




Review

The Concept of Carbon Accounting in Manufacturing Systems and Supply Chains

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Abstract: Carbon accounting is primarily a process for measuring, reporting, and allocating greenhouse gas emissions from human activities, thus enabling informed decision-making to mitigate climate change and foster responsible resource management. There is a noticeable upsurge in the academia regarding carbon accounting, which engenders complexity due to the heterogeneity of practices that fall under the purview of carbon accounting. Such plurality has given rise to a situation where diverse interpretations of carbon accounting coexist, often bereft of uniformity in definition and application. Consequently, organisations need a standardised, comprehensive, and sequentially delineated carbon accounting framework amenable to seamless integration into end-to-end manufacturing systems. This research commences with the progressive evolution of the conceptual definition of carbon accounting. Then, it delves into the current state of carbon accounting in manufacturing systems and supply chains, revealing gaps and implementation issues warranting future scholarly exploration.

Keywords: carbon accounting; emissions accounting; greenhouse gas emissions; environmental accounting; sustainable manufacturing systems; net-zero



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1. Introduction

The evolving interplay between corporate responsibility and environmental sustainability imperatives has propelled carbon accounting into sustainability discussions. As societies grapple with the profound effects of climate change, there is an elevated importance in comprehensively understanding and transparently measuring carbon emissions [1]. Manufacturing systems are central to these discussions of climate change and carbon emissions, which play a crucial role in the global economy. Such systems warrant a meticulous examination, especially concerning their greenhouse gas (GHG) emissions [2]. Manufacturing systems are complex conglomerations comprising products, machinery, personnel, information, control mechanisms, and support functions. All these elements are to be integrated to facilitate physical goods' inception, production, distribution, and overall life cycle management. This intricate process caters to both market demands and societal needs [3]. A paramount goal within these manufacturing systems is the ambition of net-zero emissions. This entails striving towards a state where the GHG emissions produced by these systems are considerably reduced, looming at a near-zero level [4]. Diminishing emissions is pivotal for decelerating the progression of climate change and alleviating its consequent ramifications [5]. Regulatory adherence plays a significant role in this context; in a multitude of nations, legal frameworks mandate organisations to transparently disclose their GHG emissions [6].

Accounting is the systematic practice of recording and analysing financial data about businesses. This includes documenting financial transactions and producing financial statements that convey an organisation's economic activities and health [7]. Financial

accounting focuses on creating detailed financial reports for stakeholders, ensuring clarity and transparency in financial communication [8]. On another note, carbon accounting measures entities' carbon dioxide equivalent emissions, including their supply chains, where there are inherent challenges in data collection, given it is outside the direct control of the organisation. This form of accounting covers a wide range of activities, such as measuring and reporting GHG emissions at various levels [9]. Both financial and carbon accounting are tools for organisations to monitor and report on essential operational facets. Carbon accounting is an instrumental process, facilitating organisations to comply with these statutory requirements, thereby circumventing potential financial penalties [10]. Despite their differences in focus and principles, as shown in Table 1, these accounting systems share certain similarities while serving unique purposes within the corporate landscape.

Table 1. Difference between financial and carbon accounting.

Differences	Financial Accounting	Carbon Accounting
Purpose and Focus	<ul style="list-style-type: none"> Tracking and reporting an organisation's financial transactions and position. It aids in decision-making for investors, creditors, regulators, and other stakeholders. 	<ul style="list-style-type: none"> Measuring, reporting, and reducing an organisation's GHG emissions. Its primary goal is to understand and manage an organisation's environmental impact and contribution to climate change [11–13].
Measurement and Units	<ul style="list-style-type: none"> Uses monetary measurements to quantify assets, liabilities, revenues, and expenses, ultimately presented in a monetary unit, such as a currency. 	<ul style="list-style-type: none"> Quantifies emissions in terms of carbon dioxide equivalents (CO₂e). It employs specific emission factors and conversion rates to convert different greenhouse gases into a common unit [12–16].
Stakeholders	<ul style="list-style-type: none"> Caters to a broad range of stakeholders, including investors, creditors, analysts, and regulatory bodies that require financial information for decision-making. 	<ul style="list-style-type: none"> Addresses a more targeted audience, including regulatory bodies, environmental organisations, socially conscious investors, and consumers interested in a company's environmental practices [17–19].
Regulatory Requirements	<ul style="list-style-type: none"> Universally mandatory for organisations subject to financial reporting regulations and standards. 	<ul style="list-style-type: none"> Some organisations are compelled to report carbon emissions due to regulatory mandates, while others voluntarily report them to demonstrate their commitment to sustainability [20–22].

The definition of carbon accounting has evolved over the years, as shown in Table 2 [12]. This happened due to several factors, including changing societal and environmental concerns, advances in the scientific understanding of climate change and GHG emissions, and developments in industry and policy [12,23]. As society has become more aware of the impacts of climate change, there has been an increasing demand for accurate and transparent reporting of GHG emissions. This has led to the development of new tools, standards, and guidelines to help organisations report and manage their emissions [24–26]. In addition, advances in the scientific understanding of climate change and GHG emissions have led to changes in how carbon accounting is conducted. For example, there is now greater recognition of the importance of measuring and reporting emissions from the entire supply chain, not just direct emissions from a single organisation [27,28]. Overall, the evolving definition of carbon accounting reflects the changing environmental, social, and

economic context in which organisations operate and the need for accurate and transparent reporting of GHG emissions.

