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Review

Bridging Sustainability and Performance: Conceptualizing Net-Zero Integration in Construction Supply Chain Evaluations

Isuru Hettiarachchi *, James Olabode Bamidele Rotimi, Wajiha Mohsin Shahzad and Ravindu Kahandawa

School of Built Environment, Massey University, Auckland 0632, New Zealand; j.rotimi@massey.ac.nz (J.O.B.R.); w.m.shahzad@massey.ac.nz (W.M.S.); r.kahandawa@massey.ac.nz (R.K.)
* Correspondence: i.hettiarachchige@massey.ac.nz

Abstract

The construction industry is a major contributor to global carbon emissions, highlighting the need to align material supply chains with net-zero targets. Evaluating supply chain performance is essential for reducing emissions, enhancing resource efficiency, and supporting sustainable decision-making. However, there is a lack of comprehensive frameworks that integrate net-zero objectives into construction material supply chain evaluation. This study aims to develop a conceptual framework that embeds net-zero principles into supply chain performance evaluation within the construction sector. A systematic literature review was conducted using PRISMA guidelines, covering 54 peer-reviewed articles published between 2016 and 2025. The review identifies key supply chain decarbonization performance indicators, tools, challenges, enablers, and improvement opportunities. The findings reveal the growing use of life cycle thinking, carbon accounting, and digitalization, shaped by policy, data access, technological readiness, and stakeholder coordination. The resulting framework integrates these factors to guide a structured, net-zero-aligned supply chain. This study contributes a novel and practical framework that addresses a critical gap by bridging digital tools, decarbonization metrics, and policy or organizational considerations. It offers theoretical insights and actionable guidance for researchers, practitioners, and policymakers pursuing climate-aligned construction supply chains.

Keywords: construction material supply chain; decarbonization; framework; green construction; green procurement; net-zero; performance evaluation; performance indicators

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1. Introduction

The construction industry is a key contributor to global greenhouse gas (GHG) emissions, with a significant portion originating from the production and transportation of construction materials [1–4]. Construction materials, such as cement, steel, and glass, are energy-intensive, resulting in substantial Scope 1 and 2 emissions [5–7]. Scope 1 covers direct emissions from owned sources, Scope 2 includes indirect emissions from purchased energy, and Scope 3 accounts for all other indirect emissions across the value chain [8]. For instance, the cement sector alone contributes a considerable share to global carbon dioxide (CO_2) emissions, due to its reliance on fossil fuel combustion and calcination processes [9,10]. Additionally, the supply chain for construction materials includes extensive logistics operations, often overlooked in emissions accounting, which significantly drive up Scope 3 emissions [11–13]. This is particularly relevant in regions with dispersed resource availability and infrastructure demands, where transportation and distribution play a central role in the lifecycle emissions of materials [14–17]. Addressing these emissions across the material value chain is essential for enabling meaningful decarbonization of the built environment.

Reducing the carbon footprint of construction material supply chains involves several essential strategies. These include efficient energy use during production, choosing alternative materials with lower carbon emissions, and improving transport systems to reduce fuel use and emissions [10,14,18]. Using digital tools like Building Information Modelling (BIM), Life Cycle Assessment (LCA), and material passports can help track emissions more accurately and support better decision-making throughout the project [5,6,19–21]. Circular economy practices, such as recycling materials, designing buildings for future reuse, and extending the life of materials, also play a key role in cutting carbon emissions [14,22,23]. These actions are significant for tackling Scope 3 emissions, which come from outsourced and indirect activities like transportation and material production [11–13]. Meeting national and global net-zero targets will require strong collaboration between material suppliers, builders, procurement teams, and policymakers [2,24,25]. This study responds to these challenges by developing a clear and practical framework to measure and support carbon reduction across construction material supply chains.

Despite growing interest in decarbonizing construction activities, integrating net-zero principles into construction material supply chains remains fragmented and underdeveloped. While numerous studies have explored aspects of life cycle assessment (LCA), circular economy (CE), and digital tools such as Building Information Modelling (BIM), there has not been a systematic effort to consolidate this knowledge and develop a unified framework that evaluates supply chain performance through a net-zero lens. The existing literature often addresses emissions reduction from isolated angles, focusing on individual life cycle stages, specific tools, or particular carbon scopes, without fully integrating them into a comprehensive decision-making framework [20]. Furthermore, the complexity of construction supply chains, combined with data and methodological inconsistencies, has hindered the development of practical tools [9,23]. For example, studies often adopt different system boundaries (e.g., cradle-to-gate vs. cradle-to-grave), use inconsistent emissions factors, or lack standardized units of analysis, making it difficult to compare results or apply tools across diverse construction scenarios [1,25,26]. While significant progress has been made in carbon tracking, LCA, and circular construction strategies, existing approaches often fall short in guiding practical decision-making and coordination across supply chain stages [27]. Many frameworks lack alignment with real-world project workflows, fragmented data systems, and organizational structures. Furthermore, most studies address emissions at isolated life cycle stages or within individual tools, without offering an integrated view that supports policy alignment, stakeholder coordination, and replicable performance evaluation.

This study addresses these gaps by developing a conceptual framework that bridges digital tools (e.g., BIM and LCA), carbon metrics, and organizational dimensions across the material supply chain. Unlike prior studies, this work explicitly evaluates supply chain performance in transparent, replicable ways. It is adaptable to diverse decision-making contexts in the pursuit of net-zero goals.

This study aims to develop a conceptual framework for evaluating the performance of construction material supply chains in alignment with net-zero goals. To achieve this, it systematically synthesizes existing literature to identify how decarbonization principles have been integrated into supply chain performance assessment within the construction industry.

This study is guided by two objectives. The first is identifying, mapping, and analyzing existing domain knowledge on integrating net-zero strategies within construction material supply chain performance evaluation, including performance indicators, tools, theories, frameworks, challenges, and enablers. Second, based on insights from the systematic literature review, the study derives a conceptual framework that holistically integrates net-zero considerations into evaluating supply chain performance. This framework supports both theoretical research and practical sustainability transitions.

This paper is structured as follows. Section 2 outlines the methodology adopted for the systematic literature review. Section 3 presents the key findings, including trends in tools, frameworks, and carbon reduction strategies. Section 4 discusses the development of an integrated framework for net-zero construction material supply chains. Finally, Section 5 concludes the study by summarizing key contributions.

2. Materials and Methods

To address the objectives mentioned above, this study systematically reviewed 54 peer-reviewed articles to synthesize the current research on carbon reduction strategies, tools, and frameworks used within construction material supply chains. The systematic literature review was carried out using PRISMA to find, select, and review existing research in a structured and thorough way. Using a systematic approach helps ensure that the review is transparent, unbiased, and reliable [28]. The review process followed the step-by-step method suggested by Daemei et al. [29], which helps researchers check how well the selected studies match the research questions and narrow down the number of papers for detailed analysis. The main steps of the review were: defining the research questions, selecting relevant studies, summarizing the collected information, and synthesizing and interpreting the findings.

2.1. Defining the Research Questions

This study establishes a conceptual framework to model and drive net-zero in construction material supply chains. It followed the PRISMA approach to identify and select relevant articles for the review (Figure 1). Four research questions (RQ1 to RQ4) were developed to understand how net-zero targets are included in evaluating the performance of construction material supply chains. These research questions were defined by combining current research priorities in decarbonization, construction management, and supply chains. The research questions are:

- RQ1: How are the net-zero indicators integrated in the construction material supply chains' performance evaluation, and what indicators and activities are considered?
- RQ2: What tools and technologies support performance evaluation and carbon tracking?
- RQ3: What are the challenges and enablers of integrating net-zero in construction material supply chain performance evaluation?
- RQ4: What key strategies, theoretical perspectives, and frameworks have been used to evaluate net-zero construction supply chains, and what research gaps remain that could advance net-zero supply chain evaluation?

