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# Greening the factory floor and reducing the climate impact of the manufacturing sector

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**Abstract**

The manufacturing sector is a cornerstone of the global economy, driving innovation, employment, and national development. Yet it is also a substantial contributor to climate change, primarily due to its high carbon emissions. To mitigate its contribution to climate change, the manufacturing sector needs to adopt a range of strategies for economic decoupling, including enhancing energy efficiency, transitioning to renewable energy, optimising material use and waste management, and embracing circular economy principles. This paper presents a study comprising a systematic literature review, complemented by case studies from companies in sectors including automotive, construction, aerospace, food, and consumer goods. It uniquely integrates cross-sectoral evidence into actionable guidelines for decarbonisation. Drawing from a systematic review of 29 peer-reviewed studies and sector-specific case studies, the study develops key guidelines to foster green growth. While selective, the analysis provides insight into key industrial pathways. One limitation of the paper is the exclusive focus on the manufacturing sector and the small sample of papers selected.

**Keyword** Climate change, Carbon footprint, Manufacturers, Guidelines, Industrial vulnerability, Green growth

## 1 The economic significance of the manufacturing sector

The manufacturing sector is recognised as a key driver for long-term economic development, technological progress, and structural transformation. It is also a pivotal contributor to job creation (K et al., 2020). The sector is also important for enhancing the capabilities of human capital, fostering research development, and driving innovation [1]. Throughout history, the manufacturing sector has played a key role in economic development [2, 3].

Despite many positive effects of industrialisation, production and consumption models have often been criticised [4, 5]. For instance, Agenda 21 acknowledged as early as 1992 developed countries' consumption and production patterns were unsustainable, given the environmental limits of global resources [5]. The Rio Declaration urged

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nations to change these standards, emphasising the unsustainable approach adopted by the manufacturing systems and social lifestyles [5], p. 2).

However, the rapid industrialization of the past two centuries, while laying the groundwork for modern economies, has also led to considerable environmental degradation and accelerated climate change. This necessitates an urgent reconsideration of manufacturing methodologies [6]. This urgency is amplified by international accords like the 2015 United Nations Framework Convention on Climate Change, which established ambitious goals to limit global temperature increases, thereby mandating a swift and thorough decarbonization of economic and social frameworks [7].

Currently, the widespread ramifications of climate change present considerable challenges at both macroeconomic and microeconomic levels for the manufacturing sector, primarily manifesting as significant reductions in productivity [8]. Consequently, adopting environmentally sustainable practices has become a priority, driven by increasing pressure from governmental entities, non-governmental organizations, and a growing base of environmentally conscious consumers [9]. This heightened awareness is prompting firms to adopt proactive strategies, including green entrepreneurship and green innovation, aimed at both environmental stewardship and the cultivation of a competitive edge [8].

Key strategies such as improving energy efficiency, transitioning to renewable energy sources, optimizing resource utilization, and embracing circular economy principles are essential for reducing carbon emissions and promoting sustainable industrial growth [10]. These initiatives are not merely compliance measures but represent strategic opportunities for manufacturers to foster resilience, develop novel product lines, and secure long-term market viability in an evolving global economy.

These operational strategies are increasingly supported by a broader international policy framework. In the last few decades, several summits, policies, and international environmental agreements have been put forward to boost national, regional, and global green growth [11, 12]. The international development agenda and academia have often remarked on the compellingness of economic decoupling [13]. Throughout the years, theories, good practices, studies, and metrics have been developed globally to better understand, mainstream, and measure green growth [14–16].

Although the negative consequences of climate change have been evident for decades, initiatives to reduce carbon emissions still need to be prioritised by both developed [17] and developing nations [18]. This historical trajectory of industrialisation, characterised by burgeoning energy consumption and greenhouse gas emissions, has directly contributed to the current climate crisis, making the manufacturing sector a critical focal point for urgent mitigation and adaptation strategies [19]. Indeed, the manufacturing and construction sectors alone accounted for 20% of global greenhouse gas emissions as of 2014, underscoring the imperative for substantial reductions to achieve climate mitigation goals [20].