Table 2. Carbon accounting concept evolution.

Year	Carbon Accounting Definition
2003	In an optimal carbon accounting system, compensation is made when carbon sequestration services are delivered, and a charge is incurred upon carbon release, like through fire or harvesting [29].
2007	Process of measuring CO ₂ amounts from sources or storage in biomass. Unlike traditional accounting linked to money, “carbon emission and sequestration (CES) accounting” focuses solely on CO ₂ levels [30].
2008	Involves assessing the worth of assets like pollution rights given and potential liabilities if an organisation needs to purchase more rights to offset their emissions [31].
2008	Formal process focused on measuring emissions that can be traded within specific legal boundaries and standards [32,33].
2009	CO ₂ carbon accounting, referring to the balancing of CO ₂ equivalents [34].
2010	Carbon accounting encompasses two distinct meanings. Firstly, it denotes the measurement and tracking of carbon emissions and storage, as companies in various sectors aim to report their GHG emissions either voluntarily or due to regulations. Secondly, it involves the financial impacts on an entity’s statements due to its carbon-related obligations and trading strategies. This includes accounting for emissions obligations, allowances or offsets held, and future allowance transfers [35].
2011	Measurement of carbon emissions, the collation of data and communication, within and between firms [36].
2012	Estimation or direct measurement of GHG emissions and removal at global level [37].
2014	Measuring, monitoring, reporting, and verifying greenhouse gas emissions at the level of projects, corporations, cities, regions, and nation states [38].
2015	System that uses accounting methods and procedures to collect, record, and analyse climate-change-related information and account for and report carbon-related assets, liabilities, expenses, and income to inform the decision-making processes of internal managers and external stakeholders [39].
2021	Measuring, disclosing, and managing greenhouse gas emissions within an organisation. It acts as an interface between carbon governance mechanisms and actual carbon performance [40,41].
2023	Quantification, reporting, and management of greenhouse gas emissions arising from construction industry activities to reduce emissions and facilitate carbon trading [42].
2023	Processes and practices for measuring, monitoring, reporting, and verifying greenhouse gas emissions across supply chains and product life cycles [43].

Analysing the definitions delineated in Table 2, Figure 1 summarises and showcases the evolution of the carbon accounting definitions over time.

Within these definitions, the significance of carbon accounting across supply chains and product life cycles is emphasised as an essential practice for accurately quantifying and monitoring emissions. This research maps the current carbon accounting in the manufacturing and supply chain literature to specific research questions, providing a structured overview of how different aspects of carbon accounting are addressed. The discussion then delves into the challenges and opportunities within carbon accounting and outlines the future research direction, thereby answering the following research questions:

- What is the current understanding of the definition of carbon accounting in manufacturing systems and supply chains? (RQ1)
- What are the current gaps in carbon accounting in the manufacturing and supply chain systems literature? (RQ2)

- What is the future research agenda for carbon accounting in manufacturing systems and supply chains? (RQ3)
- What are the challenges of carbon accounting implementation in manufacturing systems and supply chains? (RQ4)

