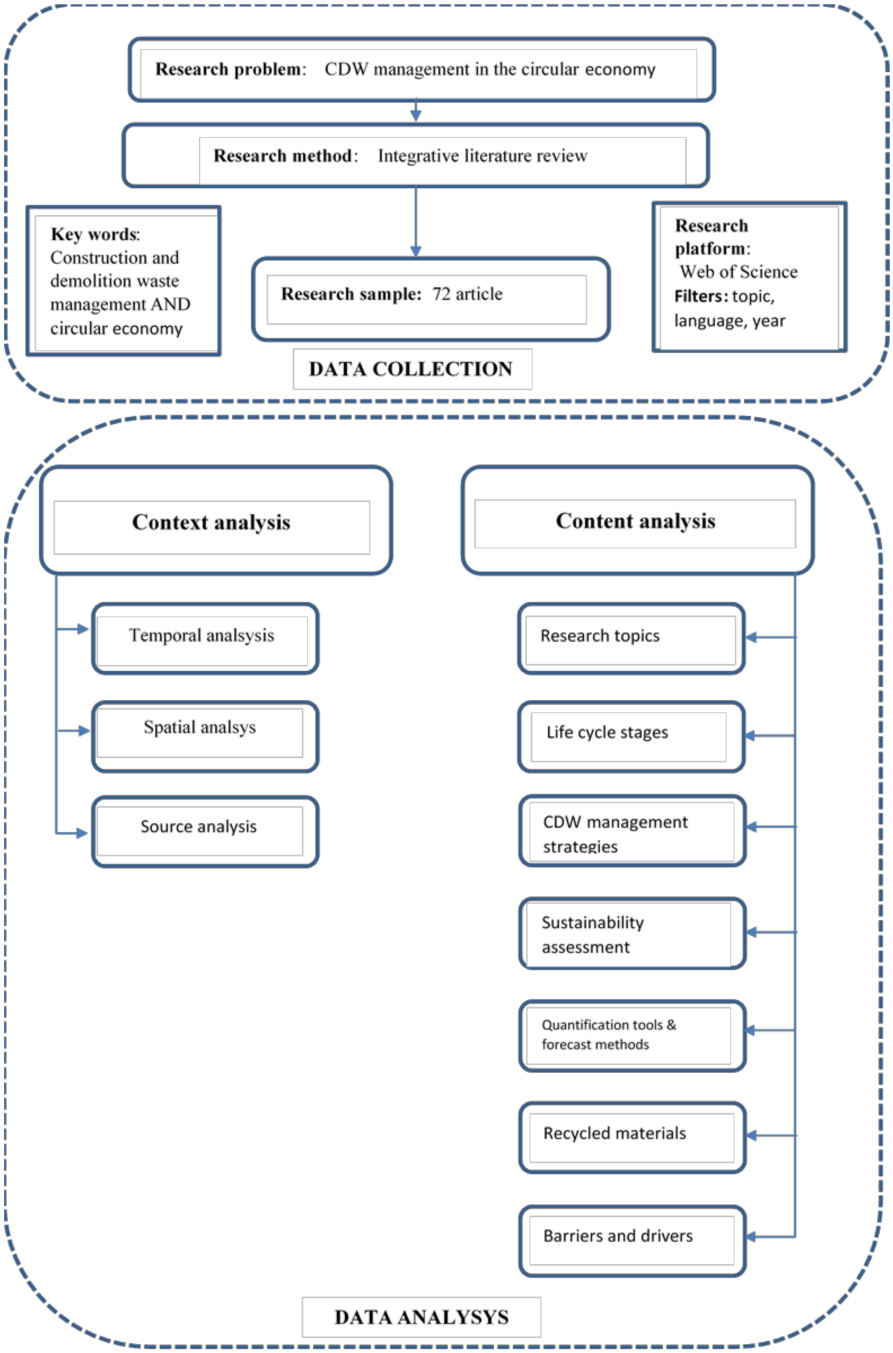


Figure 1. Methodology.

3. Results

3.1. Context Analysis

By linking the concept of CE to CDW management, the selected articles reveal a complex view of the evolution of the transition phenomenon. The context in which the academic studies were published describes the way in which the scientific community approaches the topic, disseminates relevant information and findings, and suggests further research directions. The context analysis was performed on the temporal, spatial, and data source criteria.

As shown in Figure 2, there's been a rising interest in recent years in CDW management within the framework of the CE, as evidenced by the increasing number of articles published on the topic, particularly from 2018 onward. There could be several reasons for this trend.

It is worth noting the specific waste regulations that have been implemented in recent years at the global, European, national, and, in many cases, even local or corporate levels. Simultaneously, waste management is becoming an increasingly complex issue, despite the innovative solutions presented by circular strategies.

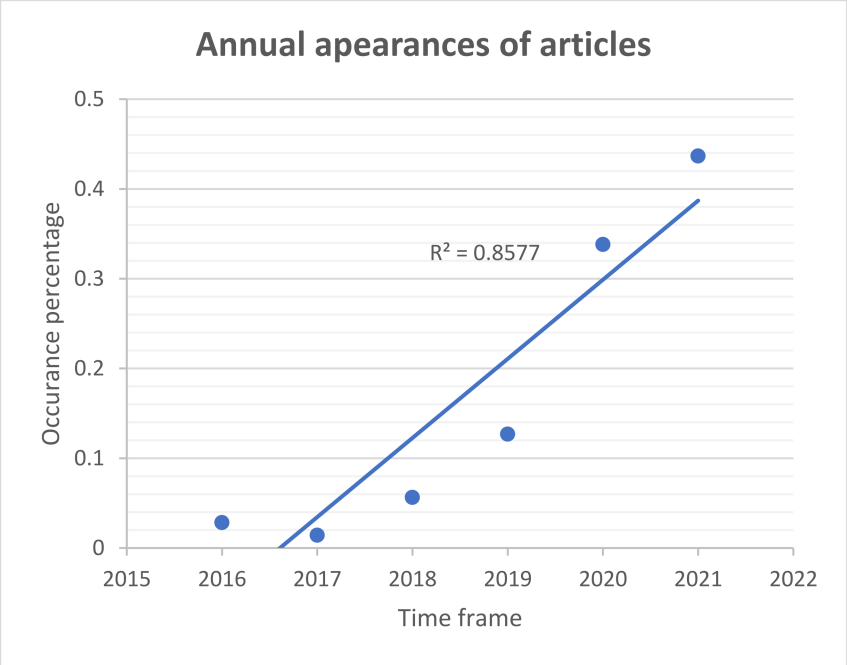


Figure 2. Annual appearances of articles.

The predominance of primary data from research articles (Figure 3) suggests that this multidimensional and interdisciplinary research field is in its early stages, with a crucial need to provide practical and persuasive solutions for construction efficiency and sustainability in the built environment. Advancements in technologies that offer data, impact assessment methodologies, and quantification tools, as well as the development of materials containing recycled CDW, could enhance resource efficiency and the effectiveness of waste management strategies.

