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Review

Circularity and Decarbonization Synergies in the Construction Sector: Implications for Zero-Carbon Energy Policy

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Abstract: This literature review explores the synergies between circularity and decarbonization principles in the construction sector, focusing on their potential to accelerate the transition to a carbon-neutral future. Through analysis of 61 studies, critical barriers are identified, such as data gaps, insufficient recycling infrastructure, and regulatory fragmentation, that hinder the integration of circular and low-carbon strategies. Regional disparities reveal that developed regions, supported by robust policies and infrastructure, lead in circularity adoption, while developing regions face systemic challenges, including limited material recovery networks and technological barriers. Previous studies have largely examined circularity and decarbonization separately, whereas this review provides a synthesis of their interdependencies, focusing on implementation challenges and regional disparities, highlighting synergetic solutions such as fiscal incentives, material passports and stricter end-of-life waste regulations, biobased and carbon-negative material innovations, and digitalization through tools like Building Information Modeling (BIM) and/or digital twins. However, complexity of circular solutions and lack of interdisciplinary collaboration forms a barrier against integration. This review emphasizes the need for standardized frameworks, cross-sectoral coordination, and targeted investments to ease integration of circularity and decarbonization.

Keywords: sustainable construction policies; net-zero carbon construction; decarbonization strategies; construction industry

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1. Introduction

The impact of greenhouse gas (GHG) emissions and waste generation from non-circular product development chains has been a central issue in climate change discussions for decades. The built environment, which accounted for 39% of global emissions in 2020 [1], remains a critical sector in achieving decarbonization targets. While various research advancements have introduced low-carbon materials, energy-efficient technologies, and circular design strategies, the construction industry has been slow to adapt [2], raising concerns about its capacity to transition to a zero-carbon future by 2050.

A key driver of this transition is the role of policy frameworks in accelerating decarbonization and circularity in construction, playing a significant part in the capacity to decarbonize construction industry and increasing circularity [2,3]. The European Union (EU) has, over the years, created multiple policies and frameworks to address emissions and resource inefficiencies in the built environment, notably, the European Green Deal, aiming to achieve climate neutrality by 2050, and the Circular Economy Action Plan (CEAP), which introduces measures to reduce material waste, promote recycling, and enhance resource efficiency. Specific directives, such as the Energy Performance of Buildings Directive (EPBD) and Energy Efficiency Directive (EED), target energy efficiency and lifecycle emissions reductions in construction. Despite these policy advances, global challenges remain in ensuring effective implementation, particularly in aligning circularity principles with decarbonization strategies.

Increasing number of articles and reviews have been focusing on reducing carbon and increasing circularity of resources, but few have holistically reviewed (sub)zero-carbon strategies in construction and their synergies with circularity principles, with focus towards new policy development. Furthermore, while an increasing number of studies have explored carbon reduction and circular economy strategies, the synergies between these two approaches remain underexplored—fragmented policies, data inconsistencies, and insufficient infrastructure are frequently cited barriers, with studies estimating that up to one-third of construction waste remains unrecovered due to inadequate material recovery systems [4], and that selective deconstruction could reduce emissions by up to 70% [5]. However, holistic understanding of how these barriers manifest across global regions and sectors is lacking. This research systematically reviews the synergies between circularity principal integration and decarbonization efforts in the construction sector, analyzing their contribution to zero-carbon energy policies, focusing on mutual reinforcement, regional differences, and adoption patterns, and providing insights for policy design and further industry transformation.

Objectives and research questions of this review are as follows:

- What dominant synergies are identified in existing literature, between circular economy and decarbonization in the construction sector?
- How do circularity and decarbonization practices in construction contribute to achieving low-carbon targets?
- What role do policy frameworks play in accelerating or hindering the integration of circularity and decarbonization in the construction sector?
- What regional differences exist and how are construction sectors adopting circularity principles to reduce carbon emissions?

2. Materials and Methods

The review took a systematic approach, to ensure transparency. PRISMA overview can be found in Figure 1. The process of inclusion had been with focus towards mainly post-2020 papers, reflecting a shift in research dynamics, where studies increasingly emphasize empirical circular economy and decarbonization integration outcomes, beyond earlier conceptual explorations. This transition aligns with the growing demand for evidence-based approaches in policy and practice, which became apparent during the preliminary review phase of this study. Research of the literature had been conducted using keywords such as:

- “synerg*” OR “interactio*” OR “strateg*” OR “policy” OR “grid”
- “circula*” OR “material efficiency” OR “resource efficiency” OR “closed-loop” OR ”resource recovery”
- “decarbon*” OR “carbon reduction” OR “carbon-*” OR “*-carbon” OR “carbon footprint” OR “CO_2 emissions” OR ”regenerat*” OR “emission factor”
- “constructi*” OR “building sector” OR “built environment” OR “building practices”

Exclusion criteria were the following:

- Papers unrelated to construction industry;
- Papers not in the English language.

Filtering through titles and abstracts focused on answering the following questions, giving a point for each question the abstract supports and excluding those answering two or only a single question:

- Is it about (both) circularity and decarbonization?
- Is it about circularity/decarbonization in construction?
- Is it about synergies of circularity and decarbonization?
- Is it about policies regarding circularity/decarbonization?

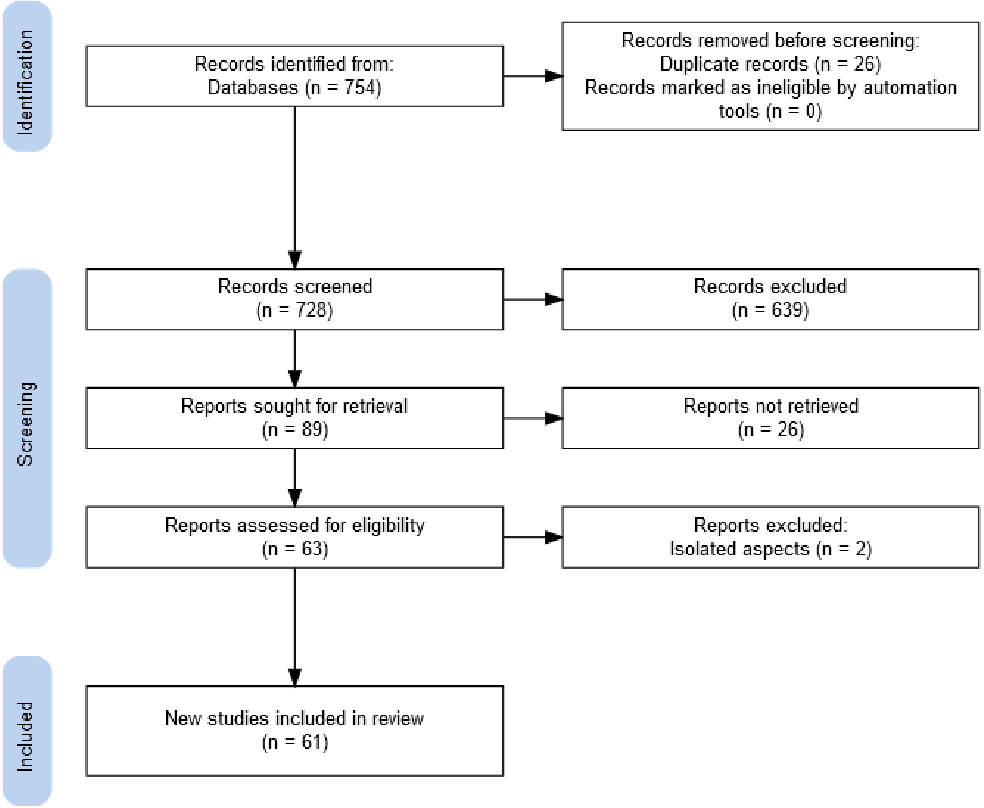

Figure 1. Literature review setup, PRISMA.