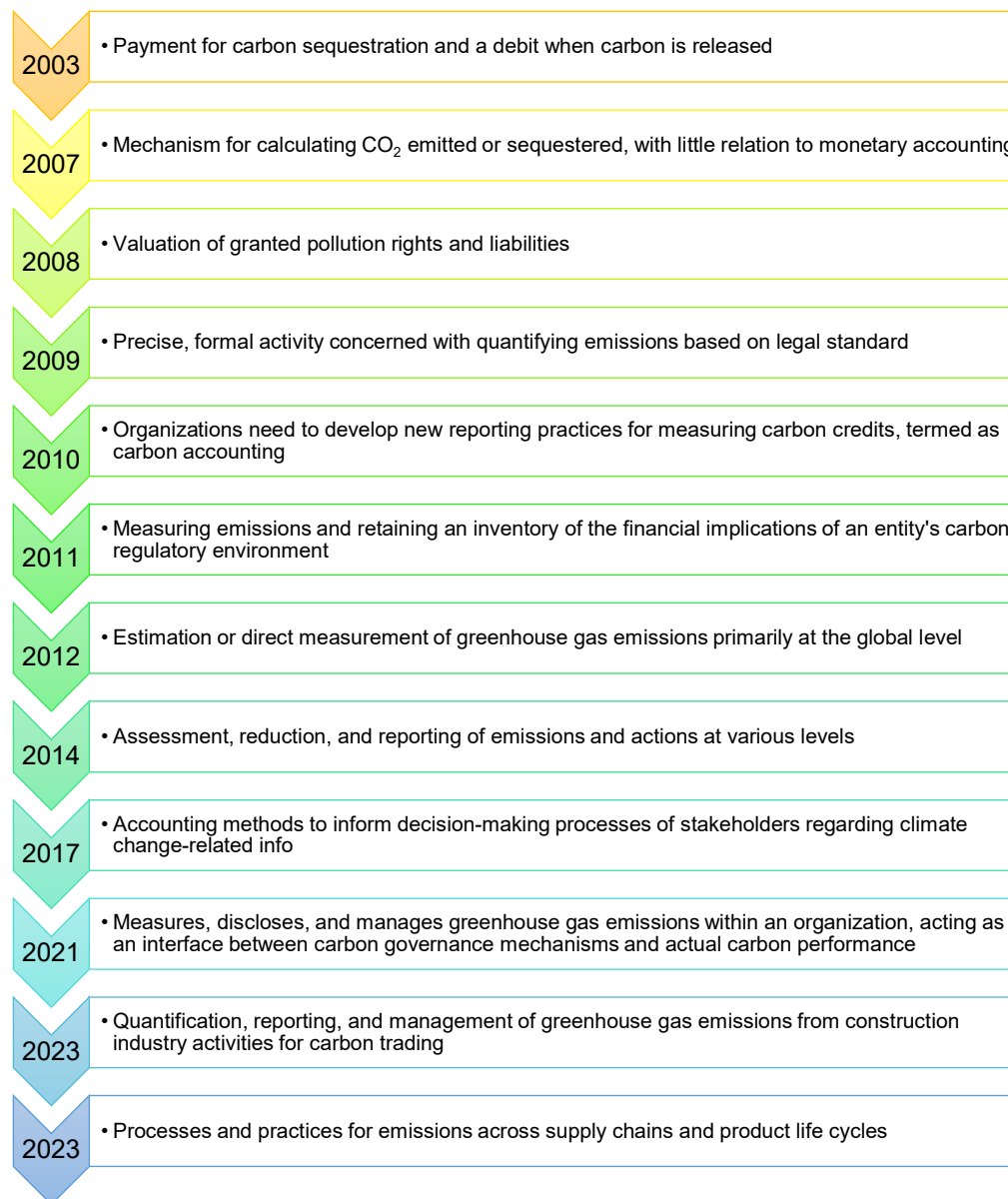


Figure 1. Carbon accounting definition evolution.

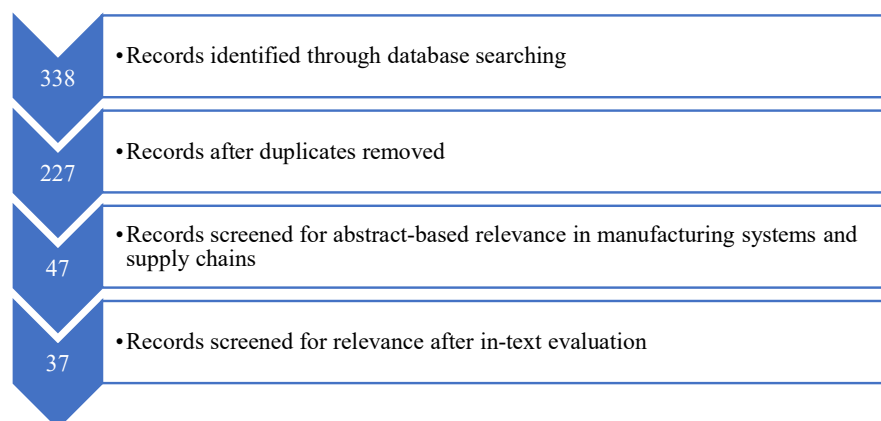
2. Methodology

PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) is a methodology for conducting and reporting systematic reviews and meta-analyses [44]. Utilising the PRISMA statement as a methodological framework [45], this study undertook a systematic examination of the domain under consideration, as explained further in this section. The search string combinations used to gather literature across two prominent academic databases—Scopus and Web of Science—are shown below in Table 3. Search string 1 was input for filtration only in the titles, whereas search string 2 was input for filtration across all the fields, including the title, abstract, and keywords.

Table 3. Search results.

Search String 1	Search String 2	Scopus	Web of Science
Carbon accounting	Manufacturing	5	27
Carbon accounting	Supply Chain	17	34
GHG accounting	Manufacturing	0	1
GHG accounting	Supply Chain	0	2
Greenhouse gas accounting	Manufacturing	1	6
Greenhouse gas accounting	Supply Chain	2	8
Sustainability accounting	Manufacturing	0	25
Sustainability accounting	Supply Chain	0	18
Emissions accounting	Manufacturing	11	23
Emissions accounting	Supply Chain	12	31
Environmental accounting	Manufacturing	13	69
Environmental accounting	Supply Chain	5	28
Total Search Results		338	

The preliminary stage encompassed a title-based filtration to identify and eliminate duplications, employing both intra-database (vertical duplicates) and inter-database (horizontal duplicates) methods. This stage resulted in 227 documents for evaluation. A further abstract-based relevance check was made of the 227 documents to maintain the scope of selected literature within the context of carbon accounting in manufacturing and supply chains, resulting in 47 documents. Out of these 47 documents, after in-text evaluation, 37 articles were selected. The summary of this PRISMA exercise is illustrated below in Figure 2.

**Figure 2.** PRISMA statement summary.

3. Literature Findings

The quantitative findings that provide inputs to the discussion that follows in Section 4 are explained below. The final shortlisted literature mapped to the research questions it answers is shown below in Table 4 where X signifies lack of input from that document to the research question, while O signifies the presence of input to that specific research question.

Table 4. Final shortlisted literature.

Reference	RQ1	RQ2	RQ3	RQ4
[18]	O	X	X	X
[43]	O	X	X	X
[46]	O	O	X	O
[47]	O	X	X	O
[48]	O	O	X	O
[49]	O	X	X	O

Table 4. Cont.