These research questions directed the review and ensured that critical areas such as performance evaluation, integration of net-zero goals, supporting technologies, challenges, enablers, and theoretical developments were thoroughly examined in the analysis.

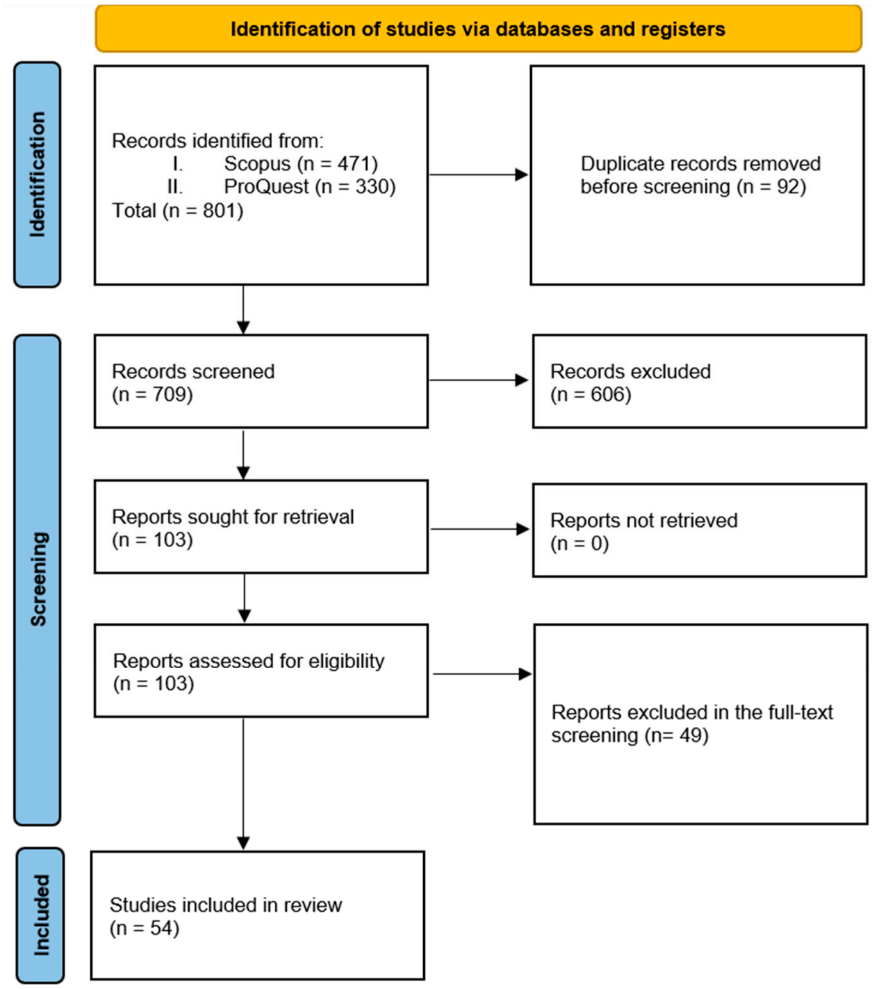

Figure 1. PRISMA flow diagram of identifying the relevant articles.

2.2. Selecting Relevant Studies

Articles were retrieved from two major databases: Scopus and ProQuest. These databases were chosen because they provide broad international coverage and maintain high-quality standards for indexed publications [30,31]. The database search was conducted on 23 March 2025 using the following keyword string: (indicator OR metric OR measur* OR assess* OR performance* OR manag*) AND ("suppl* chain*" OR "value chain*" OR "reverse logistic*" OR procur* OR "logistic*" OR sourc*) AND ("carbon footprint*" OR green OR "net zero" OR "net-zero" OR circular* OR decarbonization OR "carbon neutral") AND ("construction material*" OR "building* material*"). The search was limited to publications written in English and published between 2016 and 2025, to capture research developments that emerged after the 2015 Paris Agreement, which significantly increased global focus on carbon reduction and net-zero targets.

The database search initially returned 801 articles (471 from Scopus and 330 from ProQuest). After removing duplicates, 709 articles remained. A first round of screening based on the title and abstract was then performed, resulting in 103 articles selected for further full-text review. After the full-text review, 54 articles were included in the review. Table 1 presents the eligibility criteria used for including and excluding literature studies. Regarding source quality, of the 54 selected articles, 52 are peer-reviewed journal publications from recognized publishers. Two high-quality conference papers were also included due to their relevance and methodological contributions. Editorials, reviews, and non-peer-reviewed content were excluded to maintain scholarly rigour in the dataset.

Table 1. Eligibility criteria definitions for the screening stages.

Stage	Criteria	Decision
Searching	Journal articles, conference papers, and reports	Inclusion
	When specified keywords (e.g., net-zero, supply chain, construction materials, decarbonization, performance) are present in the title, abstract, or keywords.	Inclusion
	Duplicated studies among identified sources.	Exclusion
	Books, review papers, and editorials	Exclusion
Title and Abstract Screening	Studies focus on construction material supply chains relevant to decarbonization or carbon performance evaluation.	Inclusion
	Studies discuss performance assessment, lifecycle carbon emissions, or net-zero strategies in construction.	Inclusion
	Studies not related to material supply chains or net-zero performance	Exclusion
Full-Text Screening	Studies provide conceptual, methodological, or empirical insight into evaluating carbon performance or decarbonization in supply chains.	Inclusion
	Studies lack clear discussion on carbon metrics, emission scopes, or performance frameworks.	Exclusion
	Studies without a substantial focus on construction materials	Exclusion

2.3. Analysis and Interpretation

The study incorporated a quantitative bibliometric analysis to enhance the robustness and breadth of the review. This included publication trend analysis to examine the growth and evolution of research interest over time and keyword co-occurrence mapping to identify prominent research clusters and thematic concentrations within the literature. The keyword mapping was conducted using VOSviewer software (version 1.6.20), enabling the visualization of frequently associated terms and the detection of conceptual linkages across studies. Thematic mapping was also applied using the Bibliometrix tool (version 4.3.5) to categorize research themes based on their centrality and density, offering insights into the maturity and interconnectedness of various subdomains. These quantitative analyses provided a foundational understanding of the intellectual landscape, helping to guide and validate the subsequent qualitative coding and thematic synthesis.

The analysis followed a qualitative synthesis approach guided by the predefined research questions. Each selected article was systematically reviewed and coded to identify relevant themes, concepts, and patterns related to performance evaluation, sustainability integration, tools, enablers, challenges, and theoretical contributions within construction supply chains. A combination of thematic analysis and content mapping was employed to organize the findings, enabling cross-comparison and the identification of recurring constructs. Analytical categories were iteratively refined to ensure consistency and alignment with the scope of the review. The final step involved synthesizing the extracted insights into a conceptual framework that illustrates the relationships among key themes and provides guidance for future academic research and practical implementation in construction supply chains.

3. Results

From 2016 to 2024, publications grew from 2 to 11, an average annual increase of about 24%. Almost all outputs are journal articles (52 of 54), while conference papers appear only in 2023 and 2024, with one each year. Journal activity rose sharply in 2019, dipped slightly in 2021, and reached its highest point in 2024, showing steady growth in peer-reviewed work. Figure 2 includes a stacked bar chart that separates journal and conference counts, giving a clearer picture of how the field is developing. There was a significant rise in 2019, reaching nine journal articles, followed by continued contributions in subsequent years. The peak occurred in 2024 with ten journal articles and one conference paper, indicating heightened research activity and engagement. The data reflect a steady growth in academic attention, particularly in journal publications, with a notable surge in recent years [19,32]. The two conference papers were included in the systematic literature review due to their strong relevance to the research focus on sustainability and decarbonization within construction material supply chains. The first paper provides a foundational perspective on sustainability evaluation methods that apply to materials commonly used in construction, supporting the development of performance frameworks aligned with net-zero goals [32]. The second paper introduces a novel digital approach to track material and carbon flows, aligning closely with the review's interest in integrating digital tools like digital twins for performance evaluation [15]. Both contribute unique insights into emerging tools and conceptual approaches, justifying their inclusion despite being published as conference proceedings.