After filtering based on titles and abstracts, studies were attempted to be accessed in full text, followed by extraction of study-specific data. This extraction focused on five main aspects:

- Objectives: research aims and scope of each study.
- Findings: results related to synergies between circularity and decarbonization.
- Barriers: challenges identified in implementing circular and decarbonization strategies.
- Policy implications: recommendations for policy frameworks and interventions.
- Limitations: constraints or gaps identified.

Following extraction, data were reviewed again and synthesized into categories based on their focus:

- Synergies: overlaps between circularity and decarbonization.
- Barriers: regulatory, technical, and social challenges.
- Policy suggestions: strategic recommendations for fostering integration.

The collected literature and analysis process was managed using "LibreOffice Calc", Python (v3.12.9)-based scripts for preliminary data overview, and draw.io for holistic overview of research outcomes, in Figure 2. This review was limited to publicly available articles, excluding grey/other literature. The exclusion of non-English studies may have introduced a language bias, specifically towards comparison of regional differences. The thematic analysis, while systematic, is based on the author interpretation, thus inherently subjective. Furthermore, this study synthesizes existing research findings rather than conducting new empirical or analytical modeling—while financial incentives and material innovations are discussed qualitatively based on prior studies, detailed economic modeling or quantitative assessments fall outside the scope of this review.

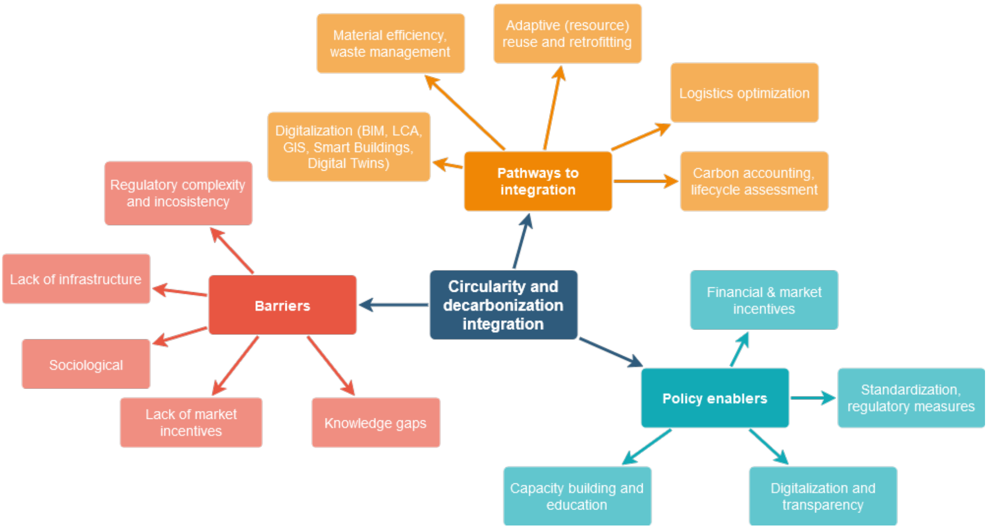

Figure 2. Holistic framework overview of literature review outcomes.

3. Results

The integration of circularity and decarbonization within the construction sector presents a complex interplay between regulatory mechanisms, market dynamics, technological advancements, and material efficiency strategies. While policy frameworks and technological interventions are being progressively developed, significant barriers persist, impeding widespread adoption. Figure 2 presents a synthesized holistic overview of literature review outcomes, illustrating the interdependencies among barriers, policy enablers, and pathways to integration.

3.1. Dominant Synergies

This section represents the commonalities between searched articles, focusing on the themes synergizing decarbonization and circularity. Decarbonization can be approached directly and lead to increased circularity, through increased efficiency of a value chain, or indirectly, by proposal of low-or-negative-emission materials, which result in disruption of unsustainable value chains within the economy. Carbon-negative materials are crucial to achieve carbon neutrality [6]. The construction sector emits a significant portion of worldwide emissions and has great accessibility to mitigate due to physical dependence of value production. With respect to this potential while enchancing both circularity and decarbonization, eight common synergies were highlighted in Table 1. Each category, except logistical optimizations, had similar number of categorized references ($n = 15$). While it is common for studies to be present in multiple categories at once, each study presented a distinct take on their problem and distinct impact at the greater scale.

Material efficiency strategies include diverse approaches for reducing environmental impacts. To reduce use of materials, post-war architectural renovations could achieve significant carbon savings from reduced embodied emissions by reusing structural components, compared to new construction [7]. While not necessarily outweighing operational performance of a new construction, the net environmental benefit is greater than of new buildings, as long as present construction can support renovation [7]. If a building must be demolished, selective deconstruction instead of landfilling reduced GHG emissions by 70%, water consumption by 67%, and fossil resource usage by 69% according to a study in Lima [5]. This approach highlights the significant potential of recovery-oriented demolition practices in lowering embodied carbon. To further this, ref. [4] emphasized that approximately one-third of construction waste could be effectively reused if unified systems for demolition, storage, and redistribution were in place. This underscores the potential environmental benefits of standardizing waste handling processes [4]. Additionally, the study called for structured public education and legal frameworks to improve the acceptance of reused materials in construction.

Waste management is a common synergy between decarbonization and circularity-continuous addition of recycled material into supply chain reduces the need for virgin materials, thus reducing the embodied emissions, when recycling is less environmentally intensive than virgin material production. However, this further extends to the waste management itself [8]. Ground granulated blast furnace slag (GGBS) concrete had the lowest CO_2 emissions at 287 kg CO_2 eq per m^3 compared to fly ash and glass powder-based concrete mixes. However, fly ash products showed significant ecotoxicity impacts and glass powder mixes resulted in increased water and land-use impacts [9]. These findings highlight the environmental trade-offs involved in using different types of recycled materials in concrete production.

Another key synergy between circularity and decarbonization is the development and use of carbon-negative/biobased materials. Kharissova et al. [6] provided an extensive overview of innovative materials, emphasizing the role of biochar, carbon-negative cements, and biobased composites in reducing greenhouse gas emissions. Biochar, derived from biomass pyrolysis, can be integrated into construction products such as wall plaster, pellets, and biochar-enriched composites, actively sequestering CO_2 throughout their lifecycle. Similarly, carbon-negative concrete formulations, including carbicrete, leverage carbon capture during production and curing processes, demonstrating a direct synergy between material innovation and emissions reduction. These materials not only mitigate emissions but also align with circular economy principles by displacing reliance on virgin resources. The reuse of low-carbon materials, such as cross-laminated timber (CLT) and recycled steel, further reinforces circularity while reducing embodied carbon emissions.