Reference	RQ1	RQ2	RQ3	RQ4
[50]	O	O	X	O
[51]	X	X	X	X
[52]	X	X	O	O
[53]	X	X	X	X
[54]	O	O	O	X
[55]	O	O	O	O
[56]	X	X	X	X
[57]	O	X	X	X
[58]	X	X	X	X
[59]	O	X	O	O
[60]	O	X	X	X
[61]	X	X	O	O
[62]	O	X	O	O
[63]	O	X	O	O
[64]	O	O	O	X
[65]	O	O	O	X
[66]	O	X	O	O
[67]	O	X	X	X
[68]	O	O	O	O
[69]	O	X	O	O
[70]	O	O	O	X
[71]	X	X	X	X
[72]	X	X	X	X
[73]	X	X	X	X
[74]	O	X	X	X
[75]	O	X	X	X
[76]	O	X	X	X
[77]	O	X	X	X
[78]	O	X	X	X
[79]	O	X	X	X
[80]	X	X	X	X

The term carbon accounting is used interchangeably with affiliated or constituent accounting approaches, as shown in Figure 3, in the literature in which it gets discussed. While the evolving definition and scope of carbon accounting is discussed in Section 4, there are some other more commonly used accounting concepts.

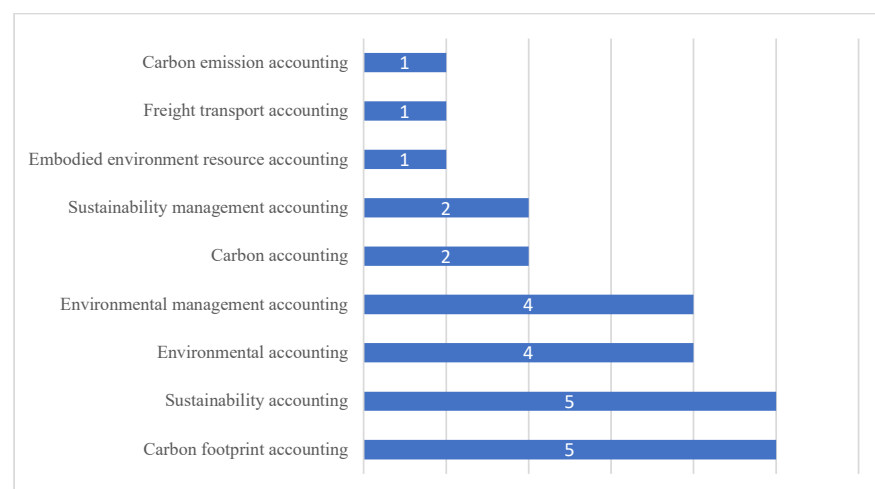


Figure 3. Frequency of occurrence of carbon accounting and affiliated concepts [18,46–50,54,55,59,60,62–70].

Carbon footprinting is defined as an indicator tool to assess corporate environmental performance in physical terms, with carbon footprints measured as the greenhouse gases produced over a period [55]. Sustainability accounting quantifies and reports economic, social, and environmental impacts, often using a triple-bottom-line approach [62,66]. It aims to support internal decision-making and external disclosures related to sustainability performance [65]. Environmental accounting encompasses the practices that account for an organisation's environmental costs, impacts, and strategies [49,50]. Environmental management accounting is a subset focused on providing environmental cost information to internal decision-makers [65].

4. Discussion

Carbon accounting has gained increasing attention as a means for companies to measure, manage, and reduce their GHG emissions and overall carbon footprint. This is especially relevant to emissions-intensive sectors like manufacturing, where carbon accounting can support emission reductions across production processes and broader supply chains [46,52,54,55,58].

Several studies have explored carbon accounting approaches tailored to the manufacturing sector. For the aerospace industry, a structured framework was proposed to facilitate consistent carbon measurement and reporting across complex extended supply chains [46]. This framework emphasised the need for complete supply chain visibility and senior leadership support. In the automotive industry, the researchers in [55] found that an environmental management accounting and eco-control approach helped Korean manufacturers align carbon management strategies with performance measurement. The study highlighted the need for quantitative carbon data to support decision-making. At a product level, researchers [52] developed a framework to compile supplier-specific life cycle GHG emissions data for liquified natural gas, from extraction through to distribution. The granular, supplier-specific data were intended to differentiate the emissions profiles of various supply chains amid growing policy interest in embedded carbon emissions. For manufactured goods like wooden furniture, GHG accounting methods were used to identify emissions hotspots across timber supply chains in China [59]. They found upstream production processes drove most emissions, urging sourcing and transport optimisation for footprint reductions. Multiple studies have also examined environmental or carbon management accounting as a tool to support emissions management internally. Across Chinese [59], Malaysian [74,75], Vietnamese [76], and Libyan [77] manufacturers, the research found environmental management accounting adoption levels were still developing. Key barriers were a lack of resources, knowledge, and regulatory incentives. The analyses underscored the need for management understanding and commitment to leverage these accounting systems towards sustainability [43]. Though carbon accounting techniques are advancing, it is noted that the complexity can still overwhelm practitioners, limiting organisational adoption and supply chain impacts [68]. They called for simplified tools and cross-disciplinary collaboration to increase connectedness. [66] also outlined research opportunities to address data reliability challenges in Indian supply chains through emerging technologies like blockchain and the Internet of Things.