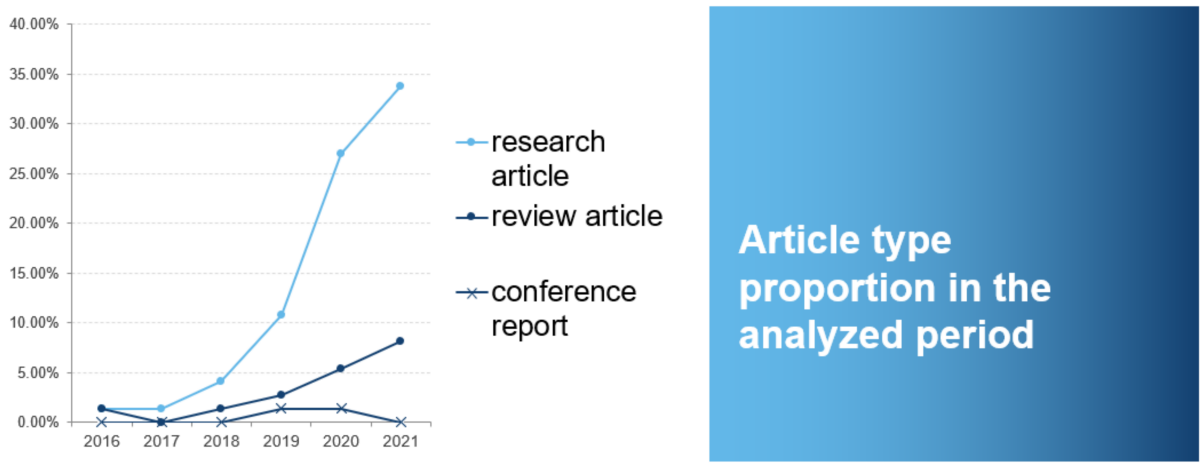


Figure 3. Reviewed articles by type number of the document or the authors h-index.

Following the time-based and source analysis (Figure 4), a mapping process was conducted to pinpoint the system level at which the research in the sample articles was

carried out. Additionally, an overview of the countries most active in researching CDW management in the context of the CE was developed.



Figure 4. Number of articles in scientific journals.

As depicted in Figure 5, excluding research articles that are agnostic to specific geographic or administrative regions, the majority of studies, over 30%, are focused at the national system level. This is followed by studies conducted at regional and then European levels. The definition of regional system level includes areas within national borders, such as the Campania Region in Italy [14], Baden–Wuttemberg in Germany [15], or Flanders in Belgium [16], but also extends to research across transnational geographical zones, like the Mediterranean area, which includes parts of Italy, France, and Spain [17], or the western Balkans [18].

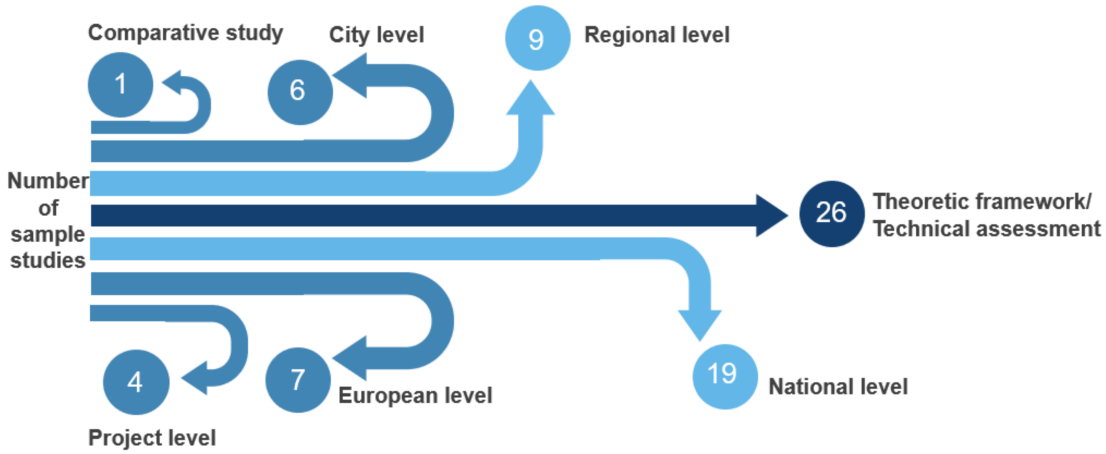


Figure 5. System level approach of CDW management in the circular economy.

Research conducted at the city level often centers around urban mining, a strategy that is seen as key to the transition to a circular economy [12,19]. Urban mining is the process of reclaiming materials and parts from discarded buildings, infrastructure, or waste, considering the built environment as a unified system functioning as a storage for materials. It perceives waste (irrespective of its origin) as an intermediary stage to produce new materials [12,19–21]. Although the concept 'urban mining' doesn't have a definitive explanation, it is commonly understood as the procedure of retrieving materials from artificial sources and could include elements such as energy reclamation and product

design [21]. Gassner et al. suggest that recycling of construction materials should be addressed at a local level due to their relatively low value and high mass, which limit their economic and environmental transport distances [22].

In terms of country-based activity (Figure 6), it is evident that researchers from all around the globe are interested in practices for managing CDW within the context of the CE. The Netherlands leads the pack, followed closely by Belgium and Germany. The level of interest expressed within or for a specific geographical region indicates existing conditions that favor sustainable solutions, either due to a lack of resources or as a result of potential future benefits being explored.

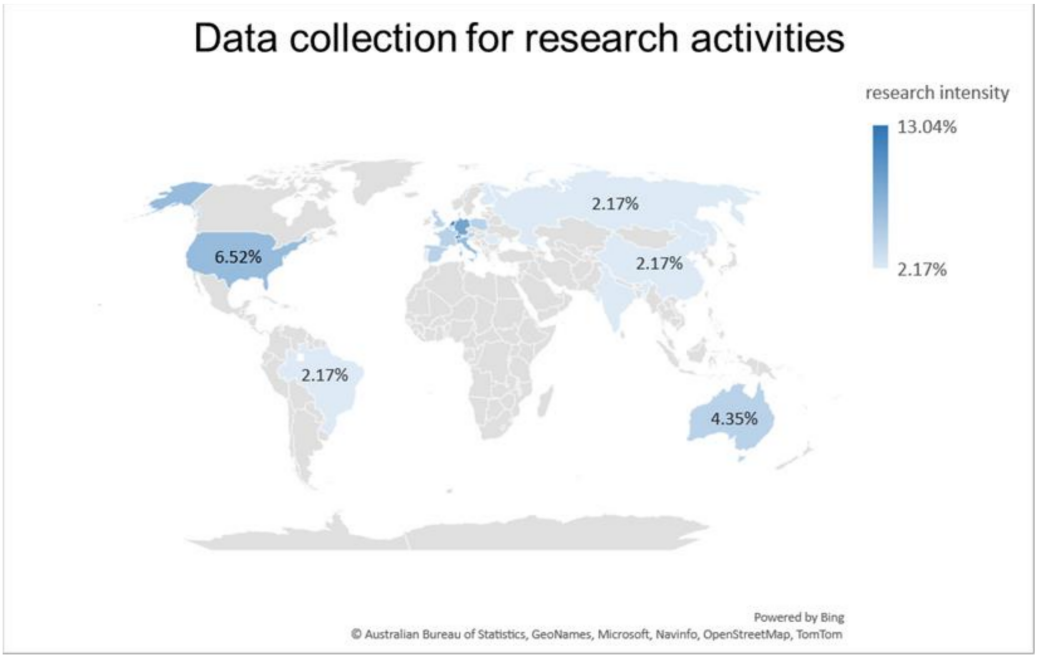


Figure 6. Countries where the case studies and research were conducted.