Agricultural by-products, including cassava peels, rice husks, and maize cobs, also hold significant promise as partial replacements for traditional cement, as highlighted by [10]. This approach fosters a circular economy for agricultural waste, simultaneously addressing emissions and waste management challenges. Biobased materials like cellulose and straw bales exhibit strong carbon storage potential and thermal performance; however, their adoption is hindered by variability in embodied energy and thermal conductivity, as well as market and sociological barriers [11]. Addressing these challenges requires advancing material certification processes and improving market readiness for these innovations.

Further research examined reclaimed timber formwork's reuse potential in structural applications. While using reclaimed timber significantly reduces embodied carbon, the associated complexities, including custom design requirements and logistical coordination, present critical challenges [12]. This highlights the technical and design hurdles that must be addressed to expand the reuse of structural materials in mainstream construction.

Regarding digitalization aspect, applying Building Information Modeling (BIM) with Life Cycle Assessment (LCA) revealed that digital material inventories could enhance material recovery by identifying reusable components in existing buildings. This approach supports the concept of viewing buildings as material banks, reducing embodied carbon while improving decision-making processes in sustainable construction [13].

Table 1. Common synergies.

Synergy	**Description**	**Reviewed/Analyzed/Discussed in**
Material efficiency	Extending material lifespans, reducing waste, and using recycled materials to lower embodied carbon. Focus on optimizing resource use while lowering environmental impacts.	[4,6,9,14–29]
Low(-er)-carbon/carbon-negative materials	Use of low-carbon/carbon-negative materials to mitigate emissions within the construction sector, or use of alternative materials to replace high-emission components of a construction material (like cement replacements).	[1,6,10,11,22,23,26,27,30–35]
Local production and recycling	Localized recycling and reuse strategies, along with challenges in coordinating material recovery across the supply chain	[10,11,24,25,27,28,31,35–40]
Resource reuse/Waste management	Diverting materials from landfills and finding ways to recycle or reuse them effectively; waste minimization. This works towards material efficiency by reducing virgin material input, and thus, commonly the embodied impacts.	[8,12,24,25,27,29,35,36,38–46]
Design for reuse and adaptability and retrofitting	Using existing structures and retrofitting rather than demolishing and building anew leads to reduction of material inputs, which leads to lower embodied emissions. The benefit of reduction of the embodied impact is greater than differences in operational emissions.	[5,7,12,17,20,27,32,34,36,38,45–49]
Smart buildings, BIM, Digital twins, Digitalization, Energy decarbonization	Efficient operational resource/energy use will lead to lower operational emissions and (potentially) extended life/reduced maintenance necessity. Greater precision and management during digitalized design phase will result in reduced material cost and better end-of-life management.	[1,13,17,24,27,31,32,46,47,49–51]
Logistic optimizations	Transport and transport-related optimizations, focused on reducing GHG emissions, also resulting in fostered local production and reduced material waste.	[10,21,24,28,37,40]

3.2. Barriers and Contributions to Zero-Carbon Future

The transition to a zero-carbon future is hindered by various barriers at both macro and micro scales, as highlighted in the reviewed literature, seen in Table 2. While fewer studies explicitly discussed macro-scale barriers to integrating circularity, several recurring challenges emerged from the analysis.

A significant macro-scale barrier identified was the lack of financial incentives to adopt circularity. Although climate change is a global issue, its impacts are uneven across regions and long-term consequences are not always apparent to policymakers or industries. This underscores the necessity of fiscal policies that promote decarbonization, such as tax reductions, subsidies, or incentives for using recycled or low-carbon materials [10,11]. Without such measures, the cost disparity between conventional and sustainable materials continues to discourage circular practices.

Another critical barrier is the lack of coordination between governing bodies to streamline material flows. Effective coordination is essential to ensure that construction and demolition waste (C&DW) is reused or recycled instead of being incinerated or landfilled.

Policies that mandate stricter end-of-life (EoL) management and provide clear guidelines for material recovery can address this issue, but such measures require cross-sectoral collaboration and substantial infrastructural investments [43,44].

The most frequently mentioned barrier in the reviewed studies was data gaps, identified in 39 studies. These gaps encompass insufficient data on material flows, carbon footprints, and lifecycle impacts, making it challenging to assess the environmental performance of construction materials and practices [32,41]. Addressing these gaps requires standardized data formats, shared repositories and digital tools such as Building Information Modeling (BIM) and material passports, which can enhance data accessibility and traceability across projects [27].

However, the complexity of lifecycle assessment (LCA) methods is another challenge, as highlighted in several studies. While dynamic LCA approaches and digital twin technologies have been proposed to address the variability and dynamic nature of biobased materials, their adoption is hindered by their technical complexity and resource-intensive requirements [11,17]. Simplifying these tools and providing stakeholder training could improve their accessibility and usability.

The adoption of biobased and low-carbon materials faces unique challenges. A key barrier is the dynamic nature of material growth and the inconsistent accounting for their environmental impacts across different LCAs. For instance, biobased materials such as timber and hemp store carbon during growth, but their performance and lifecycle emissions vary depending on regional conditions and material sourcing [9]. Additionally, high initial costs and the absence of market incentives further discourage their adoption [10].

Despite these barriers, the reviewed studies also emphasize the significant contributions of innovative technologies and policy frameworks. The integration of digital tools such as BIM, digital twins, and material passports is highlighted as a promising pathway to overcome data gaps and improve lifecycle emissions tracking [13,27]. Policies promoting financial incentives, cross-sectoral coordination, and stricter EoL management have the potential to accelerate the adoption of circular practices and reduce embodied carbon [43,45].

Table 2. Common barriers to integrate circularity and decarbonize the built environment.

Barrier	Description	References
Sociological	Lack of awareness and resistance to change. High carbon-emitting industries lobby/push against integration of low/negative carbon practices. Construction industry tends to be slow to change, and green technologies cause perceived complexity. Prevailing cultural mindset favoring linear construction models.	[1,4,12,14,19,29,30,32,35,36,39, 42,43,45,46,48,52,53]
Knowledge gaps	Lack of (transparent/open source) data sources for resource production chains. Lack of experienced workers to construct using low-emission materials, resulting in slow upscaling. Lacking knowledge on building end-of-life material recycling, resulting in slow or zero policy development to ensure circular construction. Lacking collaborative stakeholder engagement, resulting in less transdisciplinary knowledge. Non-standardized scopes and concept definitions. At the global scale, challenge to create international database due to non-standardized calculation methods.	[4,6,10–12,17,19,20,22,23,25,26, 32,35,41,46,52–58]