This necessitates a comprehensive shift towards sustainable manufacturing practices, integrating waste reduction, energy efficiency, and the adoption of renewable energy sources to minimise environmental impact and promote green economic development [21]. This involves re-evaluating production processes, integrating eco-friendly materials, and optimising supply chains to reduce the overall carbon footprint [22]. Addressing this urgent challenge requires a paradigm shift towards sustainable energy systems and

circular economy principles, which are critical for mitigating adverse climate effects by reducing greenhouse gas emissions and conserving natural resources [23].

Policymaking has further clarified this urgency. It is worth mentioning that initiatives at the EU and global level are also pivotal. Intergovernmental projects to foster green growth at the industrial level can drive policymaking and strategies formulation. Among others, as part of the Green Deal Industrial Plan [24], the EU Net Zero Industry Act [25] has the objective to enhance clean technology for manufacturing in the EU to boost the energy transition plan in Europe and accelerate decarbonisation related to them. An additional goal of the EU Net Zero Industry Act is to attract investments via net-zero technologies manufacturing and to reach the target of 40% of annual deployment needs by 2030. The Act also aims to create quality jobs and make the EU more energy independent.

At the global level, another key initiative is the UNIDO's Industrial Decarbonization Accelerator [26], to be conceived in the wider framework of UNIDO's Industrial Decarbonization Projects. The accelerator is a network of global initiatives promoted by the UNIDO and aimed at boosting energy efficiency, renewables and low-carbon alternative fuels, electrification, carbon capture, utilization and storage (CCUS), and alternative feedstocks. The initiative has the goal of facilitating industrial decarbonization policy formulation. The final target is to achieve full decarbonization by 2050.

Furthermore, practical applications of mitigation strategies, such as assessing carbon footprints in various sectors, highlight tangible pathways for emission reduction. For instance, quantifying the carbon footprint of transport activities in healthcare facilities provides a concrete example of how detailed assessments can inform targeted emission reduction strategies across diverse industrial contexts [27]. Additionally, global industrial operations, particularly in sectors like steel, cement, and logistics, are under increasing regulatory and sustainability scrutiny, necessitating innovative and energy-efficient solutions to reduce their environmental footprint and align with global carbon reduction targets [28].

Such efforts can be bolstered by advanced water resource management under various climate scenarios to enhance resilience [29], alongside decomposition analyses of CO2 emissions to identify key drivers for targeted interventions. These approaches underscore the importance of integrating robust environmental management systems within industrial frameworks, promoting not only operational efficiencies but also ecological stewardship [30]. This aligns with the theoretical framing of ecological modernisation, which contends that environmental sustainability and economic growth are not mutually exclusive but can be achieved by technological innovation, market mechanisms and regulation. For manufacturing, the framework translates into cleaner production, Industry 4.0, and circular economy approaches. Pan and Zhou [31] highlighted how China's manufacturing industries leveraged the framework in the context of green logistics and regulatory reforms to achieve decarbonisation. Reis et al. [32] contend that the Industry 4.0 paradigm can aid organisations in addressing a range of sustainability challenges. According to the authors, this approach introduces intelligence into production processes, which can result in reduced consumption of raw materials, water, and electricity, in addition to the potential to lower equivalent $CO_2$ emissions.

However, the underlying tensions of the trade-offs between environmental conservation and economic growth in the manufacturing sector have not been thoroughly

investigated in the literature, especially in the developing countries, where the challenges jeopardise their sustainability performance [33]. Moreover, most studies are sector-specific (e.g., steel, cement, automotive), limiting the ability to draw cross-sectoral lessons [34]. Meanwhile, emerging research suggests the need for cross-sector comparative insights [35]. Thus, it is pertinent to ask the research question, "How can manufacturing industries operationalise climate mitigation while maintaining economic viability?" This paper, therefore, aims to explore the multifaceted strategies available to the manufacturing sector for mitigating its climate impact and adapting to the challenges posed by a changing climate.