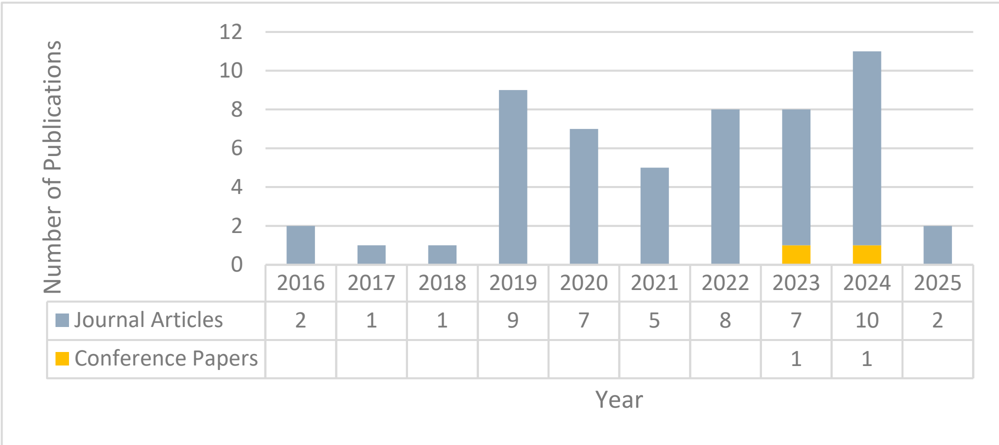

Figure 2. Summary of the eligible articles' source output and the number of associated publications.

Additionally, keyword analysis (Figure 3) conducted using VOSviewer revealed key trends and themes, providing deeper insights into the evolving research landscape and highlighting the increasing emphasis on net-zero and sustainability within construction material supply chains. The keyword co-occurrence network generated using VOSviewer reveals three prominent thematic clusters, each representing a significant area of focus within the literature on sustainable construction material supply chains. To create the keyword co-occurrence network, VOSviewer was used with a minimum occurrence threshold set to five, ensuring that only frequently appearing and thematically significant keywords were included in the analysis. All other settings were kept at their default values. General terms such as "China" and "article" were removed to enhance clarity and focus. Additionally, a manual thesaurus was applied to consolidate synonymous terms and reduce fragmentation in the network. For instance, variations such as supply chain and supply chains were merged under supply chain management. At the same time, terms like life cycle, life cycle analysis, and life cycle assessment (LCA) were unified as life cycle assessment. Similarly, construction material was standardized as construction materials, and both building and building material were, respectively, aligned with buildings and building materials. Other adjustments included combining greenhouse gases under greenhouse gas and energy utilization under energy consumption. This normalization process improved the coherence of the network, allowing for more precise identification of keyword clusters and thematic patterns within the literature.

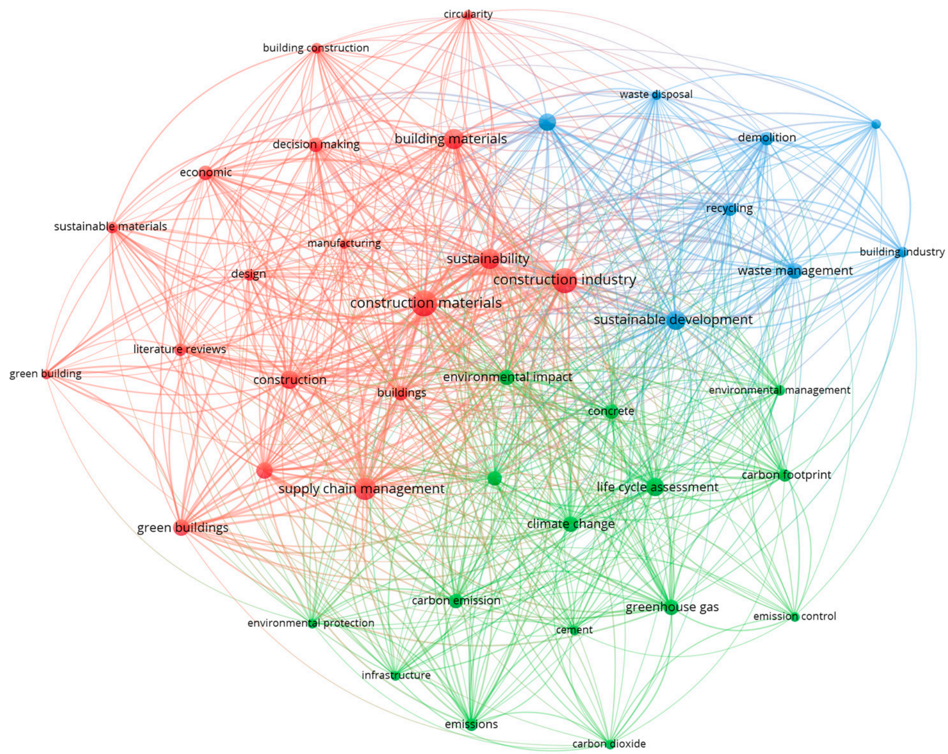

Figure 3. Keyword co-occurrence network visualization map of eligible articles generated using VOSviewer (Version 1.6.20).

The first cluster, highlighted in red, is centred around themes related to construction practices and sustainability integration. Key terms within this cluster include construction materials, construction industry, sustainability, building materials, green buildings, and supply chain management. This cluster reflects a significant body of research dedicated to embedding sustainability within the construction sector, focusing on material selection, design strategies, economic considerations, and decision-making processes that promote environmentally responsible construction practices. It also shows strong linkages between construction-related activities and sustainability-driven frameworks, underscoring the relevance of systemic thinking in achieving net-zero objectives.

The second cluster, represented in green, focuses on environmental impacts and emissions. Terms such as life cycle assessment, carbon emission, greenhouse gas, carbon footprint, climate change, and emissions are central to this group. This cluster illustrates a methodological emphasis on quantifying and evaluating the environmental performance of construction materials and processes. It points to the critical role of analytical tools like LCA in assessing emissions across the lifecycle of construction products, thereby supporting data-driven approaches to reducing the carbon intensity of supply chains. This cluster also emphasizes infrastructure and material-specific concerns, such as the use of cement and concrete, which are known for their high environmental impact.

The third cluster, shown in blue, revolves around waste management and circularity. It includes keywords such as waste management, recycling, demolition, waste disposal, environmental management, and circularity. This cluster emphasizes the importance of end-of-life considerations and circular economy principles in achieving sustainability. The focus is on reducing waste generation, promoting material recovery and reuse, and improving waste handling in the construction and demolition phases. This thematic area aligns closely with broader goals of sustainable development and resource efficiency in the built environment.

These clusters illustrate the interconnected yet distinct research directions within the field. Together, they demonstrate how sustainability in the construction material supply chain is pursued through a multidisciplinary approach encompassing construction practices, environmental assessment, and circular economy strategies.