Table 2. *Cont.*

Barrier	Description	References
Regulatory complexity and inconsistency	Limited governance mechanisms supporting sustainability transitions. Absence/lack of legal frameworks for material certifications. Limited existing policy effectiveness and inconsistent regulation across regions. Difficult to make policies due to variability in politics regionally and changing governments. Limited integration of financial and carbon accounting systems.	[1,4,6,7,10,15,18,21,24,29,32,35,36,39,40,44,45,49,52,54–58]
Lack of infrastructure	Lack of infrastructure collecting, recycling and distributing secondary/waste materials to support circular built environment. Papers suggest enforcing recycling but infrastructure is commonly not robust enough to support such immediate development, and/or existing ones are too far away, causing logistical problems. Potentially lacking infrastructure to support complete electrification of residential heating.	[12,14,23,27,28,31,34,39,40,43,45,51,59]
Lack of incentive	Market does not incentivize cooperation. High upfront costs (logistics, design adjustments, the "green tax" etc.), along with limited availability, further discourages market adaptation to use low-emission materials/green technologies.	[1,7,12,14,15,17–19,21,23,24,27,34,37,39,40,42–46,49,51,54,56–58]

3.3. Policies as Accelerator (or Hindrance)

The reviewed studies often approached policy discussions from a broad perspective, as seen in Table 3, focusing on the state of the construction sector and suggesting future policy directions rather than delving into detailed evaluations of existing policies. This general focus reflects a need for further exploration of how current policies can either support or hinder progress toward circularity and decarbonization goals.

One recurring theme is the multi-faceted nature of circularity integration, as highlighted by [21]. Circularity requires transdisciplinary approaches, and thus, policies designed to address only isolated aspects of these systems risk limited effectiveness, emphasizing the importance of integrated and cross-sectoral strategies. For instance, ref. [10] proposed incentives to encourage cooperation between the agricultural and construction sectors, such as using agricultural by-products like sheep wool—often discarded by farmers—as a resource for biobased construction materials.

Waste management and recycling policies were another significant focus, particularly regarding stricter enforcement of end-of-life (EoL) practices to reduce landfill use. Many studies advocated for mandatory recycling and reuse requirements, but fewer acknowledged the infrastructural challenges that could delay these policies' effectiveness [4,58]. For instance, the lack of robust physical recycling systems was highlighted as a critical barrier, suggesting that even with stricter regulations, immediate impacts would be limited unless infrastructure development is prioritized simultaneously.

Although most studies concentrated on embodied carbon emissions, a smaller subset explored energy use and efficiency, such as [51]. This research proposed reducing energy consumption and enhancing efficiency as pathways to decarbonization. However, these energy-focused policies often overlooked embodied emissions, limiting their holistic impact on the construction sector's carbon footprint. Addressing this gap would require combining energy efficiency measures with policies that account for the entire lifecycle of construction materials.

Another key aspect emerging from the review is the need for financial incentives to support both recycling and digitalization efforts. Several studies suggested that incentivizing recycling through tax reductions or subsidies could improve material recovery rates and promote investment in better infrastructure [4,6,54]. Similarly, digitalization initiatives, such as implementing Building Information Modeling (BIM) or digital twins, were identified as critical for tracking material flows and lifecycle impacts. However, these technologies require substantial initial investments, making targeted financial support essential for their adoption [13,27].

Finally, the review emphasized the importance of cross-sectoral coordination and standardized carbon accounting frameworks. Shared data repositories and standardized methodologies for life cycle assessments (LCA) were frequently mentioned as enablers of more effective circular practices [14,32]. Without such frameworks, stakeholders face difficulties in aligning efforts, further complicating the transition to circular systems. Standardization would not only simplify compliance but also build confidence in the reliability of environmental impact evaluations.

Table 3. Common policy suggestions.

Policy Recommendation	Description	References
Financial incentives	Incentive-based support towards recycling and facilitating more funds for better recycling infrastructure development. Continuity of financial support of heating electrification and retrofit.	[4,6,9–11,18,19,22,27,29,40,43–45,49,53,54,56,57]
Policy adjustments to support carbon-negative/low-carbon building products	Provision of (legal) room to facilitate market disruption to create bigger supply capacity (and demand) for carbon-neutral and carbon-negative products.	[1,6,10,17,19,25,30,31,40,42,60]
Cross sectoral coordination support	Standardized data formats, shared repositories of demolition waste data for better interoperability.	[1,7,10,11,14,17–19,23,24,27,32,45,55–57,61,62]
Higher producer responsibility and higher transparency	Adopting material passports/BIM (static approach), digital twins (dynamic approach)	[4,24,27,40,45,62]
Increased enforcement of (construction/demolition) material/waste flow management	More stringent requirements to collect, recycle and/or (re)use construction/demolition waste. This is commonly suggested with focus to prevent landfilling.	[4,5,8,9,12,16,20–24,28,29,31,39,40,42–44,63]
Support integration of digitalization	Incentivize (research/use of) digitalization through means such as BIM and/or digital twins	[13,17,29,46,50,56,61,62]
Support education on circularity integration	Support education to speed up integration of circularity into construction industry	[4,8,10,12–14,19,24,25,27,31,37,38,45,47,48,53,54,56,60]
Standardize calculations of and include carbon accounting	Standardizing the process of calculating project/product emissions, data use, and calculation scope and inclusion of carbon emissions for individual products within construction industry	[1,5,11,24,32,36,39,41,48,54,55,57]

3.4. Regional Differences in Circularity Adaptation

The reviewed literature highlights notable regional differences in the adoption of circularity and decarbonization practices in the construction sector. These variations arise from differences in policy frameworks, infrastructure development, economic contexts, and socio-cultural factors. While some regions have established robust systems for integrating CE principles, others continue to face significant challenges due to financial, regulatory, and technological constraints.

3.4.1. Developed Economies: Advanced Policies and Infrastructure

In developed regions, policies and infrastructure for circularity tend to be well-established, enabling higher recycling rates and greater integration of CE principles.

- Europe: The EU leads in CE adoption through the CEAP and initiatives like the EU Renovation Wave, which promote the reuse of C&DW and sustainable building design [45]. However, policy fragmentation persists across different member states, affecting net-zero transition timelines and sector-specific circularity strategies [49]. Focusing on individual countries:
    - Germany achieves a 90% recycling rate for C&DW due to strict policies on selective demolition, pre-sorting facilities, and green public procurement [43]. Additionally, Germany has been a leader in digital material tracking for CE, integrating Building Information Modeling (BIM) and material passports into construction projects to ensure traceability and resource efficiency [62].
    - Nordic countries (Sweden, Finland, Denmark) excel in design for deconstruction and modular construction, supported by government regulations [19]. Sweden, in particular, has advanced in digital circularity, using material passports and digital databases to enhance urban mining potential and secondary material tracking [62]. However, while Nordic countries excel in tracking biogenic carbon flows, they still face logistical challenges in scaling cross-border material reuse [49].
    - France has pursued circularity adaptation through ETAGG and the RE 2020 regulation [31], leading to an increase in bio-based construction materials market share from 6% in 2012 to 10% in 2020. However, France's decentralized waste collection systems create inefficiencies in secondary material processing [49]. While Germany and the Netherlands prioritize end-of-life recovery, France struggles with integrating C&DW circularity into its broader carbon neutrality roadmap. Additionally, France lacks a unified embodied carbon assessment framework, affecting the uptake of LCA tools in construction projects [1].
    - Southern and Eastern Europe struggle with funding gaps and fragmented policy implementation, which has slowed CE infrastructure investment [49]. While nations such as Spain have high C&DW collection rates, low secondary material demand results in stockpiling and landfill overflow. Similarly, Lithuania and Poland lack sector-wide CE frameworks, leading to inconsistent adoption of material recovery strategies [25].
    - United Kingdom: Unlike Germany or the Nordic countries, the UK's circular economy policies have been focused on specific industrial sectors—such as glass, chemicals, and steel—with an emphasis on material circularity and waste heat recovery through industry-government collaboration [25]. However, this focus has not extended to the construction sector, which lags in C&DW circularity adoption. The fragmented policy landscape for construction waste recycling has inhibited the overall transition toward climate neutrality. The UK also faces challenges in digital circularity adoption—while BIM use in new construction is advanced, its application for circular material tracking and reuse is limited, creating inefficiencies in demolition and secondary material markets [62].
- Japan and South Korea: Japan has one of the highest construction waste recycling rates (up to 95%), driven by mandatory waste sorting, strict landfill bans, and advanced recycling technologies. South Korea also implements extended producer responsibility (EPR) programs, requiring manufacturers to take accountability for building materials' end-of-life management [43].
- North America (USA and Canada): The USA has a fragmented regulatory landscape, where CE adoption varies by state. California leads in C&DW recycling due to landfill restrictions, while other states have minimal mandates. Canada has implemented