3.2. Content Analysis

Research topics

As awareness around sustainability increases and concerns regarding the economic, social, and environmental consequences of CDW generation intensify, attention is shifting towards repurposing waste into valuable resources. To achieve this, the primary aim is to embed circular strategies within CDW management practices, necessitating a multi-faceted and interdisciplinary approach that bolsters the decision-making process [23,24]. Research directions are diverse and include a range of assessment methodologies, subjects, geographical regions, and management levels, examined either broadly or in specific combinations. The primary themes identified from the reviewed articles are illustrated in Table 1.

Table 1. Main topics in the research field of CDW management in the CE.

Topics	References
Development of circular building materials	[25–31]
Building material stock modeling	[5,21,32–36]
Computational tools for design and assessment	[37–43]
Strategies, enablers, and interventions for achieving sustainability in CDW management	[44–49]

It is possible to minimize and manage the production of CDW at every stage: pre-construction, construction, building renovation, waste collection and distribution (the end-

of-life stage), as well as material recovery and manufacturing, more effectively. Recycling is often the main topic of CDW management, with recovery and reuse gaining momentum as frameworks for the implementation of various recycling and recovery procedures are developed and backed by case studies. Concepts such as design for deconstruction [2,37], urban mining [12,21,47], selective demolition [6,44], adaptive reuse [50,51], reverse logistics [6,36,52], and closed-loop systems are increasingly being explored. Generally, research tends to focus on the analysis of CDW generation, CDW treatment methods, enhancing the technical properties of products with recycled material content, and the human aspect of CDW management.

CDW consists of waste produced throughout all phases of a building's life cycle, leading to significant environmental consequences. Certain scholars also incorporate waste management from transport infrastructure into their investigations, acknowledging its capacity for utilizing recycled construction materials and its essential function in promoting a more circular method in the industry. As for research that deals with the management of CDW in the built environment from a life cycle viewpoint, full life cycle analyses are frequently employed, as illustrated in Figure 7.

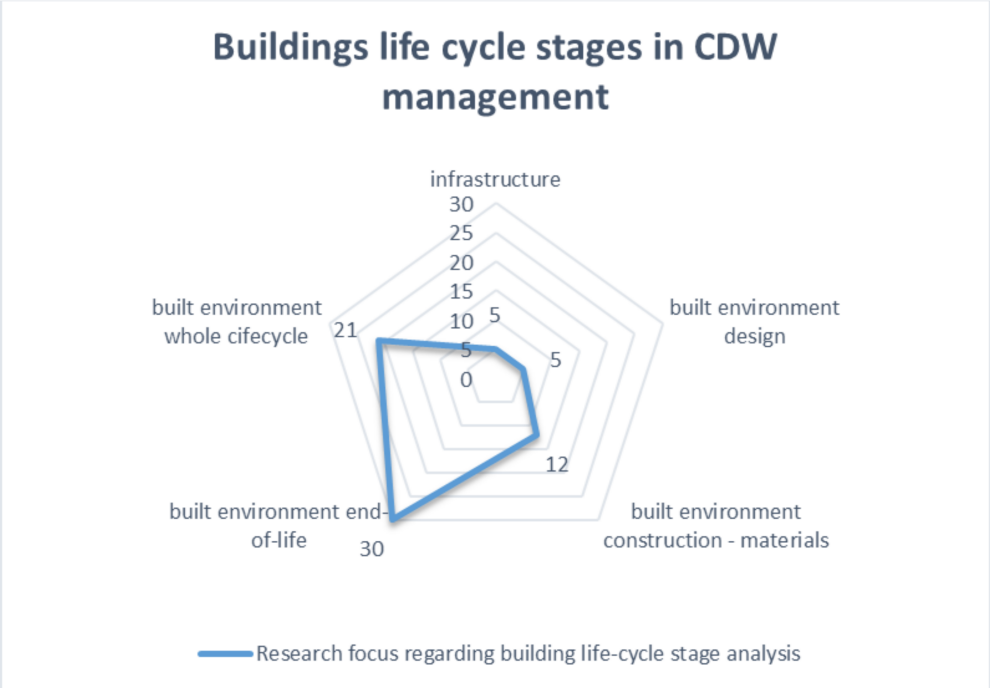


Figure 7. Buildings life cycle stages in CDW management research according to the number of occurrences in the analyzed sample.

A large number of academic papers concentrate on the cradle-to-grave strategy for CDW management, investigating every phase of a structure's lifespan. Adopting this viewpoint can benefit all stakeholders and society at large, as it provides a blueprint for deconstruction or demolition with an extended lifespan for recycled materials in the design phase. It also enables planning for construction and maintenance that minimizes resource consumption, ensuring the preservation of the value and quality of materials during operation.

Most of the research is concentrated on the end-of-life strategy, primarily because most construction components are not designed with deconstruction in mind. In order to prevent the growing accumulation of CDW, it is crucial to discover strategies, technologies, and regulations and gain stakeholder support to manage the reduction, reuse, recovery, and recycling of waste in a sustainable manner.

CDW Management Strategies and Treatment Solutions

The primary objective of CDW management strategies within the Circular Economy (CE) is to divert CDW from landfills, thus preserving the inherent value of materials and products, keeping them within a closed loop, and transforming waste into valuable resources. These strategies are based on the waste hierarchy endorsed by the Waste Framework Directive and follow the 3R, 4R, 6R, or 9R strategies in line with a whole life cycle approach. CE and waste hierarchy advocate for waste management through reimagining, reengineering, and repurposing to amplify resource efficiency and mitigate waste production and its detrimental consequences. The subtle discrepancy is that the waste hierarchy still allows for disposal, while the circular economy model does not [53]. According to the waste hierarchy, the least preferable method of waste treatment is disposal, commonly through landfilling in the construction and demolition sectors. This is followed by the recovery phase, which manages residues through burning and, occasionally, backfilling. The best CDW management strategy is prevention, followed by waste reduction, reuse, and recycling. An efficient CDW management strategy must prioritize according to the waste hierarchy, the building's life cycle stage, and available economic, regulatory, technical, and educational tools. The CE framework consists of four key elements: 1. sustainable business model innovation, 2. closed-loop systems, 3. product-service system, and 4. innovative sustainable business models aim to significantly diminish the adverse environmental effects of construction waste. The focus of closed-loop systems is on resource preservation during product design and creation, whereas product-service systems tend towards providing a service rather than products as their primary business strategy [54].

The waste hierarchy's five layers merely provide general guidelines for CDW management. Strategy development and policy formulation must consider the specific situation to which they apply, guiding increased circularity in CDW management in the future.