The thematic mapping (Figure 4) revealed several key clusters within the literature. The thematic map was generated using the Biblioshiny interface of the Bibliometrix R package (version 4.5.0) [33] to analyze and visualize the conceptual structure of the literature. A minimum keyword occurrence threshold of five was applied to focus on the most relevant and frequently used terms. To ensure consistency with the VOSviewer analysis, the same manually prepared synonym file was used to merge equivalent terms. The Walktrap algorithm was selected for clustering. All other settings were kept at default values to maintain analytical transparency and reproducibility.

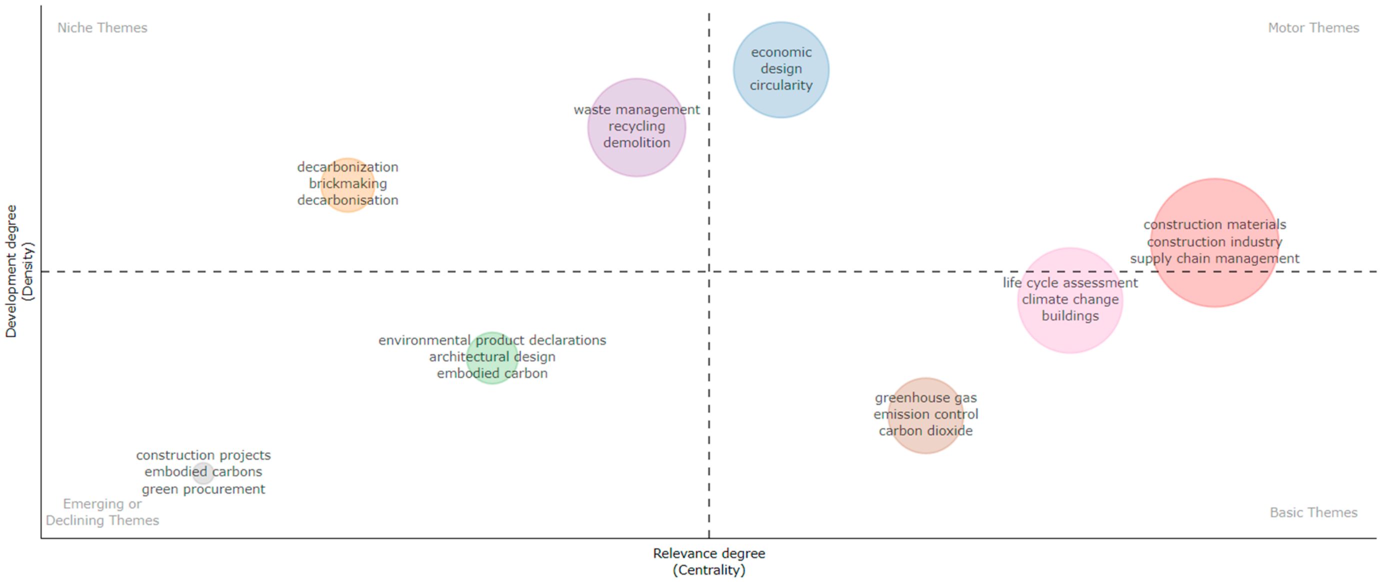

Figure 4. Thematic map of key research areas of eligible articles generated using Bibliometrix (Version 4.3.5).

The resulting thematic map categorizes research themes into four quadrants based on their centrality (relevance) and density (development). In the upper-right quadrant (motor themes), high centrality and density indicate that construction materials, the construction industry, and supply chain management are well-developed and crucial to the field. The lower-right quadrant (basic themes) features foundational topics like life cycle assessment, climate change, and buildings, suggesting they are central yet still evolving. In the upper-left quadrant (niche themes), terms such as waste management, recycling, and demolition show high internal development but limited connections to other themes, representing specialized but mature subtopics. Meanwhile, decarbonization appears to be an isolated yet developed area. The lower-left quadrant (emerging or declining themes) contains less connected and less developed topics like construction projects, green procurement, and embodied carbon, indicating either emerging trends or declining interest. Overall, the map highlights the dominant focus on materials and supply chains while identifying areas like environmental product declarations and emission control that need further integration into mainstream research.

3.1. Evaluation of Construction Material Supply Chain Performance

Construction material supply chains encompass a broad spectrum of activities covering the entire materials lifecycle, from raw material extraction to end-of-life recovery. Based on the reviewed literature, these activities are generally grouped into four main stages: material extraction and production (A1–A3), transportation and distribution (A4), construction and use phases (B stages), and end-of-life management (C and D stages). General operational activities include material sourcing and selection [5,19,22], manufacturing and processing [10,14,34], transport logistics and delivery planning [19,24,35], on-site assembly and construction [24,36], and waste sorting, recycling, and circular strategies [11,37–40].

Other system-level practices, such as industrial symbiosis [32,41], closed-loop supply chains [40], and designs for disassembly and durability [11,18], further highlight the need to integrate sustainability across all supply chain layers. Table 2 presents the performance indicators that integrate net-zero considerations into evaluating construction material supply chain performance. Increasingly, tools like BIM and LCA are used to support the coordination of these activities and quantify their impacts [3,6,9,42].

Table 2. Performance indicators for integrating net-zero in the construction material supply chain performance evaluation.

Category	Indicator	References
Policy and Regulatory	Material sourcing	[19]
	Legal compliance	[43]
	Industry standards	[13,44]
Environmental and Resource Efficiency	Global Warming Potential (GWP)	[1,5,6,9,12,25,26,34,45–49]
	Embodied Carbon (EC)	[5,6,24,45,48,50]
	Energy consumption	[3,10,26,51–53]
	CO_2 emissions	[3,10,35,36,44,46,52,54]
	Material recovery	[11]
	Recycling	[43]
	Reuse rates	[45]
	Material efficiency (e.g., recycling, reuse, eco-concretes)	[41]
	Waste reduction	[16,55,56]
	Cradle-to-gate (A1–A3) emissions	[6,22]
	Full lifecycle emissions	[5,15,41,44,45]
	Material composition	[16,43,50]
	Environmental footprints (e.g., carbon intensity)	[16,43,50]
	Waste segregation	[11,57]
	Waste recovery	[11]
	Recycled material output	[37]
Social, Organizational, and Stakeholder Collaboration	Green supplier/customer integration	[14]
	Stakeholder collaboration	[58]
	Social impact indicators	[42,56,59]
Technological and Technical Advancements	Material substitution	[18]
	Design for disassembly	[18,23]
	R&D investment	[14]
	Green design	[43]
	Durability of materials	[11,18]
	Material Performance indicators (e.g., material properties, durability, fire resistance, environmental certifications)	[1,60]
	Waste processing capacity	[38]
Economic and Financial	Warehousing, Logistics and Transportation costs	[37,38]
	Economic drivers (e.g., market costs, cost savings, ROI, financial analysis, market performance)	[13,32,37,38]

Among all supply chain activities, procurement stands out as a critical function with direct influence on construction projects' environmental, economic, and social outcomes. It governs the selection of materials, supplier engagement, and compliance with green standards such as LEED (Leadership in Energy and Environmental Design) [56,59]. Effective procurement strategies, like green procurement, early supplier involvement, and transparent sourcing, set the foundation for sustainable practices throughout the lifecycle. Because it is positioned at the front end of the supply chain, procurement can significantly shape downstream decisions related to transportation, construction methods, and material recovery [16,61].

In this study, green procurement is understood as the purchase of goods and services that minimize life cycle environmental impacts while meeting cost and performance requirements (ISO 20400:2017) [62]. Early supplier involvement refers to the collaborative engagement of key suppliers during design and planning to enhance cost, quality, and sustainability outcomes. Transparent sourcing denotes procurement processes that openly disclose selection criteria, decision steps, and supply chain information to all stakeholders (ISO 44001:2017) [63]. These standards are cited solely to clarify definitions and were not included in the 54 peer-reviewed articles analyzed in this systematic review.