progressive tax incentives for green building materials and low-carbon procurement policies but struggles with large-scale adoption due to a dispersed industry [21].

- Australia: Despite increasing C&DW emissions (61% rise since 2005), government policies have been inconsistent due to frequent political shifts. High certification costs for recycled materials also deter market growth [8].

3.4.2. Gaps Within European-Country-Specific Data

While multiple Western and Northern European countries have well-documented CE adoption strategies, the literature lacks country-specific analyses, as for example those within Eastern Europe, Mediterranean, the Balkan area, and Baltic states, making cross-country comparisons incomplete. This further limits our understanding of how different regulatory, economic, and infrastructural contexts shape CE adoption. For example, Germany and the Netherlands enforce strict C&DW recovery mandates, but it is unclear whether similar policies exist or are enforced in Poland, Romania, Bulgaria, or the Baltic states. Without such comparative insights, it is difficult to assess which policies drive higher adoption rates and which barriers persist across different national contexts.

In terms of lacking details, the case of Portugal was highlighted in the study by Joana [47], where it was found that no specific regulation for CE adoption was present at the time of the study. While principles regarding environmental impact minimization are present, their empirical efficacy in reducing environmental footprint in the case of Portugal is not clarified, leading to data gaps when comparing regional data.

In terms of Baltic states, the case of Lithuania illustrates an uneven distribution of circularity progress within sectors—while Lithuanian Railways has committed to green logistics through rail electrification and 99% waste recycling efficiency [37], the construction sector lacks comparable circular economy regulations. Unlike Germany and the Nordic countries, where C&DW recovery is a legislative priority, Lithuania's circularity progress is sector-specific, with funding limitations and continued reliance on diesel freight transport remaining significant barriers within integrating circularity and decarbonization principles. This sectoral inconsistency suggests that without cross-industry regulatory alignment, circular economy progress in Lithuania and similar regions may remain fragmented, slowing overall adoption at a national and EU-wide scale.

This lack of country-specific data also affects EU-wide CE progress, as uneven adoption across member states may slow down broader policy alignment and impact assessment. Future research should address these gaps through regional case studies and comparative analyses to identify effective policy mechanisms and structural challenges.

3.4.3. Emerging and Developing Economies: Challenges and Opportunities

Developing regions face significant challenges in circularity due to weak policy frameworks, lack of investment in recycling infrastructure, and socio-economic constraints.

- China: While producing 29% of the world municipal solid waste, China recycles only 10% of its demolition waste due to inadequate quality certification for recycled materials, weak waste sorting regulations, and unsupervised C&DW transport [49]. However, national efforts such as the Green Building Action Plan and increased funding for urban mining initiatives aim to improve these metrics.
- Latin America (Brazil, Mexico, Chile): These countries face high levels of informal recycling and low enforcement of circular economy policies. In Brazil, informal workers dominate waste collection, leading to unregulated recycling practices. Mexico has minimal C&DW recycling infrastructure, with most waste landfilled or illegally dumped [18].

- South Asia (India, Bangladesh): India's unstructured waste management system results in high levels of material loss, with an estimated 50% of C&DW going uncollected. Policies such as the Construction and Demolition Waste Management Rules (2016) aim to encourage recycling, but enforcement remains weak. In contrast, Bangladesh lacks formal recycling policies, leading to a heavy reliance on brick-based construction and inefficient demolition practices [10].
- Africa (South Africa, Nigeria, Kenya): South Africa has made progress in concrete recycling and alternative materials (e.g., hempcrete, compressed earth blocks) but lacks a nationwide regulatory framework. In Nigeria and Kenya, agricultural by-products (e.g., rice husks, coconut fibers, and bamboo) offer a low-carbon construction alternative, but poor waste collection systems hinder scalability [10].
- Middle East (UAE, Saudi Arabia): The UAE has adopted high-tech construction waste recycling plants, but overall adoption of CE remains low due to a dominance of high-carbon materials like concrete and steel. Saudi Arabia Vision 2030 promotes green building certifications (e.g., Estidama, Mostadam), but implementation is still in its infancy.

3.4.4. Policy Implications

The literature underscores how regulatory maturity, financial incentives, and industrial innovation determine CE adoption rates across regions. While developed countries benefit from strong enforcement and financial support for circular practices, developing regions face significant barriers such as lack of infrastructure, weak regulations, and informal waste economies.

Countries with structured CE regulations, such as Germany, the Nordics, and Japan, demonstrate high C&DW recovery rates and integration of digital circularity tools. However, fragmented policies in Southern and Eastern Europe, as well as in developing economies, hinder circularity progress. Aligning national CE policies with international carbon neutrality goals and mandating sector-wide digital tracking tools, such as BIM-integrated material passports, can drive systemic improvements.

Low demand for secondary materials and lack of economic incentives remain barriers to CE adoption, particularly in Spain, Lithuania, and Poland. In emerging economies, financing constraints and informal waste economies slow circularity adoption. Governments should implement tax incentives for recycled materials, public–private financing initiatives, and stricter landfill bans to stimulate CE investments.

While Germany, Sweden, and Denmark incorporate CO_2 taxation and life-cycle assessment (LCA) into construction, other EU nations such as France and Spain lack a harmonized approach to carbon accounting. Implementing EU-wide carbon pricing on construction materials and mandatory LCA assessments can ensure greater alignment between circularity and decarbonization strategies.

International roadmaps, such as the UN Sustainable Development Goals (SDG12) and Vision 2030 in Saudi Arabia, offer policy frameworks for CE expansion, but their impact is limited without regional implementation strategies. Strengthening regional CE coalitions, such as the EU Circular Economy Action Plan and ASEAN CE Roadmap, through infrastructure investments and regulatory alignment will enhance global adoption.