The first strategy to avoid waste generation and preserve natural raw materials is prevention. This strategy primarily refers to the pre-use phase of buildings, i.e., the design, construction, and production stages. From the 9R strategy, it involves refusing, rethinking, and reducing potential waste generation. Minimizing construction waste during the design stage and construction operation could be a more cost-effective approach compared to remedial actions. For the design stage, the main methods and tools developed and analyzed in the sample articles refer to design out waste, design for disassembly or deconstruction, pre-cast construction, and modular construction design. In terms of operations before construction begins, scholars highlight the importance of a site waste management plan. This involves identifying waste streams and establishing tools for monitoring, collection, and the promotion of appropriate waste management practices, complete with quantifiable indicators and objectives. Roughly one-third of waste production at a typical construction site is due to the designers' failure to incorporate waste prevention methods during the design phase [55]. Material use reduction is enhanced both by the design of circular buildings and by the site waste management plan, accompanied by efficient construction material procurement.

The emphasis of reuse is on prolonging the life of structures and incorporates the strategies of reusing, repairing, refurbishing, remanufacturing, and repurposing from the 9R methodologies. The best option for CDW management is to reuse the entire building. In many cases, the first end-of-life (EoL) strategy is demolition, as most of the buildings were not designed for disassembly. However, selective building deconstruction or adaptive reuse is an alternative to demolition. Reusing materials encompasses the continual application of materials in similar construction operations or their incorporation as new components in alternative processes. Typical uses for repurposed demolition waste materials include land restoration, road construction, and replacing concrete aggregates [2,50,51,56].

Recycling is the most studied strategy, and it covers the post-use phase of the building stock, implying the useful application of materials. The objective of recycling is to convert CDW into new products suitable for reuse in the construction industry or other economic sectors. By preventing the wasteful disposal of potentially useful materials that would otherwise be discarded in an environmentally harmful or costly manner, recycling simul-

taneously reduces the demand for new, unprocessed resources [28]. Recycling involves the on-site sorting of materials and their reprocessing to convert them into new products. Down-cycling and up-cycling differentiate between recycled materials with lower or higher quality or functionality compared to the original product. The expenses associated with handling and recycling construction and demolition waste (CDW) for the secondary production of value-added items can be substantial, given steps like material screening and reprocessing. This places a significant financial burden on companies specializing in CDW treatment, pressuring them to generate profit [48]. The most recycled material in the construction and demolition sectors is concrete for concrete recycled aggregates. The revised WFD introduced the end-of-waste (EoW) criteria to promote recycling and transform waste into valuable resources. EoW criteria fix a set of conditions that, when fulfilled, make waste cease to be waste and can be regarded as a freely marketable material. After a recovery process, if waste has a useful purpose and there is demand for it, complies with the specific technical requirements and standards applicable for similar raw materials, and does not impose risks on human health or the environment, it can be considered that it has reached EoW status. The main objectives of the EoW criteria are to remove bureaucratic burdens, encourage recycling, promote the quality of recycled materials, and develop secondary material markets.

CDW management has a complex task for which the mentioned strategies and methods must be applied contextually and in combination to create a circular use of materials and support the goal of sustainability. To achieve this, efforts need to be made to develop the entire value chain: firstly, reusing or recycling resources in such a manner that most of the material value is conserved and recovered at the end of the building's life; and secondly, designing components and using various construction methods for reuse [57].

In creating a strategy for efficient waste management in the construction and demolition sectors, other aspects need to be considered, such as transport, regulations, issues about the quality of recycled material, disposal costs, innovative recycling technologies, or economic incentives [58]. All these aspects need to be created in such a way that they support each other and enhance circularity and sustainability. The key to an effective waste management system is the involvement of stakeholders at all levels and phases of the process of creating a sustainable development strategy. The importance of stakeholder involvement and behavioral patterns to identify suitable solutions for identified barriers in the implementation of circularity principles in CDW management has been analyzed and stated by the authors in the reviewed sample.

Table 2 presents the involvement of stakeholders in research to provide efficient solutions.

Table 2. Studies based on stakeholders' involvement.

Method for Stakeholder Involvement in Delivering Solutions	Nr. of Occurrence	References
interview and questionnaire	2	[48,59]
group and questionnaire	1	[54]
interview and workshop	1	[44]
expert consultation in framework design	1	[60]
mentioning as an enabler for CDW management improvement	6	[14,16,55,61–65]

Sustainability assessment

In order to meet the goals of the circular economy, the effectiveness of construction and demolition waste (CDW) management strategies must be evaluated. The significance of sustainability in current and future endeavors, guided by principles of design-led circularity—the eradication of waste and pollution, the sustained circulation of products and materials, and the regeneration of natural systems—cannot be overstated. Many

studies have explored the impacts of CDW management, often utilizing the life cycle assessment (LCA) methodology, which is established by the ISO 14040 standard.

The LCA approach is designed to assess the economic, social, and environmental impacts of a product, service, or activity. It involves four stages: setting the goal and scope, conducting a life cycle inventory (LCI), executing a life cycle impact assessment (LCIA), and interpreting the results. Underpinning LCA is a cradle-to-grave framework, encompassing the entire lifecycle of a product—from the extraction of raw materials through its production and use to its final disposal at the end of its lifespan. The LCA method provides a valuable resource for gauging the environmental influence of a product, not just during its production phase but throughout its entire life cycle. In the context of CDW management, LCA allows for a comparative evaluation between recycled and virgin materials, thereby substantiating its environmental sustainability.

In the literature review, most LCA studies contrasted the environmental impact of natural aggregates with recycled aggregates. However, some studies also evaluated the effect of waste management strategies in different scenarios. For example, [14] performed an LCA for three scenarios in Italy's Campania Region, assessing economic and environmental impacts as well as land use impacts for the landfilling case, the status quo case, and the best-case scenario, where advanced selective demolition and treatment techniques were implemented. The LCA studies with impact categories and the goal and scope definitions are illustrated in Table 3.

Table 3. Studies based on LCA.

Goal and Scope	Reference
Assessing the energy conservation achieved by executing recycling scenarios for the various segments of non-hazardous construction and demolition waste (C&DW) generated in the Metropolitan City of Naples in the year 2017	[27]
Analyzing the life cycle assessment (LCA) of concrete mixtures with recycled aggregates and Portland cement (PC) versus ground granulated blast furnace slag (GGBFS)-based mixtures	[30]
Evaluating the sustainability of a novel noise barrier manufactured from porous concrete made from seashell waste (PCSW) in comparison to a traditional noise barrier constructed from concrete produced with natural aggregates from a quarry (PCNA)	[66]
Investigating the environmental consequences of circularity-focused buildings (timber-based) and comparing these with those of conventionally built structures (concrete-based) of similar shapes and sizes	[20]
Assessment of the environmental impacts of the nine asphalt road pavement mixtures (binder course: HMA_{binder}, $HMA_{binderCDW}$, $HMA_{binderJGW}$, $HMA_{binderFA}$ and base layer: HMA_{base}, $HMA_{baseJGW}$, HMA_{baseFA}, $CMRA_{RAP}$, $CMRA_{RAPJGW}$) during their life cycles	[26]
Performing a comparative footprint analysis to measure the climate and resource footprints of recycled concrete (RC)-concrete versus business as usual (BAU)-concrete	[25]
Investigating the impact of substituting natural aggregates (NA) with recycled concrete aggregates (RCA) from precast concrete block waste to manufacture precast concrete building blocks	[67]
Analyzing the life cycle of gypsum plasterboard consumed in the EU-27 in 2013 and using scenario-based modeling to assess the greenhouse gas emissions and primary energy implications of varying levels of plasterboard recycling in the EU-27	[68]
Calculating and evaluating the environmental impacts of manufacturing, using, and disposing of pallets made from different materials such as wood, plastic, and wood-plastic composite	[69]
Comparing the environmental and economic impacts of natural aggregates (NAs) and recycled aggregates (RAs)	[70]
Evaluating the sustainability of three scenarios: 1. A linear economy scenario highlighting the benefits of avoiding landfilling; 2. A status quo scenario; 3. A best practice scenario based on the systematic application of selective demolition and increased production of high-quality recycled aggregates (RAs)	[14]