The evaluation of supply chain performance in the literature relies heavily on environmental indicators, particularly those derived from LCA. These include Global Warming Potential (GWP), embodied carbon, energy consumption, waste reduction metrics, and Environmental Product Declarations (EPD) [1,3,5,9,26]. Economic indicators such as life cycle costs, material and transport costs, and investment payback periods are also commonly used [10,46,64]. Social indicators, while less frequent, include factors like stakeholder collaboration, safety measures, and labour conditions [2,16,59]. Additionally, multi-criteria decision-making (MCDM) approaches are employed in several studies to balance trade-offs among environmental, economic, and social criteria [13,19,48]. Three studies adopt Data Envelopment Analysis (DEA) to benchmark the eco-efficiency of alternative materials or transport routes [12,40,64]. One study employs the Simple Weighted Aggregated Rating (SWARA) method to set indicator weights before ranking supply chain options [46]. Another uses VIKOR to balance conflicting criteria when selecting green suppliers [41], and one paper relies on the Analytic Hierarchy Process (AHP) to derive weights for a circular-performance scoring model [1].

In summary, assessing the performance of construction material supply chains involves a multi-layered understanding of lifecycle activities and performance indicators. Procurement, in particular, plays a pivotal role as a strategic entry point that enables the integration of sustainability from the very start. Therefore, aligning procurement practices with circular economy principles is essential for enabling net-zero outcomes in construction supply chains.

3.2. Application of Tools and Technology

Various tools and technologies play a crucial role in supporting performance evaluation and carbon tracking in construction material supply chains (Table 3). LCA tools are the most commonly used for carbon tracking, helping to evaluate emissions across different supply chain stages such as material production, transportation, construction, and end-of-life [3,5,57]. LCA provides detailed insights into environmental impacts, offering a systematic approach to measure and reduce carbon footprints. BIM is also frequently employed, with applications ranging from design optimization to energy modelling [6,42]. BIM enhances data integration, enabling real-time analysis of materials and energy usage, facilitating evidence-based decisions and carbon reduction strategies.

In addition to LCA and BIM, technologies like digital twins and blockchain are gaining traction. Digital twins enable real-time monitoring and simulation of supply chain processes, aiding in predictive analysis and resource optimization [37]. Meanwhile, blockchain is being explored for its potential to improve supply chain transparency, particularly in tracking carbon emissions and sustainability credentials from suppliers [9,24].

Other tools, such as carbon calculators and EPDs, are used to quantify emissions at various stages of the supply chain, supporting carbon footprint assessments [26,48]. These technologies contribute to a more robust framework for evaluating supply chain performance in terms of both sustainability and carbon reduction.

EN 15804 [65] is a European standard that provides a consistent framework for assessing the environmental performance of construction products throughout their life cycle [66]. It divides the life cycle into clearly defined stages: A1–A3 (product stage) includes raw material extraction, transport, and manufacturing; A4–A5 (construction stage) covers transport to the site and installation; B1–B7 (use stage) involves use, maintenance, repair, replacement, and operational energy and water use; C1–C4 (end-of-life stage) includes deconstruction, waste transport, processing, and disposal. Additionally, stage D accounts for benefits or burdens beyond the system boundary, such as recycling or energy recovery. This standardized structure improves transparency, comparability, and consistency in environmental declarations and Life Cycle Assessments (LCA) for construction materials and systems [66]. These tools can be applied across all EN 15804 life cycle phases as appropriate.

Table 3. Tools for integrating net-zero targets into construction material supply chain performance evaluation.

Tools	References
Building Information Modelling (BIM) and Extensions	[5,6,15,16,19,23,24,41,42,45,49,58]
Life Cycle Assessment (LCA) Tools	[1,3,5,6,9,10,12,15,23–26,34–36,38,41,47–54,60]
Environmental Product Declarations (EPDs)	[6,9,12,23,25,45,49]
Evaluation and Decision-Making Methods	[2,13,14,32,40,44,48,56,61,67,68]
IoT, Sensors, Automation and Integration	[14–16,19,37,61]
Energy and Emission Modelling	[3,6,12,36,46,51]
Standards, Labels and Certifications	[1,19,25,26,55,57–59]
Databases	[1,5,6,34–36,39,49,51,54]
Survey and Stakeholder Tools	[2,18,32,42,43,56,57,69]
Geographic and Mapping Tools	[16,19,35,37,54]
Material and Flow Assessment Tools	[10,15,18,47,68]

3.3. Challenges and Enablers

The challenges and enablers identified in the literature for integrating net-zero targets into construction material supply chain performance evaluation are summarized in Table 4. These factors have been categorized by analyzing their nature into six main categories: data-related, policy and regulatory, economic and financial, technological and technical advancements, social, organizational, and stakeholder collaboration, and environmental and resource efficiency. Each category represents a key aspect that impacts the successful integration of net-zero targets.

Data-related factors are essential because accurate and consistent data are needed to track carbon emissions and assess the sustainability of the supply chain. However, challenges around data availability, quality, and standardization remain [9,18,23]. Policy and regulatory factors are also essential, as clear policies and regulations can drive the adoption of sustainable practices and ensure that net-zero goals are met [26,51,52]. Economic and financial factors, such as cost implications and funding availability, can either facilitate or hinder the integration of net-zero strategies, depending on financial resources and incentives [24,25]. Technological and technical advancements support the tracking of emissions, efficiency improvements, and optimization of supply chain processes. However, the adoption of new technologies may be limited by high costs or a lack of technical expertise [14,15,42]. In practice, integrating BIM with LCA is often hindered by data fragmentation, inconsistent material libraries, and platform-compatibility issues, all of which can undermine the reliability and efficiency of carbon assessments [6]. Social, organizational, and stakeholder collaboration is a key factor, as coordination among various stakeholders, like government bodies, industry players, and consumers, is crucial for achieving sustainability goals [61]. Finally, environmental and resource efficiency factors highlight the importance of optimizing resource use, reducing waste, and ensuring more sustainable production practices [12,54].

Table 4. Challenges and enablers for integrating net-zero in construction material supply chain performance evaluation.

Category	Challenges	Enablers	References
Policy and Regulatory	Ambiguous laws Weak enforcement Fragmented standards Ineffective subsidies Corruption risks Misaligned policies (e.g., neglecting net-zero)	Policy support (e.g., carbon tax, GPP) Government subsidies Regulatory protection Policy incentives Legislative mandates Industry standards Harmonization of practices	Challenges: [3,11,13,25,26,37,38,41,43,51,56,58,68] Enablers: [1,10,13,14,22,23,32,38–40,51,54,58,60,68]
Environmental and Resource Efficiency	High emissions Pollution regulations Landfill scarcity Informal waste practices Limited CE impact Geopolitical disruptions	Use of recycled materials Resource efficiency Waste management Renewable energy Energy optimization Eco-friendly transport Sustainable sourcing	Challenges: [10,12,22,39,40,46,51,52,54,60] Enablers: [10,12,15,18,22,24,51,54,56,58,68]
Social, Organizational, and Stakeholder Collaboration	Low awareness Resistance to change Industry fragmentation Lack of skilled labour Client reluctance Poor collaboration	Stakeholder collaboration Public–private partnerships Industry consensus Community engagement Shared knowledge platforms Capacity building	Challenges: [2,16,18,24–26,32,36,37,39,41,43,50,55,58,59] Enablers: [2,3,13–15,23,38,41,67,68]
Technological and Technical Advancements	Immature/inefficient technology Scalability Infrastructure gaps Testing/data process limitations Slow implementation	Use of modern technologies BIM integration R&D investments Innovative construction methods Digital tools Real-time monitoring Energy-efficient solutions	Challenges: [3,15,19,22,47,48,51–53,57,59,61,68] Enablers: [12,15,19,24,36,43,47,54,58,64,69]
Economic and Financial	High costs (production, treatment, data, green materials) Low demand, Financial fragility Infrastructure investment barriers	Financial incentives Government funding Investment in infrastructure Cost-effective supply chains Tax incentives Support for green products Investment in R&D	Challenges: [2,3,24,25,32,37,38,41–43,46,47,49,64,67,69] Enablers: [11,12,25,35,41,44,56,57,59,60,64,67,69]
Data Availability, Accuracy and Integration	Lack of standardization Data accuracy Interoperability issues Inconsistent/hypothetical data Dataset quality Subjective judgments	Data integration of BIM and other digital tools like WMS Real-time data Standardized data exchange Harmonized EPDs Better data availability	Challenges: [1,5,6,9,15,18,23,25,34,36,45,47–50,53,54,61] Enablers: [6,15,16,19,23,25,36,42,45,50,54]