4. Discussion

4.1. Carbon-Negative and Regenerative Practices

Most of the papers evaluated discussing policies have primarily focused on reducing resource consumption. This is significant because the increasing impacts of climate change, such as wildfires and ocean acidification, are reducing the ability of natural ecosystems to absorb carbon [64,65]. Consequently, carbon-negative practices are becoming a higher priority to achieve carbon neutrality. Many studies have emphasized waste recirculation into material streams as a pathway toward regenerative practices. However, while this contributes to circularity, a completely circular loop—where all waste streams are reused as inputs—is not by itself regenerative. It only indirectly supports ecosystem regeneration by allowing time for natural restoration processes.

No studies in the review explicitly demonstrated the potential for net-regenerative practices in terms of environmental impact, though several discussed carbon-negative materials as a promising approach. Carbon-negative materials, such as biochar and biochar-enriched composites, consume more CO_2 over their lifetime than they emit during production. For instance, ref. [6] highlighted the potential of biochar in construction products, such as wall plaster and pellets, as a practical example of carbon sequestration integrated into building materials. Additionally, carbon-negative cements like carbicrete not only avoid emissions associated with traditional cement production but also sequester CO_2 during curing processes, illustrating a direct synergy between carbon-negative practices and material innovation.

Despite these advancements, whether carbon-negative materials, when used primarily for virgin material production, are always the most sustainable approach in the long term, remains a question. An alternative lies in directly supporting soil organic carbon cycles, such as through the application of biochar to degraded soils. This practice has dual benefits: enhancing soil health and acting as a carbon sink, improving nutrient and water cycling [66,67]. Increasing soil organic carbon is crucial for global ecological recovery, yet it requires interdisciplinary approaches to connect the construction, agricultural, and ecological sciences. For instance, biochar derived from agricultural waste could be integrated into soil recovery systems, aligning carbon-negative material use with ecosystem restoration efforts [6,47].

Furthermore, coupling the use of biobased materials with afforestation initiatives or agricultural waste composting could extend carbon storage benefits beyond material lifecycles. Biobased materials, while promising, need to be carefully managed to avoid trade-offs such as ecological damage or unintended emissions during production [6,47]. While incineration of waste materials releases carbon into the atmosphere—further exacerbating current excesses—approaches like biochar integration offer a regenerative alternative by stabilizing carbon within the soil.

Carbon-negative materials true potential lies in their systemic integration into regenerative practices that rebuild lost biomass and restore degraded ecosystems. Interdisciplinary collaboration is critical to advancing this transition, synergizing construction, agriculture, and ecological sciences. Future studies should prioritize evaluating the long-term carbon absorption and biomass growth potential of integrating construction by-products into agricultural applications. Such efforts would align material flows with ecosystem recovery, paving the way for a model where the built environment actively contributes to ecological regeneration and carbon sequestration.

4.2. Circularity and Decarbonization in Certification Systems

While many studies emphasize carbon-negative practices, integrating them into widespread certification frameworks remains a challenge. Certification schemes such as BREEAM and LEED are commonly adopted tools for assessing sustainability in the built environment, yet their role in supporting circularity and decarbonization is still evolving.

BREEAM has historically placed a greater emphasis on whole-building LCA, requiring material reuse, recyclability, and embodied carbon tracking as part of its assessment criteria [68–71]. By contrast, LEED has prioritized operational energy efficiency but has only recently started incorporating embodied carbon requirements—LEED v5 will mandate embodied carbon quantification as a prerequisite [72], aligning more closely with the BREEAM approach. Both frameworks encourage material reuse and circular economy strategies but lack explicit requirements for digital tracking of materials, such as material passports or real-time LCA integration. Additionally, there remains a gap in how both certifications account for biogenic carbon emissions and storage. The European standard EN 15804+A2 introduced specific guidelines on biogenic carbon accounting in life cycle assessments [73], yet neither BREEAM nor LEED fully enforces these methodologies. Current frameworks often overlook how absorbed carbon in biobased materials interacts with end-of-life emissions, leading to potential discrepancies in long-term carbon impact assessments.

SRI offers a complementary approach to sustainability assessment by focusing on building intelligence, automation, and energy flexibility [74,75]. However, it remains largely limited to operational energy performance and does not currently address embodied carbon, recyclability, or material circularity. Expanding SRI to integrate real-time material tracking, circularity scoring, and lifecycle-based carbon monitoring would help bridge the gap between operational performance and whole-building sustainability [74,76]. Moreover, integrating IoT-driven SRI evaluations with LEED and BREEAM could provide dynamic sustainability tracking, ensuring buildings adapt to long-term decarbonization goals [75,76].

4.3. Digitalization

Digitalization is emerging as a transformative enabler for advancing circularity and decarbonization in the construction sector. Several studies highlighted the pivotal role of digital tools, such as Building Information Modeling (BIM), Geographic Information Systems (GIS), and Life Cycle Assessment (LCA), in optimizing material use and reducing greenhouse gas (GHG) emissions. For instance, the integration of BIM and LCA has proven effective in treating existing buildings as material banks, enabling detailed assessments of reusable components to lower embodied carbon [13]. Similarly, combining BIM, GIS, and LCA allowed for comprehensive evaluations of environmental impacts, achieving GHG reductions of up to 29.35% during materialization stages [50]. Digital visualization tools, such as color-coded schemes for identifying recyclable materials during selective demolition, have also demonstrated potential in optimizing recycling rates and prioritizing high-value materials for recovery [43]. Common building sustainability assessment tools—LEED and BREEAM—acknowledge digital tools in their frameworks, but do not fully integrate real-time tracking mechanisms for circular material flows or embodied carbon impacts [69,70].

The widespread adoption of digital solutions faces challenges, including a lack of standardized data formats, interoperability issues, and resistance to adopting new technologies among stakeholders [41]. These findings underscore the transformative potential of digitalization in promoting circularity, while also highlighting the need for standardized frameworks and stakeholder collaboration to unlock its full benefits. However, while digital twins have emerged as a trending concept, their quantified emissions reduction remains underexplored [62].

4.4. (Lack of) Recycling Infrastructure

A recurring barrier in achieving circularity in the construction sector is the lack of adequate recycling infrastructure, with many studies highlighting the challenges associated with limited facilities for material recovery and processing. For instance, insufficient infrastructure for waste separation and recycling was identified as a major obstacle, restricting the reuse of materials such as concrete, steel, and wood [34]. Additionally, the absence of unified systems for demolition, storage, and redistribution further hinders the effective reuse of construction waste, with studies estimating that up to one-third of construction waste could be reused if such systems were in place [4]. The lack of market demand for recycled materials adds further complexities, as low-quality recovered materials and regulatory constraints limit their use viability [58]. Moreover, the absence of standardized frameworks and policies to guide recycling practices creates confusion among stakeholders, further slowing the adoption of circular economy principles in construction. These findings emphasize the critical need for investment in recycling infrastructure and the establishment of clear, enforceable policies to support large-scale material recovery and reuse.