Quantification tools and forecast methods

To assess the efficiency of CDW management, a framework incorporating methods, tools, and instruments is required, which can underscore the progression of efforts.

Decision-making about recycling, material reuse, or recovery gets obstructed and can result in errors due to the imprecise quantification of CDW. The unavailability of precise data on building materials and components is a global issue.

The majority of studies use calculation methods like the "waste index" and the material flow analysis (MFA), which are based on data gathered from registries and field research. MFA is a method extensively utilized in CDW management for building stock and flow accounting. This is based on the principle of mass conservation, which asserts that the sum of material inputs always equals the sum of material outputs plus the material stored within a system, defined within a specific spatial and temporal context [21]. The bottom-up MFA approach uses the material intensity coefficient (MIC) [67]. The building inventory is segmented into distinct material sections according to their application, and the volume of materials in these sections is determined by multiplying the physical parameters of the specific section size by the material intensity per capita (MIC). However, as MIC data is typically site-specific and not easily accessible, researchers must infer this data from a variety of sources, such as site surveys, architectural data, construction norms, blueprints, cadastral maps, energy requirements, or corporate data. This results in a procedure that is both laborious and time-consuming [21]. Data availability plays a crucial role in reducing uncertainties and preventing inaccurate stock estimations.

The analysis of building stock and flow delivers critical quantitative information for predicting future CDW generation and modeling estimated stock and flows for scenario-based circular waste management. MFA is an essential model for formulating circular economy strategies and provides an ideal tool for a thorough assessment of material flows and inventories, as well as their potential for recovering value from waste [33]. Table 4 illustrates the usage of MFA in the reviewed literature.

Table 4. Quantification of building material stock and MFA.

Quantification of Building Material Stock and MFA	References
MFA performed	[22,34–36,43,47,60]
MFA—literature review	[21]

New assessment models have been developed using MFA and geographic information systems (GIS). The combination of MFA with GIS has evolved into a potent tool for analyzing and interpreting material building stocks and CDW flows to create circular strategies [33].

The quantification models using GIS are presented in Table 5.

Table 5. Quantification models with integrated GIS.

Quantification Models with Integrated GIS	Reference
StAR model (an analysis tool for strategic decision-making in CDW management using MFA and GIS)	[5]
ABM (agent based modeling integrating GIS)	[39]
BTFlux model (using data mining, BIM, MFA and GIS)	[33]

The creation of a sustainable and circular scenario needs dependable and error-free data, which can be fulfilled through digital models of buildings. Building information modeling (BIM) allows for the creation of a 3D digital model of a structure, encapsulating both geometric and non-geometric properties of all components. BIM facilitates the automatic acquisition of the total volume of materials, their attributes, and the dimensions of the object. BIM is a smart, object-oriented model where any quantitative or qualitative change to an object is reflected throughout the model's views and sections [71].

Building information can be efficiently exchanged and conveyed via a unified platform across the lifespan of a project. This makes it well-suited for design synchronization,

material quantity evaluation, 4D planning, and cost projection, all of which are crucial for CDW management. Through accurate forecasting of waste output, the order of waste creation, and disposal expenses, BIM can assist in making informed decisions regarding CDW management planning [2].

The BIM method fosters a collaborative environment in construction by using a digital representation of the building. It amplifies circularity in the CD sector by aiding decision-making in waste reduction and prevention through BIM-based deconstruction frameworks, BIM-assisted waste management, material and component banks, BIM-based LCA, and BIM-based DfD, as well as through visualization and simulation of waste performances and waste management reporting [54]. Table 6 presents the BIM literature and the development of BIM tools found in the review sample.

Table 6. BIM tools.

BIM Tools	Reference
Material and Component Bank	[37]
A-WAS (ANFIS based waste analytics)	[38]
Quantification model based on European Waste List for 3 BIM platforms	[40]
BIM based Whole Life Performance Estimator	[41]
D-DAS (Deconstruction and Disassembly Analytics Systems)	[42]
BIM modeling for visualization of climate and resource footprint result	[25]
Benefits and challenges for BIM in Australia—descriptive analysis	[2]

Recycled materials

Waste from construction can be sorted either by its source or its characteristics. When sorting by characteristics, researchers have divided waste into physical waste (remaining debris) and non-physical waste (cost and time overruns). As for the source, the waste could be anthropogenic (public construction and maintenance work, building construction, renovation, and demolition) or natural (earthquakes, floods, hurricanes, and tsunamis).

Concerning materials, academic research often focuses on the recycling of concrete and enhancing the mechanical properties of recycled concrete aggregates for use in mixtures of cement, mortar, and recycled concrete. Every component of construction and demolition waste (CDW)—from concrete [10,46,55], bricks [34,72], tiles, timber [73], glass, gypsum, asbestos [74,75], plastic, and cardboard [68]—is the subject of numerous studies. There's also interest in exploring the potential for recovery and recycling of materials like wood [76], bricks, and insulation [44,77], and the use of mineral waste fractions for water filtration [78].

Concrete forms the largest fraction of CDW, ranging from 32% to 75% depending on the source [79]. It constitutes 40 to 80% of total on-site waste. New buildings can generate 18 to 33 kg of waste concrete per m^2 of built area when utilizing concrete structures. Residential building demolition can result in up to 840 kg of waste concrete per square meter demolished. Concrete is widely used globally, making it the most popular building material, excluding excavated materials [25,55].

In *The European List of Waste*, concrete waste falls under code 17 01 01. As per the waste hierarchy, end-of-life (EoL) concrete treatment levels are ranked [47]:

- Preventing EoL concrete;
- Reusing concrete components;
- Recycling waste into aggregates for use in concrete production;
- Recycling waste into aggregates for road construction or backfilling;
- Landfilling.

Despite landfilling being the least preferable waste treatment method, a significant fraction of concrete ends up in landfills. Repurposed concrete aggregates (RCA) are applicable for uses such as filling in road sub-bases, in hydraulically or bitumen-bound formations,

rigid pavement construction, and as a component in concrete manufacturing [25,55,80]. The most common recycling process is crushing CDW to create secondary aggregates based on required mechanical properties and strict standards (like EN 12,620 aggregates for concrete or EN 13,242—aggregates for unbound and hydraulically bound materials for civil engineering work and roads).