Given the urgent need to understand how climate risks affect industrial systems, this study adopts a sector-specific definition of *vulnerability*, referring to the susceptibility of manufacturing activities to both rapid and slow-onset climate-related changes. This encompasses both acute events (e.g., extreme weather) and slower-onset phenomena such as desertification, salinisation, rising sea levels and temperatures, forest degradation, and biodiversity loss, among others.

The novelty of the paper lies in the fact that it focuses on more than just energy efficiency. It proposes a new framework that directly incorporates circular economy principles into production lines. It shows how tracking resources in real time and turning waste into valuable materials can separate manufacturing growth from its environmental effects. This approach offers a scalable way to achieve a truly sustainable industry.

## 2 Climate change and the manufacturing sector

The relationship between the manufacturing sector and climate change is multifaceted and significant. For instance, manufacturing industries are important greenhouse gas emitters [36–39]. These emissions result from the use of fossil fuels for energy generation, chemical reactions from processes [40], and energy-intensive activities like heating, cooling, and material transport [41].

In addition, the manufacturing sector is one of the largest consumers of energy globally [42, 43]. This high energy demand often relies on fossil fuels, contributing significantly to greenhouse gas emissions worldwide [44, 45]. Transitioning to renewable energy is essential for reducing the sector's carbon footprint [46].

Moreover, manufacturing processes often involve the extraction and processing of raw materials, activities that can result in deforestation, habitat loss, and biodiversity decline [47]. Additionally, if not properly managed, waste generated from manufacturing operations can cause significant environmental harm [48, 49].

Life cycle assessment (LCA) details the environmental impacts arising from production systems across the entire supply chain. This encompasses stages from raw material extraction, transportation, and the production process, to commercialization, use and end-of-life disposal [50–52].

Without disregarding the other stages, the post-use phases are particularly problematic. In response, the manufacturing sector has increasingly prioritised developing sustainable products and reducing waste through circular economy strategies [53]. Growing pressure from governments and consumers has accelerated global efforts to develop technologies that mitigate climate change. These include, in addition to technologies associated with industry 4.0, innovations in energy efficiency, renewable energy systems, and low-carbon materials [54, 55].

In response, governments globally are enacting policy measures to curb carbon emissions from the manufacturing sector. These include emissions reduction targets, carbon pricing mechanisms, and incentives for the adoption of cleaner technologies [56]. At the operational level, Fig. 1 illustrates the risks that climate change poses to manufacturing infrastructure and supply chains.

Overall, climate change compels manufacturers to adapt and innovate in order to mitigate associated risks. This may include investing in climate-resilient infrastructure, diversifying supply chains, adopting sustainable practices, and developing products aligned with climate targets and broader sustainability goals [57]. The sector must therefore adapt by enhancing its resilience to extreme weather events and shifting climate conditions [58, 59]. Given its transnational scope, the manufacturing sector's response to climate change requires coordinated international action. In this context, industrialised nations—with more advanced manufacturing capabilities and higher historical emissions—bear a greater responsibility to lead in reducing carbon outputs and advancing sustainable practices [60, 61].

Although renewable energy technologies are becoming more affordable, their uptake in manufacturing is still limited by structural and operational barriers. High-heat needs, round-the-clock operations, old equipment, and tight margins make many manufacturing subsectors difficult to electrify [56, 62]. Moreover, uncertainties about trade, policy, and grid integration further discourage large-scale investment [63, 64]. Overcoming these barriers calls for coordinated policy and sector-specific support to enable a just, effective transition to low-carbon manufacturing [56, 62].