4.5. Literature Limitations

The reviewed literature on circularity and decarbonization in the construction sector provides valuable insights but is not without limitations. A major issue lies in the inconsistent methodologies used for assessing carbon footprints and material impacts. Several studies identified the lack of standardized frameworks for life cycle assessments (LCA) and carbon accounting, leading to challenges in comparing findings across different research efforts [41]. This inconsistency undermines the reliability of results and complicates the development of actionable strategies for stakeholders.

Another limitation is the narrow focus of many studies on specific materials or processes, such as selective deconstruction or individual material alternatives like ground granulated blast furnace slag (GGBS) concrete [5,9]. While these findings are valuable, they often overlook the broader systemic challenges, such as the integration of these methods into existing construction practices or their scalability. Moreover, many studies emphasize material production and usage phases, often neglecting the end-of-life stage or the operational complexities associated with circularity, such as logistics and stakeholder collaboration [27].

A significant number of papers were excluded during the filtering process, which may have inadvertently limited the discussion of indirect synergies, such as those related to business management strategies, policy alignment, and interdisciplinary approaches. The focus on specific material or technical aspects in the included literature may have constrained the ability to explore how broader systemic barriers and facilitators interact within the transition toward a circular built environment. Furthermore, the research mostly included recent publications (post-2021), excluding earlier studies and researcher opinions. This exclusion limits the ability to evaluate the progression of barriers over time and how these barriers have evolved alongside policy developments, technological advancements, and industry practices.

Regarding digitalization, while digital twins are often mentioned as an emerging topic, only two studies in the reviewed literature discussed it at all. Additional research found that although digital twins show great potential for supporting decarbonization and circularity, there is not enough existing work to fully evaluate their impact. A key challenge is complexity of building the data systems needed to support digital twins. The issues related to data (complexity) emerged as a recurring theme. Studies frequently point to gaps in reliable and comprehensive datasets for material recovery, embodied carbon, and construction waste streams. This absence of data limits the ability to perform robust LCAs and inhibits the development of digital tools, such as material banks or digital twins, that rely on accurate and granular information [13]. Furthermore, regulatory and market barriers, often cited in the literature, are rarely analyzed in depth, leaving questions about the practical implementation of suggested strategies unanswered.

Lastly, there is a lack of interdisciplinary approaches in many studies. While some research recognizes the importance of combining technical, economic, and policy perspectives, the majority focused primarily on technical solutions without adequately addressing behavioral, cultural, and economic barriers to adoption [14]. These limitations highlight the need for more integrated, comprehensive, and standardized research to effectively tackle the challenges of circularity and decarbonization in construction.

4.6. Policy Directions for Circularity and Decarbonization

A recurring issue in existing policies is the fragmentation and lack of standardized frameworks for evaluating environmental impacts. Discrepancies in life cycle assessment (LCA) methodologies hinder the comparability and reliability of results, creating confusion for stakeholders and impeding the adoption of circular economy principles [41]. While BREEAM mandates whole-building LCA and LEED v5 now requires embodied carbon quantification [72], neither certification fully standardizes assumptions, boundaries, or impact categories, making cross-project comparisons difficult. Unified regulatory frameworks that define essential LCA dimensions and provide clear metrics for assessing the environmental footprint of materials are critical to addressing this challenge. Additionally, policies often fail to incentivize or mandate critical practices like material recovery and recycling. The absence of robust infrastructure for recycling construction waste, combined with insufficient enforcement mechanisms, limits the effectiveness of circular strategies [4,34].

The lack of interdisciplinary collaboration between construction, agriculture, and ecological sciences further restricts the development of integrated solutions, such as incorporating agricultural by-products into construction materials or linking building deconstruction with soil regeneration strategies [14]. While EN 15804+A2 provides clear methodologies for biogenic carbon accounting, neither BREEAM nor LEED fully integrates these guidelines, leading to inconsistencies in how biobased materials—such as timber, hemp, and straw—are credited for their long-term carbon storage potential [69]. Without a standardized approach, biobased materials remain underutilized despite their potential to reduce embodied emissions and contribute to carbon sequestration.

To overcome these challenges, future policies should prioritize carbon-absorbing technologies by providing financial incentives or tax reductions for using biobased materials such as timber, straw, hemp, and bamboo. These materials not only reduce embodied carbon emissions but also support broader sustainability goals when coupled with flexible construction standards [15]. Policies should shift focus from rigid material performance metrics to innovative techniques of use, ensuring compatibility with the variable properties of biobased materials [9]. Additionally, institutional support for education and training programs could accelerate the integration of biobased materials into mainstream projects, reducing costs and enhancing industry-wide adoption.

Developing robust recycling infrastructure is another critical priority—up to one-third of construction waste could be effectively reused with unified systems for demolition, storage, and redistribution [4]. However, existing certification schemes primarily reward waste diversion rather than incentivizing high-value reuse. Both BREEAM and LEED provide credits for reducing landfill waste, but neither distinguishes between downcycled materials and materials reintegrated into new construction projects [72,77]. This limitation means that much of the recovered material is used for lower-value applications, missing an opportunity to establish a truly circular construction sector. Policies should mandate more rigorous disassembly practices, require project developers to incorporate recycled materials into new builds, and enforce higher-value reuse quotas. Expanding certification requirements to prioritize material reintegration, rather than just landfill diversion, would help close material loops and promote circular economy principles within the built environment [72].

The role of financial incentives in accelerating circularity is evident in the present literature. Government-backed subsidies and near-zero-cost land allocations for recycling facilities have significantly reduced the financial burden on businesses seeking to invest in sustainable waste management infrastructure—landfill levies in Shenzhen, set at 3 CNY per ton, have reduced waste disposal expenses by up to 69,132 CNY in the highest recycling scenarios [43]. Such fiscal mechanisms highlight the potential for economic policy to drive market transformations in material recovery and circularity. Similarly, tax incentives for construction projects utilizing recycled and biobased materials can lower the cost barrier, addressing one of the primary obstacles to market adoption. Selective demolition is often hindered by high labor costs and tipping fees [47,54]. Targeted financial support, such as grants for deconstruction projects or tax rebates for the use of secondary materials, could improve adoption rates, bridging the economic gap between conventional and circular construction practices [53].

Standardizing environmental impact assessments is essential for ensuring consistent and reliable carbon accounting. Policies should establish clear guidelines for evaluating construction products, with baseline LCA requirements tailored to the built environment [41]. Innovative materials like alkali-activated binders, which combine carbon sequestration potential with strong mechanical performance, could benefit from tailored evaluation methods that recognize their unique properties [30]. Such standardization would simplify compliance and promote the adoption of low-carbon technologies by reducing complexity for stakeholders.

Material passports should be at the center of this transition, increasing transparency and enabling lifecycle-based emission calculations [13,27]. By documenting the properties, origins, and environmental impacts of materials, passports can facilitate reuse and improve traceability throughout the construction lifecycle. Linking these passports to digital platforms would enable real-time material tracking, fostering trust among stakeholders and improving circularity outcomes. Despite their potential, neither BREEAM nor LEED currently mandates material passports and their use remains limited to voluntary initiatives [69,71]. Expanding certification requirements to include material passports, alongside integration with SRI and BIM systems, would create a stronger foundation for circular material flows and enable more accurate emissions tracking over the lifecycle of a building.