Manufacturing organisations have not kept up with the best practices for comprehensively tracking and disclosing emissions sources. The authors in [81] discussed how current carbon accounting methods declare bioenergy to be carbon-neutral, failing to account for biogenic CO₂ emissions at the point of combustion. This means emissions from industrial bioenergy processes often go unreported or are zeroed out in emissions reporting frameworks. Other analyses have shown how agricultural emissions receive much more scrutiny and mandatory reporting requirements compared to biogenic emissions from industry. The authors in [82] demonstrated that many countries with climate commitments do not include some industrial process emissions like waste/biomass incineration in their national reporting. This leads to under-reporting of substantial indirect emissions in developed countries. Specifically looking at differences by industry, the authors in [83] found

that while agricultural methane emissions are comprehensively tracked and targeted for reduction by most countries, CO₂ emissions from bioenergy are categorically excluded from reduction targets. They argue this imbalance hinders effective, holistic climate mitigation policy. In terms of territorial versus polluter-pays emissions accounting, the author in [84] discussed how under purely territorial accounting of emissions from traded biomass, substantial indirect emissions can go unreported. He advocated for improved emissions reconciliation and shared producer/consumer responsibility for bioenergy emissions. All these challenges add up to the need for manufacturing organisations to keep up with the carbon accounting practices that are evolving in other industries and sectors.

Overall, the literature reveals ongoing developments in carbon accounting. Still, a persistent need for standardisation, simplified tools, regulatory incentives, and skills development is needed to drive broader adoption across manufacturing supply chains. More empirical research into accounting techniques and digitisation opportunities can support the transition towards carbon transparency and emissions reductions in global manufacturing systems.

4.1. What Is the Current Understanding of the Definition of Carbon Accounting in Manufacturing Systems and Supply Chains? (RQ1)

The concept of carbon accounting is fundamental in the context of manufacturing and supply chain management. Still, it is essential to note that there is no single universally accepted definition of this term within the literature. Nevertheless, some common themes have emerged, shedding light on the various aspects and purposes of carbon accounting. One perspective on carbon accounting is that it serves to quantify an organisation's GHG emissions, typically expressed in terms of carbon dioxide equivalent. For instance, ref. [46] describes carbon accounting as measuring the carbon dioxide equivalent emitted by any organisation. Similarly, ref. [59] defines a product's carbon footprint as the total carbon dioxide emissions and other GHGs during a product's life cycle. In this view, carbon accounting is primarily seen as a tool for assessing the environmental impact of an entity. Expanding on this, ref. [55] employs "carbon emissions data as a proxy for energy use and, hence, exposure to rising carbon risks". This suggests that carbon accounting not only measures emissions but also serves as an indicator of an organisation's vulnerability to the challenges posed by carbon emissions. In this sense, carbon accounting can be viewed as a tool to quantify climate-related risks. Another broad definition of carbon accounting comes from [68], which defines it as the "measures of greenhouse gases produced by activities". This definition encompasses a wide range of applications, from organisational emissions to product life cycles, emphasising the role of carbon accounting in assessing the environmental impact of various activities. Moreover, some researchers conceptualise carbon accounting as a more holistic approach that extends beyond measurement and instead focuses on identifying, monitoring, and ultimately reducing emissions. As ref. [52] suggests, carbon accounting can "improve GHG emission estimates and differentiate supply chains," informing business and policy decisions about transitioning to a low-carbon future. Similarly, ref. [55] argues that systematic carbon accounting and monitoring can help identify existing carbon exposure and serve as a starting point for developing strategies for carbon management. Here, carbon accounting plays a pivotal role in overall emissions management and sustainability efforts. Furthermore, carbon accounting is recognised for its significance in tracking emissions across complex supply chains. In [49], carbon accounting is used to estimate the variable environmental impacts of agricultural commodity supply chains, while ref. [48] applies it to quantify embodied emissions in global trade flows. In another example, ref. [60] calculates the carbon footprint across a seafood product supply chain. These cases demonstrate the practical relevance of carbon accounting in understanding and mitigating emissions within intricate production networks.

In summary, as shown in Figure 4, the literature aligns around carbon accounting's purpose as quantifying GHG emissions, especially across complete product life cycles and supply chains. It is predominately viewed as an emissions measurement tool, though

some note its broader role in informing carbon management strategies. More standardised terminology could support the further development of carbon accounting approaches, tools, and applications across the manufacturing sector.

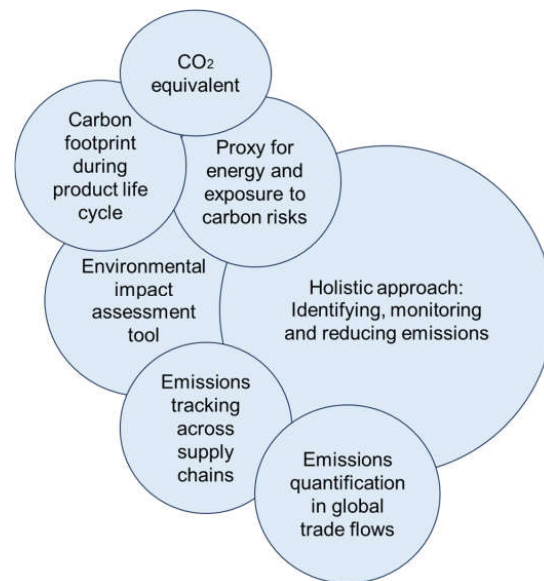


Figure 4. Various definitions of carbon accounting.