Across the 54 studies, data-related issues are mentioned most often, while policy, regulatory, and economic–financial points also appear frequently. Social collaboration and technological factors receive moderate attention, and environmental and resource efficiency challenges are noted slightly less but still form a substantial body of evidence. These patterns suggest that reliable data and supportive policy remain the biggest levers for progress, with finance, collaboration, technology, and resource efficiency following close behind.

As summarized in the table, these categories illustrate the various challenges and enablers that must be addressed to successfully integrate net-zero targets into the construction material supply chain performance evaluation process.

3.4. Advancing Net-Zero Supply Chain Evaluation

The integration of net-zero and carbon reduction targets into supply chain evaluations is evident across several studies, but often lacks depth in practical application. While many studies acknowledge net-zero goals, fewer incorporate them into core supply chain activities, beyond general mentions. Several studies employ life cycle-based emissions tracking to monitor carbon impacts across stages such as material production, transportation, use, and end-of-life [3,5,9,48]. These methods help identify the most carbon-intensive stages and inform strategies such as material substitution [69], reuse, recycling [18,40], and circular material flows [41,68]. A smaller subset of studies indicates that net-zero targets influence upstream activities, including procurement policies, supplier selection, and material sourcing [13,19]. This reflects a growing trend towards aligning supply chain processes with long-term carbon neutrality goals.

However, many studies primarily focus on quantifying emissions without providing transparent methodologies or frameworks for achieving net-zero outcomes across the supply chain. Deep integration of net-zero objectives, which would guide decisions from the outset of the supply chain process, is still underrepresented [47,52].

The evaluation of net-zero supply chains in the construction industry has gained significant attention, with various studies highlighting the need for improved methodologies and frameworks. Advancing net-zero supply chain evaluation requires integrating more comprehensive data, including LCA, carbon footprint analyses, and incorporating advanced digital tools such as BIM and blockchain. These tools enhance transparency, data accuracy, and enable real-time tracking of emissions and resource use [19,32]. Furthermore, a focus on circular economy principles, such as material reuse, recycling, and waste reduction, can play a key role in achieving net-zero targets [39]. As the industry moves forward, collaboration between stakeholders, including contractors, suppliers, and policymakers, will be essential to overcoming barriers and driving innovation in net-zero supply chain evaluation [5]. Additionally, the alignment of regulatory frameworks with industry goals is necessary to ensure effective and widespread adoption of net-zero practices across the construction sector [14].

4. Discussion

Up to this point, this study has explored how net-zero goals are included in construction material supply chain evaluation. The systematic literature review found that performance indicators, tools, technologies, challenges, and supporting factors are all important when aiming to reduce carbon emissions in the supply chain. These aspects help guide efforts to make supply chains more sustainable and aligned with climate targets. The following sections will introduce the PESTED framework, which explains the factors that affect supply chain decarbonization, and presents a new conceptual framework for driving decarbonization in evaluating construction material supply chains.

4.1. PESTED Framework

This study proposes a new framework, PESTED, to systematically categorize the challenges and enablers associated with integrating net-zero goals in the construction material supply chain. The framework was derived through thematic synthesis of the selected literature and comprises six dimensions, as shown in Figure 5. The six dimensions are policy and regulatory; environmental and resource efficiency; social, organizational, and stakeholder; technological and technical advancements; economic and financial; data availability, accuracy and integration.

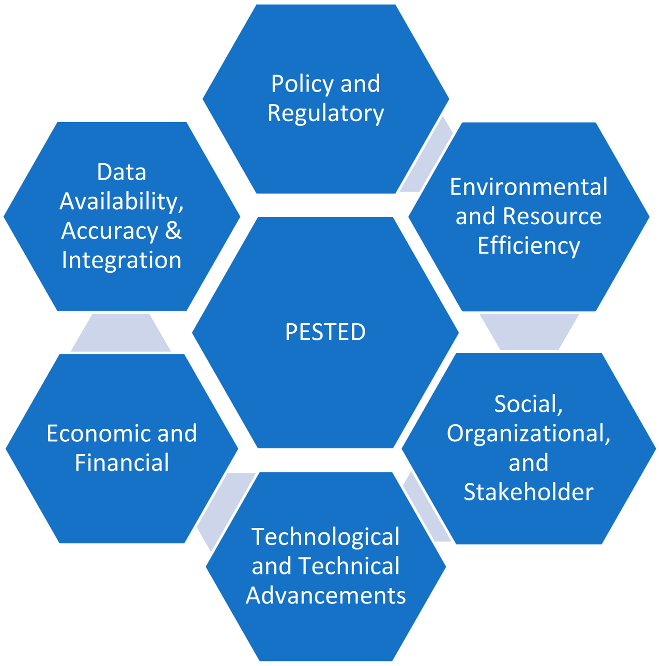

Figure 5. PESTED Framework.

While the PESTED framework builds upon the well-known PESTLE model (political, economic, social, technological, legal, and environmental), it has been adapted to better reflect the dynamics specific to net-zero transitions in the construction sector [70]. The key difference lies in integrating political and legal aspects into a single dimension, policy and regulatory. This is because, in the context of construction and sustainability, political decisions are increasingly executed through binding regulations and strategic policy instruments, especially those aligned with climate agreements and national carbon reduction goals (e.g., Paris Agreement, European Green Deal, Baylean legislation) [26,51]. Therefore, treating policy and regulation as a unified driver aligns better with how interventions are implemented in practice [71,72]. A comparison of PESTED framework vs. PESTLE framework is presented in Table 5.

Another distinction is the explicit inclusion of data as a standalone dimension. While data is often implicitly embedded within traditional frameworks like PESTLE's technological or managerial categories, the literature emphasizes its critical role in enabling accurate carbon accounting, evidence-based decision-making, and supply chain performance evaluation. This includes data from digital systems and data accuracy and consistency in environmental reporting tools such as EPDs, life cycle inventories, and emission factors [1,9,50]. Issues like inconsistent formats, lack of third-party verification, or regional variability in datasets can significantly hinder reliable benchmarking and target-setting for net-zero goals [1]. By recognizing data as a separate dimension, the PESTED framework highlights the growing demand for high-quality, transparent, and interoperable data across all construction material supply chain stages, from extraction to end-of-life. Making data a dimension shows how information supports every other PESTED factor. Reliable, shareable data feeds into digital tools like BIM and simulations, improves cost and carbon calculations, gives regulators proof to enforce rules, and helps stakeholders check sustainability claims. Better data governance, clear formats, open links between systems, and trusted verification are key enablers of net-zero progress. By identifying data explicitly, the framework stresses that better data quality, access, and compatibility are essential before any policy, technology, or financial measure can work well along the whole construction material supply chain.

Table 5. PESTED vs. PESTLE.