Relatedly, biodiversity loss, waste, and consumer pressure are interconnected, showing that manufacturing transitions must be seen as value-chain shifts, not isolated challenges. Global supply chains displace land-use change and biodiversity impacts to producer regions, making downstream consumption an indirect driver of species decline with epistemic and cultural consequences that are widely underappreciated and difficult to quantify [65, 66]. Circular-economy strategies can help mitigate these pressures by limiting extraction, recirculating materials, reducing waste, and easing biodiversity losses from raw-material demand [67]. At the same time, sustained customer pressure can push firms to adopt greener practices and products, advancing circular transitions

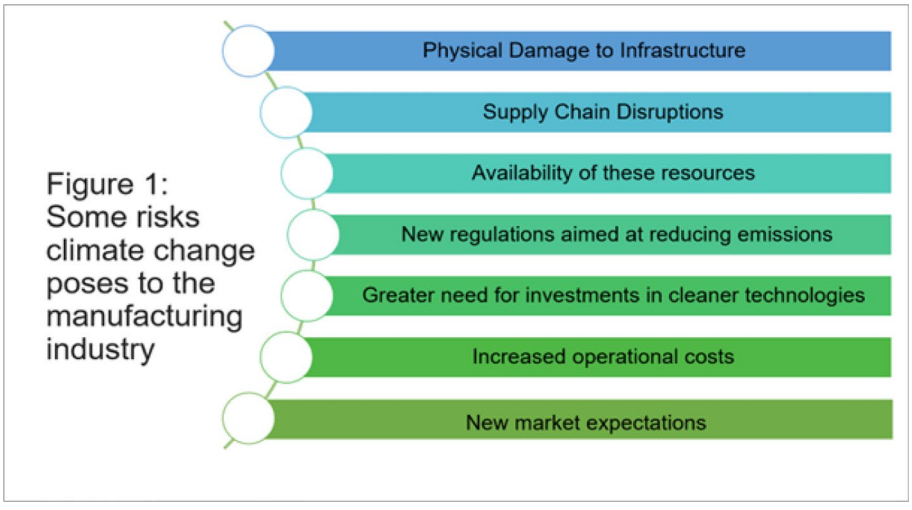


**Fig. 1** Key Climate-Related Risks Affecting the Manufacturing Sector. (Source: Authors)

[68]. Taken together, manufacturing transitions should be seen as value-chain redesigns rather than end-of-pipe fixes, ensuring social legitimacy and safeguarding biodiversity [65, 66].

The imperative to combat climate change can be a significant catalyst for industrial innovation, manifesting across several key areas: (a) the integration of renewable energy sources, such as solar panels, wind turbines, and geothermal systems [69–71],(b) product design for circularity, which involves developing products specifically for easy disassembly, component recovery, reuse, remanufacturing, and recyclability [72],(c) process innovation for cleaner production, entailing the redesign of industrial and commercial processes to reduce pollution at source, enhance energy efficiency, minimise material consumption, and eliminate hazardous substances [54, 55, 73, 74], and (d) dematerialisation and lightweighting, which refer to the systematic reduction of material weight or embedded energy in products during the design phase [75, 76].

Beyond the initiatives undertaken by manufacturers, numerous scholars acknowledge the fundamental role of trade unions in advancing sustainable development. According to Räthzel and Uzzell [77], the significance of trade unions in this regard was formally established at the 1992 Rio Earth Summit within Agenda 21, a document which explicitly recognizes the influence and role of workers and their representatives. The authors emphasize that trade unions constitute a fundamental tier of a tripartite system, alongside government and employers. Through the implementation of collaborative, win–win strategies, this system is instrumental in designing, implementing, promoting, and strengthening green jobs. This process entails making substantive improvements to product design, production processes, and workplaces to mitigate global greenhouse gas emissions. Furthermore, scholars such as Thomas [78] and Felli [79] contend that trade unions, as key social actors, possess a unique capacity to mobilise substantial numbers of people. This mobilization is critical for lobbying governments to provide essential support, foster social dialogue, and institute protective measures to safeguard both workers and communities throughout the transition to a low-carbon economy.