4.2. What Are the Current Gaps Identified in Carbon Accounting in the Manufacturing Systems and Supply Chain Systems Literature? (RQ2)

Numerous studies within the domain of carbon accounting in manufacturing supply chains have drawn attention to several critical gaps and challenges that need to be addressed for more effective and widespread adoption. One prominent theme that emerges from these studies is the need for standardisation and simplified tools in the field of carbon accounting. As pointed out by [46], the proliferation of various carbon calculators, reporting standards, and certification schemes has created a confusing landscape, lacking a unified and practical framework that enterprises can readily employ for carbon accounting. This fragmentation can deter organisations from engaging in comprehensive carbon accounting efforts. The researchers in [68] further underscore this concern by highlighting how the complexity of existing approaches can limit their adoption within organisations and hinder their impact throughout supply chains. To address this, they [68] suggest the importance of simplified tools and emphasise the need for transdisciplinary collaboration to enhance connectivity and coherence in carbon accounting practices.

Another challenge pertains to the reliability and availability of data required for carbon accounting. Ref. [66] identifies opportunities for leveraging emerging technologies such as blockchain and the Internet of Things to address data challenges in Indian supply chains. These technologies can enhance data transparency and accuracy, improving carbon accounting efforts' quality. Similarly, ref. [52] tackles the issue of data gaps by developing a framework specifically designed to capture supplier-specific emissions data within LNG supply chains. Ref. [47] addresses the data limitations by creating a model that connects agricultural commodity supply chain data across different geographic scales, responding to the inadequacies of coarse national-level data. These examples underscore the need for more granular and transparent emissions data, which are crucial for informed decision-making.

Furthermore, studies have raised concerns about the narrow scope of carbon accounting efforts. For instance, ref. [55] highlights that widely recognised guidelines like the GHG Protocol predominantly focus on direct or first-tier suppliers, potentially overlooking the broader carbon footprint associated with global trade flows. Ref. [48] argues that addressing embodied emissions in global trade necessitates a more comprehensive approach to carbon management that spans across countries. Similarly, ref. [64] suggests that the current

systems often have limited boundaries when it comes to implementing environmental management accounting systems within supply chains. These critiques underscore the need for a more holistic and expansive approach to carbon accounting that considers the full extent of emissions throughout supply chains.

Another challenge identified by researchers is the gap between carbon information and management decisions. Ref. [55] points out the lack of research on how managers collect and utilise carbon data, raising questions about the practical application of carbon accounting insights within organisations. Ref. [54] notes that the existing methods frequently overlook emissions related to labour and capital, indicating the need for a more comprehensive approach that encompasses all facets of emissions. Ref. [70] further highlights that even organisations committed to sustainability often struggle to translate sustainability data into meaningful and holistic business changes. This implies a need for more effective strategies to bridge the gap between carbon information and decision-making processes.

Finally, the studies indicate the lack of empirical evidence regarding the implementation of carbon accounting techniques. Both [55,68] advocate for expanding case studies and surveys to provide practical examples and insights into the effective use of carbon accounting methodologies. Ref. [64] cautions against overlooking the complex causal links between capabilities and environmental performance, emphasising the importance of empirical research to understand the dynamics of implementation. Ref. [52] also recognises the lack of bottom-up facility-level emissions data across supply chains and proposes innovative frameworks to address this gap.

The literature highlights several challenges in the field of carbon accounting in manufacturing supply chains, including the need for standardisation and simplified tools, data reliability and availability, expanded accounting scopes, carbon information to be linked to management decisions, and the generation of empirical evidence on implementation. Addressing these gaps is crucial for advancing carbon accounting practices and fostering more sustainable supply chains to reach the ideal maturity level possible, as shown in Figure 5.

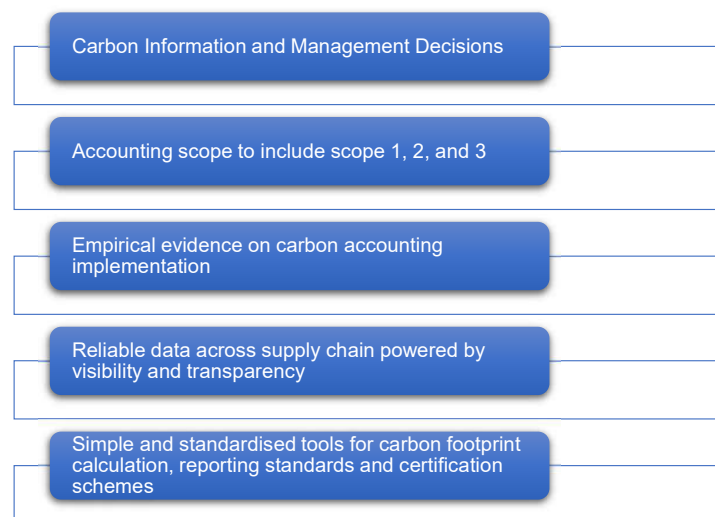


Figure 5. Gaps crucial for advancing carbon accounting practices.

4.3. What Is the Future Research Agenda for Carbon Accounting in Manufacturing Systems and Supply Chains? (RQ3)

Carbon accounting in the context of manufacturing and supply chains presents a dynamic and evolving field, offering a promising avenue for future research and development. Several key themes emerge from the existing literature, which point towards the need for comprehensive and precise carbon accounting methods and tools to improve the accuracy of emissions estimation within complex global supply chains.

A recurring call in the literature, exemplified by studies such as [52–55], emphasises the necessity for more robust carbon accounting practices. These calls stem from the recognition that reliable tools are essential to bolster confidence in climate-driven policy decisions and to bridge gaps in emissions data at the facility level of specific suppliers. By enhancing granularity and transparency in emissions data across various tiers of supply chains, stakeholders and policymakers can make informed decisions and foster more sustainable practices [52,55].