PESTED Dimension	PESTLE Focus	Comparison
Policy and Regulatory	Political drivers Legal compliance	Combines policy and legal instruments into one actionable lens for supply-chain governance and incentives
Economic and Financial	Cost and market forces	Unchanged; emphasizes capital flows, carbon-pricing signals, and life cycle cost trade-offs
Social, Organizational and Stakeholder Collaboration	Demographics and culture	Expanded to Social, organizational and stakeholder collaboration to capture multi-actor coordination essential for circular, low-carbon practices
Technological and Technical Advancements	R&D and innovation	Refined as technological -and technical advancements to include digital construction platforms (BIM, IoT) and low-carbon material technologies
Environmental and Resource Efficiency	Natural resources and emissions	Recast as environmental -and resource efficiency to align with circular-economy metrics
Data Availability, Accuracy and Integration	-	data availability, accuracy &and integration (new): highlights data quality, interoperability, and transparency as critical enablers of net-zero verification

Moreover, the environmental and resource efficiency dimension in PESTED shifts the focus from general environmental impacts to specific aspects of material use, circularity, and resource optimization, key priorities in achieving net-zero in material flows [18]. Similarly, the social, organizational, and stakeholder collaboration dimension underscores the importance of interdisciplinary and multi-stakeholder approaches, which the literature consistently identifies as both a challenge and an enabler in implementing net-zero strategies [2].

Overall, the PESTED framework offers a tailored lens for understanding systemic barriers and opportunities across the construction material supply chain. It emphasizes external macro factors and internal organizational and technological capacities essential for advancing toward net-zero outcomes.

4.2. Conceptual Framework Development

The review identified a comprehensive set of performance indicators, tools, technologies, challenges, and enablers that influence the integration of net-zero targets within construction material supply chain evaluation. Building on these insights, this study advances toward a structured model to support decarbonization efforts across the supply chain [73]. This framework represents further development and enhancement of the initial model proposed in a previous publication of the authors [63], which laid the foundation for evaluating supply chain decarbonization. The current work expands on that foundation by incorporating a broader range of external influences captured through the newly introduced PESTED framework and integrating them into a more management-driven holistic model. This progression reflects the deepening of knowledge from literature synthesis to a conceptual contribution designed to guide research and practice in the construction sector's journey toward net-zero.

Hettiarachchi, I. et al. [74] discuss a conceptual framework that analyzes the impact of the carbon footprint of the construction material supply chain along the value chain. A value chain refers to the full range of activities that businesses undertake to produce a product or service, from raw material extraction to final delivery, use, and disposal. In the context of the construction material supply chain, these stages encompass material extraction, manufacturing, transportation, construction, usage, and end-of-life management [12,75]. Within the value chain, emissions are categorized into three scopes (Scope 1, 2, and 3), as defined by the Greenhouse Gas Protocol [8]. Mapping these emission scopes across the value chain enables organizations to identify carbon hotspots and design more effective carbon reduction strategies [76]. Hettiarachchi. I, et al. [74] provides a comprehensive structure integrating supply chain stages (inbound, manufacturing, outbound, consumer, and reverse logistics), emission scopes, and strategies such as LCA, circular economy, and industrial symbiosis to guide carbon mitigation efforts across the value chain. LCA is a method for evaluating the environmental impacts associated with all stages of a product's life cycle, from raw material extraction to disposal or next cycle, providing a data-driven basis for identifying emission hotspots and improvement opportunities [77]. Circular Economy promotes resource efficiency by extending the life of materials through reuse, recycling, and regeneration, reducing the need for virgin resources and minimizing waste and emissions [78]. Industrial Symbiosis refers to the collaborative use of resources, energy, and by-products between industries, enabling cross-sectoral efficiencies that contribute to emission reduction and improved sustainability performance [79].

However, the findings of this systematic literature review highlight the importance of addressing carbon reduction not only through technical and operational improvements but also via management approaches like organizational strategy, procurement standards, and regulatory frameworks. Building upon the previously established operational-level framework for reducing carbon footprints in construction material supply chains, this study proposes an extended conceptual framework (Figure 6) incorporating management-level mechanisms, focusing on procurement practices and institutional governance. Procurement is critical to enabling by influencing material selection, supplier behaviour, and embedded emissions upstream in the supply chain [16]. Therefore, this framework introduces an organizational and strategic integration layer that connects top-down policy drivers with bottom-up operational interventions, ensuring that sustainability objectives are embedded in both decision-making processes and implementation pathways. While the earlier model emphasized emission reduction through analyzing and improving across supply chain stages, such as manufacturing, transport, usage, and reverse logistics, this extended framework incorporates a broader perspective by aligning emission scopes with procurement requirements along the value chain activities and life cycle stages. It introduces procurement as a pivotal function that bridges internal operations with the external environment, playing a critical role in influencing Scope 2 and Scope 3 emissions by governing material, energy, and service sourcing decisions.