Overall, the manufacturing sector's relationship with climate change is complex, presenting both challenges and opportunities for innovation and sustainability [80]. Reducing the manufacturing sector's environmental impact is essential for achieving the global climate targets established in the 2015 Paris Agreement [81]. Given the manufacturing sector's dual role as a major contributor to climate change and as one of its most exposed industries, this paper reviews the relevant literature and proposes guidelines to mitigate its environmental impacts.

## 3 Theoretical framework

This study is grounded in the complementary perspectives of industrial ecology (IE) [82] and systems thinking (ST) [83], which together provide the conceptual foundation for interpreting the relationship between manufacturing and climate change, as well as for formulating guidelines for sectoral decarbonisation [84, 85].

Industrial ecology conceptualises industrial systems as analogues of natural ecosystems, where materials and energy are cycled to minimise waste and maximise efficiency [86]. Its core premise is that the environmental impact of production can be reduced by optimising resource flows across the life cycle of products and processes [87].

Within manufacturing, IE emphasises strategies such as eco-efficiency, waste valorisation, product life-cycle assessment, and the implementation of circular economy principles [88]. By treating waste streams as potential inputs for other processes, IE promotes "closed-loop" systems that reduce reliance on virgin raw materials and mitigate greenhouse gas emissions [86]. Moreover, industrial symbiosis, a subfield of IE, highlights opportunities for cross-industry collaboration in which the by-products of one facility serve as inputs for another, fostering collective reductions in environmental impact [89].

Systems thinking, in turn, extends this perspective by situating manufacturing within complex, adaptive socio-technical systems [90]. ST emphasises interdependencies, feedback loops, and dynamic interactions between production processes, supply chains, regulatory structures, and societal expectations [91, 92]. From this perspective, the challenge of decarbonising manufacturing cannot be reduced to discrete technological fixes; it must be approached as a systemic transition that requires coordination across actors and scales [93, 94].

ST directs attention to structural barriers (e.g., such as high-heat demands, legacy infrastructure, and fragmented supply chains) that are reinforced through feedback mechanisms and institutional lock-ins [95]. At the same time, it underscores the leverage points where targeted interventions (e.g., carbon pricing, procurement standards, collaborative networks) can trigger broader shifts towards sustainable trajectories [90].

Together, IE and ST form a synergistic theoretical framework. IE provides analytical perspective for assessing material and energy flows within and across manufacturing systems, while ST broadens the scope to include governance, organizational practices, and societal drivers of change [84, 85]. By integrating these perspectives, this study ensures analytical depth and coherence: IE anchors the technological and operational aspects of decarbonisation, whereas ST highlights the systemic nature of transitions, ensuring that proposed guidelines address not only efficiency improvements but also the structural, institutional, and cultural dimensions of sustainable manufacturing.

## 4 Methodology

This study employed a systematic literature review to identify scholarly publications addressing the interface between the manufacturing sector and climate change. Using inductive content analysis, the selected literature was organised into thematic categories. Based on these categories, the study developed a set of guidelines grounded in the reviewed literature.

In the first step, a structured search string was applied to the Scopus and Web of Science databases: ("climate change" OR "climate impact" OR "carbon emission*" OR "carbon emission*" OR "carbon footprint" OR "greenhouse gas" OR "greenhousegas" OR "Paris Agreement" OR "climate") AND ("manufactur*") AND ("vulnerability" OR "influence") AND ("case stud*"). The search was limited to the title, keywords, and abstract fields.

The search string returned 71 papers from Web of Science and 94 from Scopus. After removing duplicates, a total of 104 unique papers remained. These were screened based on their titles and abstracts to assess their relevance to the research focus. The selection criteria were: 1) the study must focus on the manufacturing sector; 2) the study must focus on climate change. This process resulted in a final selection of 29 papers. The screening procedure is summarised in Fig. 2 using a flow diagram.