Moreover, researchers advocate for the testing and refining of existing carbon accounting frameworks, tools, and implementation strategies through empirical research within the manufacturing sector. This area currently lacks substantial empirical evidence [55,59,64]. For instance, [55] suggests applying their carbon management framework to diverse industries to validate its effectiveness. At the same time, case studies and large-scale surveys are seen as valuable tools for gaining insights into successful carbon accounting practices [55,64].

The intersection of carbon accounting with emerging technologies is another promising avenue. Studies such as [48,62,66] highlight the potential of incorporating carbon accounting into technologies like Industry 4.0, the Internet of Things, and blockchain. Ref. [62] suggests utilising Industry 4.0 data flows for sustainability accounting. At the same time, ref. [48] argues that blockchain technology could enhance the reliability and traceability of emissions data in trade, providing a novel approach to improving the quality of carbon accounting efforts.

Furthermore, there is a need to explore the integration of carbon accounting into various organisational functions, including supply chain management, performance management, and broader sustainability practices [55,64,66]. Ref. [64], for instance, calls for investigating the integration of sustainability accounting into supply chain management within developing countries, such as Indonesia.

Geographically, researchers emphasise the importance of extending carbon accounting research into developing country contexts and emerging markets, where implementation can be particularly challenging [64,70]. Conducting research and testing frameworks in these settings can facilitate the adoption of carbon accounting practices [58] and contribute to a more comprehensive understanding of the global carbon footprint.

In conclusion, as shown in Figure 6, the future research direction for carbon accounting in manufacturing and supply chains encompasses efforts to refine the measurement approaches, integrate carbon accounting into cutting-edge technologies and organisational processes, validate implementations through empirical research, and expand applications into developing country settings. By striving for more granular, transparent, and integrated carbon accounting practices, the field can play a vital role in strengthening climate governance across global supply chains.

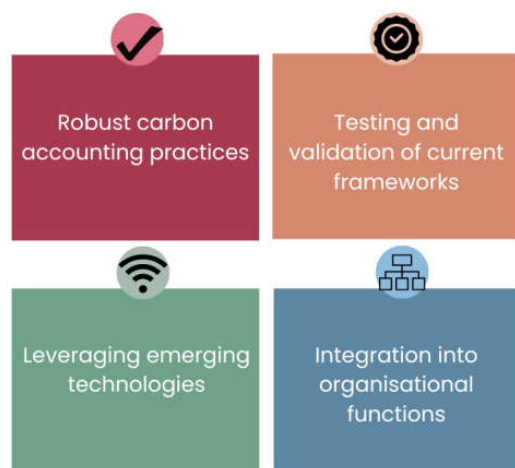


Figure 6. Future research agenda for carbon accounting in manufacturing and supply chains.

4.4. What Are the Challenges of Carbon Accounting Implementation in Manufacturing Systems and Supply Chains? (RQ4)

Carbon accounting in manufacturing and supply chains is crucial in pursuing sustainability and reducing greenhouse gas emissions. However, as discussed further, it faces various challenges that impact its practical implementation.

4.4.1. Lack of Standardised Methodologies and Tools

One major hurdle in carbon accounting is the absence of standardised methodologies and tools [49,54–56]. Various approaches, such as the GHG Protocol, life cycle assessment, and product carbon footprinting, differ significantly in terms of their scope, boundary setting, emissions factors, and allocation methods [52]. This lack of standardisation creates difficulty in obtaining consistent and comparable carbon accounting data across different companies and supply chains [46,53]. As ref. [53] points out, the absence of standardised measures hampers the differentiation of emissions between different import routes and supply chains.

4.4.2. Lack of Quality Emissions Data

The challenge of obtaining quality emissions data is frequently highlighted [46,55,56]. Collecting accurate and complete data on energy use and emissions from suppliers proves to be challenging [46]. High monitoring costs and the absence of appropriate data are barriers to adopting green and sustainable supply chain management [55]. Many companies resort to secondary or proxy data sources due to suppliers' lack of monitoring or the non-disclosure of primary emissions data [52].

4.4.3. Complexity of Supply Chains

Global multi-tiered supply chains are characterised by complexity, spanning multiple tiers of suppliers across different countries [56,68]. This intricacy makes emissions data collection, boundary setting, and allocation extremely challenging [56]. As ref. [68] highlights, the “lack of visibility of extended supply chain relationships” remains a significant concern for manufacturing company executives.

4.4.4. High Implementation Costs

Implementing carbon accounting across entire supply chains can be prohibitively expensive, especially for small and medium-sized enterprises (SMEs) [61,63]. Developing the necessary capabilities for carbon accounting demands investments in data collection systems, analytics tools, and personnel [61]. Resource limitations, particularly for SMEs, pose a significant barrier [63]. While outsourcing to consultants is an option, it can also be costly.

4.4.5. Organisational Culture and Commitment

A lack of organisational commitment and a culture that supports sustainability initiatives can hinder the adoption of carbon accounting [61,63]. Many companies are reluctant to integrate environmental strategies due to the perceived costs and low perceived benefits [63]. Top management commitment is essential to drive the organisational changes required for practical carbon accounting [61].

4.4.6. Lack of Regulation and Incentives

The absence of robust regulation, policy incentives, and stakeholder pressures can relegate carbon accounting to a low priority for many companies [61,63,66]. Voluntary carbon accounting initiatives may have limited uptake because the perceived costs often outweigh the benefits for individual companies [61]. Stronger regulation and policy incentives are required to motivate companies to prioritise carbon accounting [63,66].