For inert waste containing concrete, recycling CDW into RCA to produce recycled concrete (RC) is a key strategy for reducing the environmental impact of the construction and demolition sectors. While RCA is of high quality, its cost and purity requirements can limit the feasibility of recycling. RCA, usually derived from pulverized pre-used concrete structures, is required to adhere to particular quality criteria. They should be devoid of impurities such as sulphates (originating from plaster), clays (coming from bricks or tiles), or an overabundance of fine materials [10,46].

Portland cement, a principal ingredient in concrete and various cement-based materials, is frequently employed. Nevertheless, its manufacture is both energy-demanding and environmentally detrimental, given the substantial use of natural resources during clinker production and rotary kiln operation, accounting for around 6–7% of total CO_2 emissions.

Prior studies [46,80,81] have indicated that compared to natural aggregates (NAs), recycled aggregates (RAs) tend to have increased porosity, decreased density, reduced mechanical strength, and lessened durability owing to the presence of sulphates and chlorides. They also exhibit reduced workability because of their porous nature, contain a higher percentage of fine particles, absorb more water, and possess a greater friability coefficient. Several studies [46] have discovered that combining recycled aggregates (RAs) with other industrial by-products such as fly ash, coal bottom ash, blast slag, silica fume, plastics, and rubber tires can have advantageous effects in certain situations.

Morón et al. [81] carried out lab experiments to assess the physical and mechanical characteristics of cement mortars made with recycled concrete aggregate (RCA) and strengthened with aramid fiber. They tested six mixtures, with results indicating that the inclusion of aramid fibers in mortars created with RA increased the flexural strength, albeit not to the level of mortars made with natural aggregate (NA). The experiment also showed a reduction in capillary water absorption, while the aggregate's density and surface hardness remained the same. The research concluded that adding aramid fibers to RA reduced the adhesion of mortars, increased resistance to freeze–thaw cycles, and lessened shrinkage of mortars prepared from RA with aramid fibers compared to recycled mortars without fibers.

Jesus et al. [31] evaluated the decrease in cement content in render mortars with RCA and recycled mix aggregate at three different ratios. The findings indicated that mortars with a lower cement ratio and a concurrent incorporation of 20% RCA performed quite satisfactorily.

Numerous researchers have investigated the environmental impact and potential energy savings of different mixtures of recycled concrete using the comparative life cycle assessment (LCA) approach. For example, Colangelo et al. [30] studied the environmental impact of concrete with recycled aggregates and geopolymer mixtures, concluding that producing concrete with 25% recycled aggregates was the best environmental choice.

In a 2021 study, Mostert and his colleagues [25] assessed the greenhouse gas emissions associated with the use of recycled aggregates. They used data from a project in Kornbach, Germany, and a building information modeling (BIM) application to illustrate their findings. Their research covered three scenarios related to the life cycle of concrete and examined four different mixtures of varying strengths and exposure classes. The results suggested that a mixture with 43% recycled aggregates could yield up to 37% savings in raw material, though the reductions in climate and water footprints were less significant.

Ghisellini et al. [27] investigated potential energy savings from various waste management scenarios in the Metropolitan City of Naples. Using the LCA method, they compared concrete made with natural aggregates, recycled aggregates, and green aggregates. Their

study indicated that both recycled and green concrete required significantly less energy than their conventional alternatives.

In the same year, [14] also studied the socio-economic and environmental impact of managing construction and demolition waste in Italy's Campania Region. Their study suggested the potential for significant carbon savings and job creation with a best practice scenario, though economic challenges could be a barrier.

Lederer et al.'s [34] study utilized material flow analysis for a case study in Vienna, demonstrating a potential 32% reduction in the annual consumption of construction minerals through waste hierarchy implementation. The study considered various reuse scenarios involving materials such as concrete, brick, asphalt, and gravel.

Zhang et al. [47] looked at two EU-funded projects, the VEEP and C2CA, to analyze the recovery of end-of-life concrete and predict the future of construction and demolition waste management in the Netherlands. The results pointed to a promising increase in recycling rates from 5% in 2015 to as much as 32% in 2025.

Kioupis et al.'s [72] research investigated the use of waste from construction and demolition sites, specifically glass and brick, in the production of alkali-activated binders. Their findings suggest that these binders have properties competitive with conventional building materials and are compliant with EU regulations.

Ramírez et al. [77] explored the possibility of using recycled fibers from mineral wool insulation panels in the production of mortars for coating. Their results indicated that these recycled-fiber mortars showed similar performance to those made with commercial fibers, suggesting potential applications in external coatings.

Superti et al. [10] examined the entire value chain of insulation materials, identifying the requirements for recycling thermal insulation materials.

Rose et al. [73] discussed the possibility of using reclaimed timber to make cross-laminated timber, a process that avoids the downcycling common in conventional timber recycling. Their testing suggested that secondary timber could be used effectively in structural applications without significant differences in performance.

Rivero et al. [68] looked at the environmental impact of plasterboard recycling, using life cycle assessment to examine three potential scenarios. They found that while energy usage did not vary significantly between the scenarios, there was a noticeable decrease in greenhouse gas emissions.

Finally, a 2021 study developed by da Silva et al. [82] presented a method for recycling polyethylene terephthalate waste into soil-cement brick production. Their results showed that adding up to 30% PET waste to the brick mixture could be a viable option for non-structural applications.

Barriers and drivers in implementation of CE in CDW management

There is a growing interest in the academic community to identify and tackle hurdles in applying circular principles to the management of construction and demolition waste. Enhancing and identifying key processes in CDW management is essential, as it informs future research and assists stakeholders in crafting effective strategies for resource efficiency and sustainability.

Purchase et al. [1] analyzed components of the circular economy to integrate into construction projects. They categorized the primary challenges into six groups: policy and governance, quality and performance, information, cost/capital, perception and culture, knowledge, education and lack of technology, and permits and specifications.

Concurrently, another study [48] pointed out logistics as the foremost obstacle to recycling and reuse, followed by cost and time/health and safety regulations.

Han et al. [2] segmented the barriers to effective CDW management into three categories: technological, policy-related, and human barriers.

Further, researchers like Charef et al. [63] and Çetin et al. [83], through a literature review and using the Delphi method, categorized the obstacles under environmental, economic, sociological, organizational, technical, and political challenges.

These various classifications of impediments faced in the execution of CDW management principles were collected and summarized in Table 7.

Table 7. Barriers in implementation of circularity in CDW management.