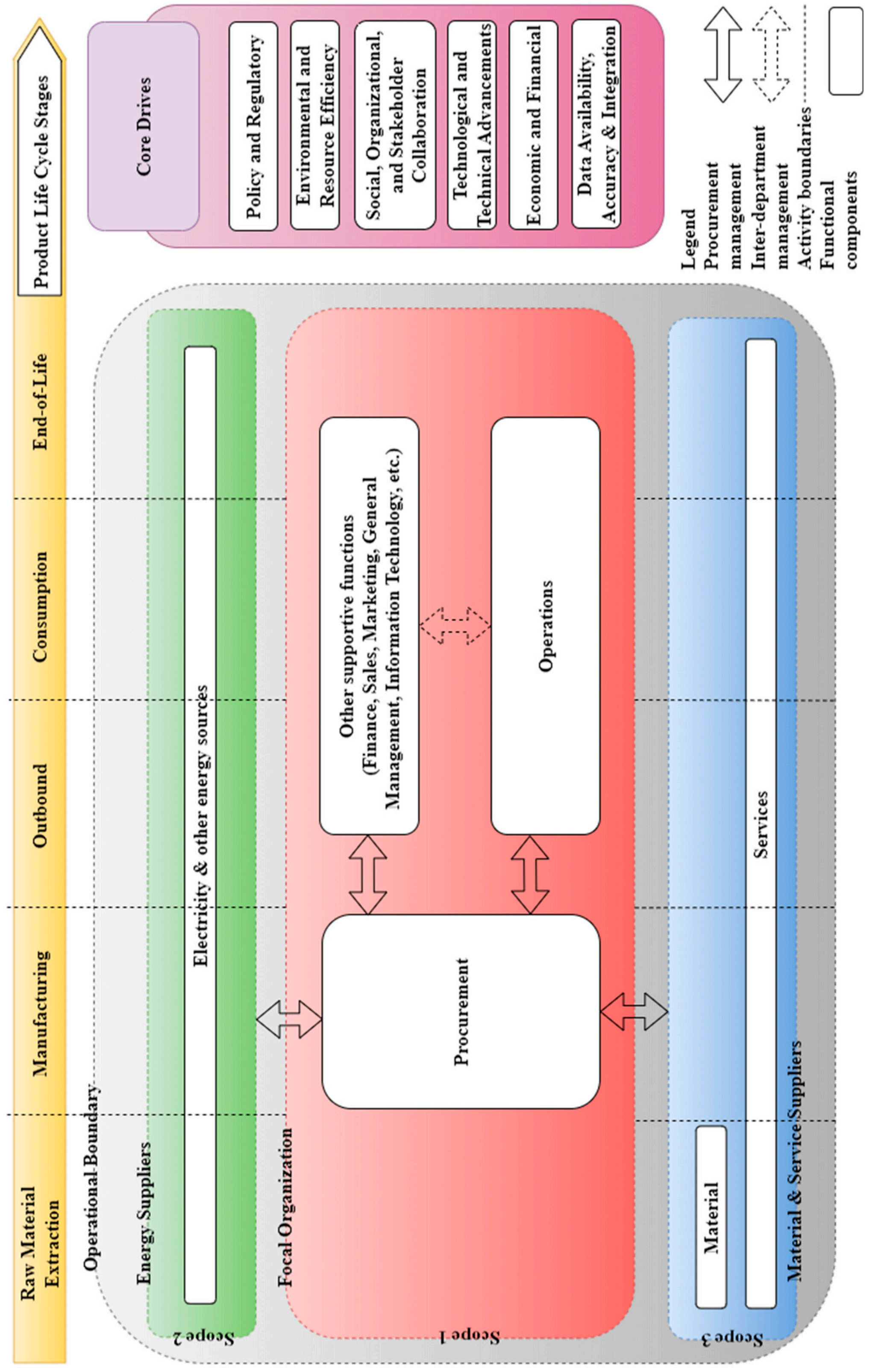

Figure 6. Conceptual framework for reducing carbon footprint in construction material supply chains by incorporating the higher-level management layer derived from insights identified in this study (source: authors' creation).

This framework follows the same system boundary structures: Scopes 1, 2, and 3 in the operational boundary and product life cycle stages. The framework identifies the decarbonization drivers via the PESTED framework. By capturing the interlinkages between organizational departments, procurement governance, and life cycle performance, this extended framework offers a comprehensive approach to support carbon management strategies and the transition toward net-zero supply chains in the construction sector. The diagram shows three nested layers that operate together across the product life cycle stages (top band). Scope 1 represents the focal organization, where the procurement team interacts directly with operations and other support functions, ensuring that purchasing choices align with production needs. Scope 2 (energy suppliers) feeds electricity and other energy inputs into the focal firm, while Scope 3 (material and service suppliers) delivers physical products and external services. Surrounding these operational layers are the six core-driver PESTED dimensions, which act as forces that guide decisions within each scope. Procurement criteria affect supplier selection, and the environmental impact is measured along the life cycle stages.

Therefore, procurement is a pivotal interface between an organization and its external environment, which is critical in sourcing materials, services, and energy required for operations. Because it governs purchasing decisions and supplier engagements, procurement is uniquely positioned to influence the environmental performance of a company's value chain [26]. Specifically, procurement decisions directly affect Scope 2 emissions through acquiring electricity or energy contracts and Scope 3 emissions from outsourced production, transportation, and upstream supply activities. By integrating sustainability criteria into procurement policies, such as selecting low-carbon suppliers, requiring Environmental Product Declarations (EPDs), or prioritizing renewable energy contracts, organizations can exert significant control over the embedded carbon footprint of their supply chain [26]. This enables procurement to fulfil its operational role and act as a lever for achieving net-zero targets by mitigating indirect emissions beyond the organization's direct control. Moreover, procurement's impact extends throughout all stages of a product's life cycle, from raw material extraction and manufacturing to construction, use, maintenance, and end-of-life phases. Strategic procurement choices influence the immediate environmental footprint of acquired goods and services and determine long-term implications for carbon performance, circularity, and resource efficiency [58]. As such, procurement acts as a key enabler for reducing carbon across the full lifecycle, contributing substantially to achieving net-zero goals, especially in sectors with material-intensive supply chains like construction.

The proposed framework aligns with key organizational theories that help explain how firms respond to decarbonization pressures. The Resource-Based View (RBV) supports the idea that internal capabilities such as data infrastructure, skilled procurement teams, and digital tools are critical for low-carbon performance [80]. At the same time, Institutional Theory reinforces the role of external pressures, such as regulations and industry standards, in shaping organizational behaviour across the supply chain [81]. By combining these perspectives, the framework reflects both internal capacity and external expectations as drivers of sustainable transformation.

This framework advancement contributes to a more systemic, multi-level approach for achieving net-zero construction supply chains, where management directives reinforce and enable operational efficiency and carbon reduction.

4.3. Future Work

This review highlights several gaps that point to clear research priorities. Although the proposed framework brings together indicators, tools, and management drivers, it has not yet been applied in practice. To test the framework, future studies will select case-study organizations positioned at different life cycle stages, such as raw material extraction, manufacturing, transport hubs, and on-site assembly. The results from these pilot studies will show how well the model works in real settings and where adjustments are needed. The case studies will also be used to verify and adjust each PESTED dimension. For example, they will help clarify how policy and regulatory drivers translate into procurement rules, how economic signals influence supplier choices, and how data quality interacts with technological advancements. Comparing results across life cycle stages will reveal which dimensions carry the most weight in different contexts and how they interact. Insights from the case studies will inform practical policy tools, such as green-procurement rules or data-sharing mandates that can activate specific PESTED dimensions and speed up the adoption of the framework across the construction material supply chain.

Future work will also explore emerging digital technologies, such as BIM–LCA integration, rapid 3D modelling [20], point-cloud reconstruction, and AI-enhanced digital twins, that can enrich the framework's data dimension. Recent studies show how these tools support building energy simulation [82] and material stock estimation [83,84], offering new data streams for more precise life cycle inventories and carbon hotspot mapping.

Focusing on case-based applications, data integrity, emerging digital tools, and targeted policy support, the following research stage will sharpen the framework and increase its usefulness to organizations pursuing net-zero construction material supply chains.

5. Conclusions

This study developed a comprehensive conceptual framework for integrating net-zero targets into construction material supply chain evaluation by synthesizing insights from 54 academic articles selected through a systematic literature review following the PRISMA approach. Initially, it identified a broad range of environmental, economic, social, technological, and policy-related performance indicators. Next, the review mapped various digital tools and methods that support carbon tracking and performance measurement, such as LCA, BIM, and EPDs. Then, the challenges to and enablers of net-zero integration were categorized into six groups (PESTED), highlighting key barriers like fragmented data systems and enablers such as supportive policy incentives. Finally, the study explored the theoretical and strategic foundations in the existing literature, identifying gaps that informed the development of the proposed framework.

The framework developed from this review aims to provide researchers, practitioners, and policymakers with a structured tool to assess and manage carbon impacts holistically. By bridging theoretical gaps and offering a practical pathway, this work contributes to advancing the sustainable transformation of the construction sector in line with global climate goals. To enhance the practical applicability of the proposed conceptual model, policy instruments such as carbon credit incentives, green procurement regulations, and mandatory data reporting can play a critical role in operationalizing its components. These tools not only create accountability and market-based motivation but also enable consistent performance monitoring and the integration of net-zero targets across the construction material supply chain.

Future research should focus on operationalizing and testing this framework in real-world construction material supply chains. This includes integrating reliable and standardized data sources, leveraging digital technologies such as BIM and LCA tools, and incorporating supportive policy mechanisms. Such efforts will enhance the framework's effectiveness as a practical tool to guide decision-making and accelerate the construction industry's transition to net-zero emissions.

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Abbreviations

The following abbreviations are used in this manuscript:

BIM	Building Information Modelling
CE	Circular Economy
EPD	Environmental Product Declarations
GHG	Greenhouse Gas
GPP	Green Public Procurement
GWP	Global Warming Potential
ISO	International Organization for Standards
LCA	Life Cycle Assessment
LEED	Leadership in Energy and Environmental Design
MCDM	Multi-Criteria Decision-Making
PESTED	Policy and Regulatory, Environmental and Resource Efficiency, Social, Organizational, and Stakeholder Collaboration, Technological and Technical Advancements, Economic and Financial, and Data Availability, Accuracy and Integration
PESTLE	Political, Economic, Social, Technological, Legal, and Environmental
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RQ	Research Question
WMS	Warehouse Management System

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