4.4.7. Gaps in Capabilities and Understanding

Finally, gaps in carbon-related capabilities, skills, and understanding present adoption challenges [61,66]. There is a need to integrate environmental cost recording into financial reports, but organisations often lack the necessary capabilities [61]. Training and education are crucial to building organisational capacity for practical carbon accounting [66].

Addressing the challenges summarised in Figure 7 is essential for successfully implementing carbon accounting in manufacturing and supply chains. Standardisation, data quality improvement, supply chain transparency, cost-effective solutions, cultural change, regulatory support, and capacity building are all vital components in overcoming these hurdles and advancing the cause of sustainability in manufacturing and supply chains.

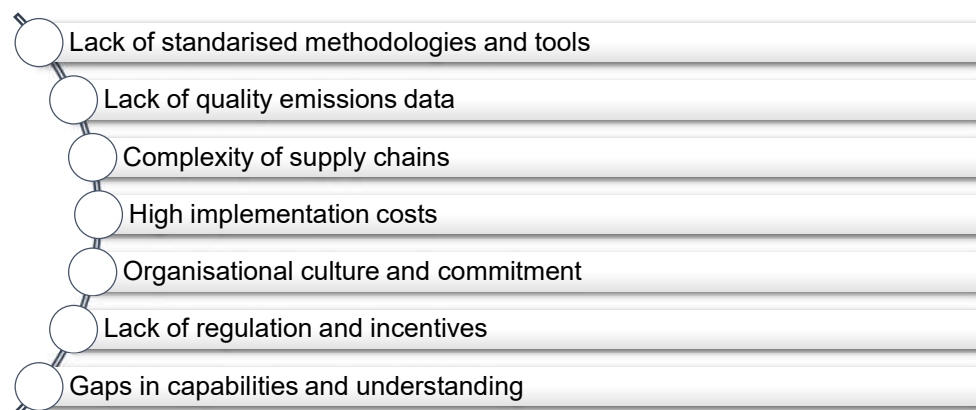


Figure 7. Challenges to carbon accounting in manufacturing and supply chains.

5. Conclusions

This research work has explored the evolving landscape of carbon accounting in manufacturing systems and supply chains through a systematic literature review. It has given the current understanding of carbon accounting definitions (RQ1), identified gaps needing scholarly attention (RQ2), suggested future research directions (RQ3), and outlined implementation challenges (RQ4), as in Section 4.

However, some limitations provide avenues for further research. Comparative assessment of recurring methods and tools could enrich analytical insights, while investigating sectoral and regional differences may reveal additional nuances. Aligning the terminology across sectors could strengthen the possibility of detailed carbon accounting framework development.

Nevertheless, this review carries several implications for industry, which are listed below:

- **Need for Standardised Approaches:** The lack of standardised carbon accounting methodologies makes it difficult for companies to measure, report on, and compare emissions across different suppliers and facilities. Industry associations need to collaborate on developing sector-specific tools and protocols.
- **Leveraging Emerging Technologies:** Blockchain, IoT, and other digital innovations offer opportunities to enhance carbon data transparency, accuracy, and integration with operational decisions. Companies should actively explore technology adoption.
- **Strengthening Organisational Commitment:** Top management buy-in and internal capability development is crucial for the success of carbon management initiatives. Firms need to foster a culture that incentivises sustainability.
- **Focus on Full Supply Chain Visibility:** Complex global supply chains with multiple tiers of suppliers pose carbon accounting challenges. Businesses must invest in traceability systems that map emissions across entire product life cycles.
- **Collaboration with Policymakers:** Robust regulation and incentives are required to motivate industrial carbon management, especially given high abatement costs. Industries need to constructively engage with governments on pragmatic policy approaches.

This research relates directly to several of the United Nations Sustainable Development Goals (SDGs):

- **SDG 12**—Responsible Consumption and Production: The paper discusses how robust carbon accounting practices can help quantify and reduce greenhouse gas emissions across product life cycles and supply chains. This aligns with SDG 12’s emphasis on sustainable production and consumption patterns.
- **SDG 13**—Climate Action: By enhancing the transparency and management of carbon emissions, the approaches analysed in the paper can accelerate climate change mitigation efforts in line with SDG 13.
- **SDG 9**—Industry, Innovation and Infrastructure: The analysis touches on emerging technologies like blockchain and the Internet of Things, which have the potential to enhance carbon data management. Leveraging these innovative industrial technologies links to SDG 9.
- **SDG 17**—Partnerships for the Goals: The paper discusses the need for collaboration between stakeholders, policymakers, companies, and researchers to standardise and advance carbon accounting globally. Such cross-sectoral partnerships embody the spirit of SDG 17.

Additionally, the issues covered by the paper, including data reliability, transparency in emissions reporting, and integration of sustainability into business decisions, indirectly connect with principles underlying SDG 16 (Peace, Justice and Strong Institutions) and SDG 8 (Decent Work and Economic Growth).

By outlining how improved quantification, monitoring, and management of carbon emissions can facilitate the shift towards more sustainable manufacturing, the research work relates directly to key SDGs that are driving the climate change and sustainable production agenda globally. Its analysis has relevance for decision-makers and stakeholders seeking to align industry practices with urgent climate and development priorities.

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The concept of carbon accounting in manufacturing systems and supply chains

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