Category	Barriers
environmental	lack of storage space in reverse logistics, adaptive reuse, and deconstruction
	site access limitations
	health and safety risks from contaminated materials
	emissions from transport and reconditioning for 3R and prefabrication
Economic	underdeveloped market for recycled materials
	high or equivalent cost of secondary material compared to primary materials
	high purchasing costs for circular materials
	low cost of landfilling
	costs of labor and time-intensive nature of deconstruction and reuse
	high upfront investment costs
	limited funding for circular projects
	Profit-driven decision-making
cultural	lack of awareness and demand
	cultural resistance of the stakeholders
	lack of systemic vision regarding sustainable buildings, revers logistics, DfD
	uncertainty regarding quality of recycled materials
	lack of awareness about the benefits
Organizational	lack of information, experience, and skills
	lack of partnership networks between stakeholders
	operating in a linear system
	limited top management commitment and support for circularity
	lack of time and human resources
	poor partnership with the supply chain
technical	high costs for new technology
	lack of tools for material recovery
	lack of circular design guidelines
	lack of an information exchange system
regulatory	lack of standardization
	lack of global consensus about CE
	limited circular procurement
	uncertainty regarding future legislation

The underdeveloped market for secondary materials appears to be a considerable hindrance in all facets of the subject under scrutiny and is frequently highlighted as a pressing need. Concurrently, the call for effective legislative and financial incentives frequently emerges as a challenge. While these obstacles fall into various categories, their interconnections make it more difficult to address them individually. As a result, a comprehensive strategy should be developed by considering these barriers collectively [2,35,52].

On the other hand, researchers have identified certain enablers that could significantly boost initiatives aiming to promote circularity in the construction and demolition (CD) sector. The effectiveness of any sustainability-enhancing initiative in the building sector largely depends on technical viability (like durability), legal enforcement (minimum performance standards set by laws), and the competence and preparedness of the organizations involved (in terms of knowledge, skills, infrastructure, and innovation) [84]. The drivers

identified by the authors of the reviewed studies are illustrated in Table 8, using a similar categorization approach as used for the barriers.

Table 8. Drivers for implementation of circularity in CDW management.

Category	Drivers
environmental	scarcity of landfill sites
	reduction in use of virgin material
	energy and carbon footprint reduction
economic	funding for circular projects
	circular business model
	financial incentive to use circular or secondary materials
	lower costs for recovery actions
	development of secondary material market
	increased landfilling costs
cultural	social awareness
	education, training, workshops
	awareness-raising event and projects
	increased awareness of the benefits of the CE in CDW management
Organizational	commitment and support from the management
	high priority on circularity within the organization
	collaboration between stakeholders
	promoting the green image of the companies
	integrating CE principles in the design phase
	availability of storage space
Technical	development of tools and guidelines (collection and separation)
	development of enabling technologies
	development of digital marketplace for secondary materials
	development of circular procurement system
Regulatory	global agreement on regulations
	waste management directives
	policy support
	circular economy legislation

Prioritizing the barriers and drivers should be tailored to the specific application, considering factors such as national or regional legislation, the degree of circularity incorporated in construction and demolition waste (CDW) management, the availability of natural raw materials, and the waste treatment technology integrated into the waste management system, all of which can vary significantly depending on the local or regional context. The construction sector tends to be traditional in nature, heavily reliant on standards, and primarily driven by economic factors. Moreover, the multitude of stakeholders involved in the CDW value chain contributes to a complex network of responsibilities, characterized by a range of differing decision-making processes [55].

4. Discussion

The challenge associated with the underdevelopment of a secondary material market and quality assurance systems is multifaceted and rooted in both technological and systemic issues. The secondary material market for CDW has faced apprehensions due to

concerns over the quality, durability, and performance of recycled materials compared to their primary counterparts [85–88]. Quality assurance is paramount in addressing these concerns. An efficient quality assurance system not only validates the quality of recycled materials but also instills confidence among end-users. From an economic perspective, a thriving secondary market reduces the dependency on primary raw materials, thus reducing extraction pressures and associated environmental impacts. There have been successful precedents in other industries. For instance, the automotive industry has managed to establish a viable market for recycled metals, plastics, and rubber by investing heavily in quality assurance mechanisms. Similarly, the electronics industry, through Extended Producer Responsibility (EPR) frameworks, has made significant strides in reclaiming precious metals from e-waste. Adopting analogous strategies, tailored to the specifics of the CDW sector, could accelerate the development and acceptance of secondary materials in construction [89].

The review of the literature suggests that the circular economy may offer solutions to contemporary global problems like environmental degradation by fostering a system where resource consumption is uncoupled from economic growth and social equity is promoted. To achieve sustainability and circularity goals, the optimization of construction and demolition waste (CDW) management is crucial. The assessment of academic research on CDW management helps to identify development trends, key research interests, and the spread of research influence according to geographical areas, research centers, timeframes, areas of concern, and methods of performance evaluation. Scholars have focused on creating strategic development frameworks, developing environmentally friendly and circular materials, and enhancing quantification and assessment methods with advanced computational tools. The novelty of this study consists of structuring the various researched aspects of CDW management and identifying the main trends representing interest, methodology, tools, strategies, and secondary materials related to the CDW.

From the analyses, it is evident that due to thorough studies and increased attention towards various aspects of CDW management, rapid progress is being made towards finding practical technical, economical, and environmental solutions. However, the lack of studies on the harmonization of legislative, technical, and organizational solutions for their synergistic use to improve CDW management is noticeable. To efficiently implement these solutions, addressing the specific application context is required, considering legal, economic, and technical aspects on sectorial and local levels, and defining clear conditions for expected outcomes and best practices. Active involvement of stakeholders at all stages of the CDW management strategy is essential to align the realities on the ground with the chosen management plan's requirements and to leverage expert consultation.

For instance, the recycling of CDW is influenced by proximity factors, and CO_2 emissions from transportation should be included in the total environmental impact assessment of the process. Yet to ensure feasibility, on-site sorting and processing technology is required, which involves additional financial investments and legislative support.

In the reviewed sample, proposed improvements for CDW management are largely assessed from an environmental perspective. Few authors have focused on economic performance assessments, and social impact evaluations are almost non-existent. The current CDW management operates under the principle of linear thinking in a profit-driven system. In creating a circular, climate-neutral, and resilient economy, the environmental focus needs to be embedded in a coherent economic framework. The real-life economic sphere is a growth- and profit-driven one; thus, innovations for sustainability require not just value-added, disruptive refitting actions but also economic returns. The premise of the survival of private-sector companies in the capitalist system is profit generation. The economic enablers and barriers to implementing a circular strategy in CDW management stress the need to develop circular business models based on high upfront investment costs and long-term projection plans and turn-outs in a developing and unstable secondary material market. In assessing the economic impact of the CDW management strategies, economic indicators for profitability, stability, autonomy, productivity, and economic inno-

vation must strengthen the environmental benefits [90]. Cost-effectiveness and a proper risk management approach are key elements in the development of circularity in the CD sector, which are achievable with policy support, financial incentives, and governmental funding. Positive results from economic assessments of circular strategies could shape the expansion of sustainable enterprises. To separate natural resource consumption from economic growth, economic assessments and financially feasible strategies using clearly defined financial levers are needed. The three-pillar structure of the circular economy based on sustainability regarding environmental, economic, and social transformation requires a balanced development along these dimensions. The focus on the environmental assessment must be completed with an economic and social assessment to ensure sustainability. Funding for the implementation of innovative solutions for waste management and a financially self-supporting profit-generator business model is a sine qua non of a healthy, stable, and autonomous sustainable development process in a socially inclusive, human well-being, and dignity-granting system. Indicators for the economic and social development of the circular CDW management, assessing profitability, productivity, autonomy, and economic stability on the one hand and education, employment, working conditions, health conditions, safety, community acceptance, and community engagement on the other, could represent valuable instruments for future research.