Addressing these gaps requires a combination of regulatory enforcement, financial support, and digitalization. LEED and BREEAM provide a starting point, but both frameworks, in order to utilize for carbon neutrality/negativity and circularity, need to go beyond static LCA calculations and incorporate real-time monitoring tools for material flows and emissions tracking. Integrating material passports, embodied carbon tracking, and financial incentives within certification systems and national policies would enable a more robust transition toward circular and low-carbon construction practices.

5. Conclusions

This review identifies key synergies, barriers, and policy directions necessary to advance circularity and decarbonization in the construction sector. By synthesizing results and discussions, it emphasizes the intersection of technical, policy, and systemic challenges that must be addressed to achieve a climate-neutral future.

5.1. Key Insights and Synergies

The integration of circularity principles and decarbonization strategies demonstrates significant practical synergies. Designs for disassembly emerge as a critical approach, such as selective demolition and reuse, resulting in greenhouse gas emission reduction by up to 70% and reduction of natural resource extraction. Material efficiency, reuse, and waste management presents itself as another key synergy, with approximately one-third of construction waste having the potential to be effectively reused with adequate systems for sorting, redistribution, and quality control. Furthermore, promotion of regional/local developments in recycling infrastructure and coordination of material recovery could result in net reduction of transport-related emissions, with an indirect benefit of bridging sociological barriers in integrating circularity and decarbonization into construction.

Low-carbon and carbon-negative materials represent a transformative opportunity for synergizing circularity and decarbonization. Biobased materials—such as cellulose, straw, and timber—provide dual benefits of carbon storage and circularity, but require further refinement in lifecycle assessments to address their performance variability and environmental trade-offs. Materials such as biochar and carbon-negative cements (e.g., carbicrete) actively sequester CO_2 during production and use. These innovations demonstrate the potential to disrupt unsustainable value chains by reducing embodied carbon and enabling long-term carbon storage. Agricultural by-products, such as cassava peels and rice husks, further expand these synergies by replacing traditional cement, reducing emissions and creating circular pathways for agricultural waste.

Digitalization continues to be a key actor, with BIM and GIS enabling optimization of material use, tracking of lifecycle impacts and enhancing decision making, with emission reductions of up to 29.35% during materialization stages when these tools are integrated. However, challenges such as data interoperability, standardization gaps, and limited adoption hinder their scalability. Expanding the adoption of digital solutions remains essential for aligning material flows with decarbonization goals.

5.2. Barriers and Limitations

Systemic barriers impede the scalability of circular and decarbonization strategies. A persistent challenge is the lack of recycling infrastructure, particularly in regions with underdeveloped material recovery systems. The absence of centralized systems for material sorting, redistribution, and quality control limits the effective reuse of construction and demolition waste. Data gaps further constrain the effectiveness of lifecycle assessments and digital tools, as reliable and consistent information on material flows and carbon footprints remains scarce.

Financial barriers, including the absence of market incentives for recycled and biobased materials, exacerbate the cost disparity between sustainable and conventional practices. Studies highlighted the lack of direct financial incentives, such as tax benefits or subsidies, preventing widespread adoption of low-carbon materials.

Sociological barriers, such as resistance to change, lack of awareness, and stakeholder inertia, further hinder progress. The integration of carbon-negative materials is constrained by technical complexities, high initial costs, and the need for interdisciplinary collaboration. The intergration of carbon-negative materials remains constrained by technical complexities, high upfront costs, and the need for interdisciplinary collaboration between material scientists, policymakers, and industry stakeholders.

5.3. Policy and Research Directions

To address these barriers and unlock the potential of circularity and decarbonization, the following priorities must be emphasized:

- Standardization and data sharing: establishing standardized LCA frameworks, material passports, and shared repositories of demolition waste data to improve data consistency and stakeholder coordination. Certification systems such as LEED and BREEAM should integrate real-time material tracking, digital passports, and standardized biogenic carbon accounting (e.g., EN 15804+A2 compliance) to ensure accurate

circularity and decarbonization assessments. Similarly, expanding SRI to account for whole-building sustainability indicators rather than just operational energy performance could help bridge digitalization and material recovery strategies.
- Infrastructure development: investing in centralized systems for material recovery, storage, and redistribution, particularly in regions where infrastructure gaps remain significant.
- Financial incentives: introducing fiscal policies such as tax reductions, subsidies, and government-backed incentives to stimulate market demand for recycled and biobased materials, ensuring their scalability and economic viability. Standardized carbon accounting could facilitate targeted incentive structures based on material performance.
- Interdisciplinary collaboration: promoting cross-sectoral partnerships, such as between construction, agriculture, and ecological sciences, to explore regenerative practices.
- Scaling digital solutions: expanding the adoption of BIM, digital twins, and other digital tools, while addressing barriers such as data interoperability and training gaps. Aligning digitalization efforts with environmental impact assessments would enable real-time tracking of embodied carbon and material flows.
- Tailored regional approaches: recognizing regional disparities, with developed regions focusing on scaling innovations and developing regions prioritizing capacity building, technology transfer, and policy alignment.

5.4. Further Directions

Achieving a zero-carbon construction sector requires systemic interventions and interdisciplinary approaches. Carbon-negative materials—biobased (cellulose, straw, timber, biochar) and carbon-sequestering cements—represent a critical area for innovation, offering pathways to address both circularity and decarbonization goals. The integration of digital tools and lifecycle assessments provides additional opportunities to enhance material recovery and optimize resource use. Future research should assess how real-time LCA tracking, IoT-enabled material passports, and automated sustainability scoring could be integrated into certification frameworks. While these technologies have the potential to increase circularity transparency, their impact on adoption remains underexplored and requires empirical validation. Key challenges include data standardization, interoperability, and stakeholder adoption.

Regional disparities in the adoption of circular and decarbonization practices remain a key challenge. Developed regions benefit from established infrastructure and advanced policies, while developing regions face constraints related to funding, technology access, and policy implementation. However, even within Europe, disparities exist—Eastern European, Balkan, and Baltic countries remain underrepresented in CE adoption studies, limiting the comparability of policy effectiveness. Addressing these gaps through targeted policies, financial incentives, and international collaboration is critical to enabling equitable progress.

While this review synthesizes current literature on financial incentives and material innovations, it does not conduct independent cost–benefit analyses or economic modeling. Future research should prioritize the quantification of financial impacts, such as the cost-effectiveness of biobased materials, the economic feasibility of material recovery systems, and the scalability of carbon-negative technologies. Additionally, more empirical studies are needed to quantify the impact of digitalization on emission reductions and material efficiencies. The development of interdisciplinary regenerative practices that integrate construction, agriculture, and ecological restoration should also be further explored.

Aligning material flows with ecological recovery remains an urgent priority. By fostering a systemic transition toward net-zero carbon construction sector, future research can bridge existing knowledge gaps and advance scalable, economically viable circularity and decarbonization strategies that align with global climate goals.

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Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
LCA	Life cycle analysis
BIM	Building information modeling
GHG	Greenhouse gas
CDW	Construction and demolition waste
CE	Circular economy
GIS	Geographic Information Systems

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