The use of recycled material in new construction is a major concern. Two principal problems with reintroducing recycled materials into the closed loop are the underdeveloped state of the secondary material market and the lack of quality certification for secondary materials. This indicates a clear need for further research in this direction. Innovative strategies adapted to the local context and reinforced by strong government interventions could accelerate the development of a secondary material market for the CDW. The success of the CDW management implemented was analyzed by [91] in Shenzhen, China, identifying the elements contributing to a thriving CDW recycling market: recycled product quality control is assured by a staged charging program based on the CDW composition collected by recycling companies. Also, profitability for the recycling companies is bolstered by tendering strategies constructed around public projects using recycled products. Closing all landfills constrained all waste generators to engage with recycling companies, further creating a constant waste inflow for recycling. Investing in research and development in the CDW industry is a complementary strategy that directly boosts the secondary material market through governmental subsidy allocation based on counting patents for recycled products. Although the secondary material market is underdeveloped, examples of successful strategies implemented in the given context are paving the way for progress. With clear rules when waste becomes a freely tradable material, the EoW criteria introduced in the WDF in the EU strengthen the development of the secondary material market. Reduction, reuse, recovery, and recycling in CDW are the primary strategies for maintaining the used virgin materials in the cycle and extending their lifespan for as long as possible. Landfilling is not thought to be the next-best solution. Other possibilities exist, barely covered at all in the analyzed studies, such as using CDW to directly generate energy or as a resource for alternative solid fuels used in the cement industry. Refuse-derived fuel (RDF) has a high calorific value and, compared to fossil fuels, has a reduced GHG emission rate, high energy efficiency, and no residues at the end of the process. In the scientific literature, we can find research showing that RDF is mostly produced from municipal solid waste and less from CDW [92–94]. Using CDW to produce RFD is a sustainable case to be explored in future research.

The main interest in CDW management research, as concluded from the sample studies, relies on handling non-hazardous CDW in a sustainable manner. But CDW also comprises hazardous materials, like asbestos, solvent vapors, gases, or fumes, that also need to be studied in future works as they manifest special characteristics, are unsafe for human health and the environment, but are still necessary to be incorporated into the circular economy loop.

The development of digital tools for design, quantification/assessment activities, and collaboration platforms is another heavily researched topic. Innovative technologies and digital tools pave the way for new processes that eliminate human error and reduce waste in the design phase. These tools can significantly reduce not just CDW but also time and labor waste, thereby enhancing CDW management efficiency. Although BIM, MFA, GIS, and LCA are the most studied computational tools for enhancing the circular economy in CDW management, other digital technologies that are enabling the circular built environment are worth mentioning: additive/robotic manufacturing, artificial intelligence, big data and analytics, blockchain technology, digital marketplaces, digital twins, or the internet of things [95]. Guiding sustainable decision-making and innovative problem-solving in CDW management, the system thinking framework as a holistic analysis based on mirroring the complex relation networks of system components offers insights for creating an integrative methodology by outlining the system's boundaries and components, creating visual tools, and detecting connection nodes to elaborate an integrative and circular approach for CDW management strategy design [96]. Design thinking incorporates tools and principles of system thinking to focus on system leverage points as an iterative problem-solving, human-centered, sustainability-oriented framework methodology that involves stakeholders from different backgrounds [97]. These frameworks are based on multidisciplinarity, creativity, simplicity, and technological innovation, offering solutions for complex problems. Assessment tools and methods discussed in the analyzed sample could produce increased value when incorporated into a holistic system approach by acting in a synergetic way along with the CDW management system components and stakeholders' interests.

Transitioning to a circular economy requires a shift in mindset from linear to circular thinking. Enhancing stakeholder awareness of the benefits of circularity could influence decision-making processes. Education is a key factor in progressing towards circularity. Circular strategy development in CDW management requires a multi-disciplinary, integrated approach, with stakeholders' involvement being fundamental in this process. A public-private partnership framed in a relational contract is a successful example of procurement innovation in CDW management in Suzhou, China, where the interests of both parties are protected by functional mechanisms backed by a transparent information sharing platform [98]. Public-private partnership and collaboration among stakeholders are crucial elements in advancing circularity in the CD sector, as interconnected environmental, economic, social, regulatory, technical, and cultural aspects need to be placed in a practical, operational, viable, and innovative solution to engender societal benefits for all. Creating involvement not only presumes enthusiasm and an active role in developing change towards circularity but also shares responsibility for the outcome. Developing and reinforcing education are essential when introducing concepts related to the transition to a circular economy. Raising awareness among stakeholders is a good first step, but to enact a global mindset shift, non-governmental organizations, consumers, and society as a whole need to be involved.

5. Conclusions

This investigation scrutinized the scholarly activity pertaining to CDW management within the framework of a CE through a comprehensive review of the literature. The study commenced with a contextual analysis aimed at discerning the academic focal points and the temporal, geographical, and source-based diffusion of concern for CDW management. It was determined that this subject has seen heightened interest over the last three years, attracting scholars globally, with substantial research activity centered in European nations such as the Netherlands, Switzerland, and Germany. The necessity to examine CDW management's circularity at a local level was underscored, considering the specific local circumstances and the transportation restrictions due to the waste's bulk.

Next, a content analysis was performed to systematize the key elements of research on circularity in CDW management. The analysis was based on variables like research topics,

life cycle stages, strategies and CDW treatment methods, sustainability assessments, quantification tools, forecast methods, circular materials, and drivers and barriers to circularity in CDW management.

Lastly, following a comprehensive evaluation of the current state of CDW management, several areas of weakness were identified for future research where alternatives and solutions are required: limited emphasis on economic impact assessments; a dearth of studies that consider legal, environmental, economic, technical, and organizational aspects in an interconnected manner for suggested strategies or processes; an underdeveloped secondary material market and quality assurance system; and inadequate emphasis on educational mechanisms and tools for enhancing awareness and knowledge of circularity in CDW management.

Author Contributions: Conceptualization: I.-E.G., E.-S.L., F.L., V.V.C. and S.D.C.; methodology: I.-E.G., E.-S.L., F.L., V.V.C. and S.D.C.; validation: E.-S.L., L.I.C. and E.C.R.; investigation: I.-E.G., F.L., V.V.C. and S.D.C.; resources: E.-S.L.; writing—original draft preparation: I.-E.G., E.-S.L., F.L., V.V.C. and S.D.C.; writing—review and editing: E.-S.L., L.I.C. and E.C.R.; supervision: E.-S.L., L.I.C. and E.C.R.; project administration, E.-S.L.; funding acquisition, E.-S.L. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Institute for research in circular economy and environment "Ernest Lupan", project number CI034/11.02.2022-"Study on the implementation of circular economy in the construction sector: an analysis based on secondary data".

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

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