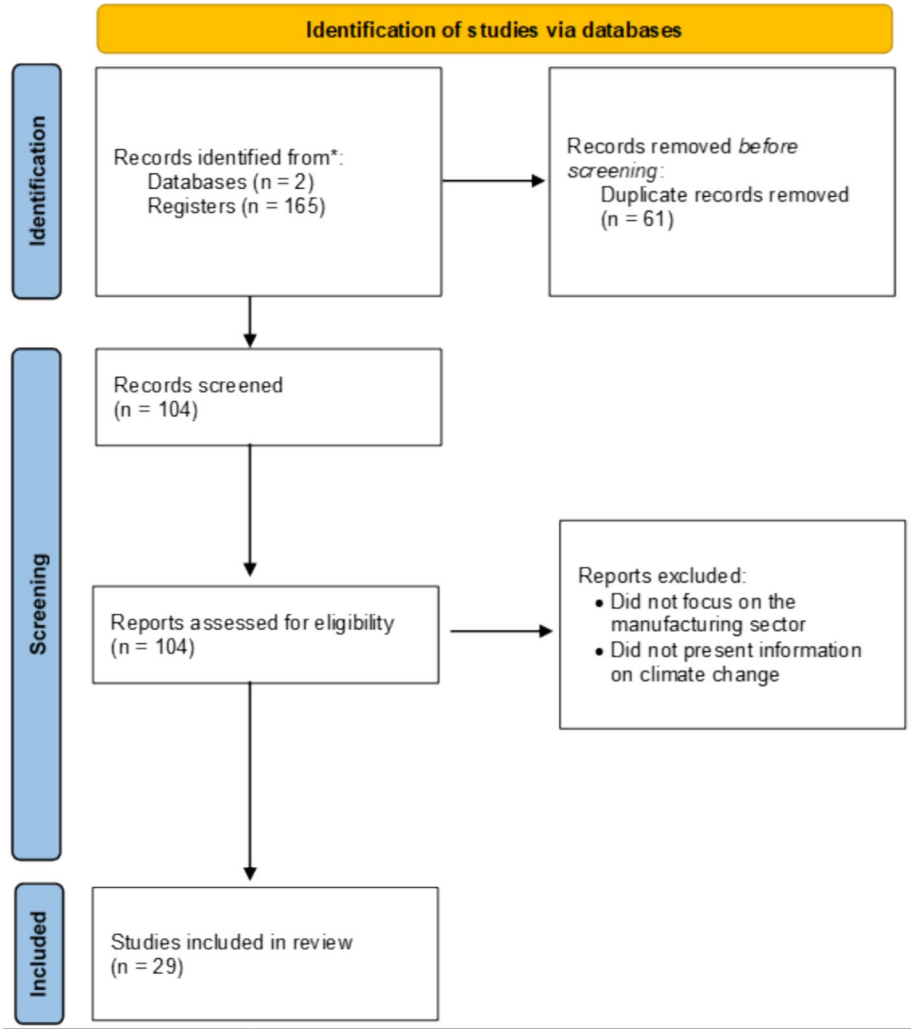


**Fig. 2** Literature Screening and Selection Process. Source: Adapted from Page et al. (2021)

The 29 papers remaining after the screening process were analysed using inductive content analysis, following the guidelines proposed by Elo and Kyngäs (2008). This type of analysis involves the following steps: (1) open coding, in which notes and headings are generated during a close reading of the material to create coding sheets and initial categories; (2) category creation and grouping, where related codes are clustered under higher-order headings; and (3) abstraction, the process of formulating general descriptions and synthesising the categories into overarching themes. Finally, the results are reported based on these abstracted categories.

Based on the results of the inductive content analysis, this study proposes a set of guidelines outlining actions the manufacturing sector can take to address climate change.

## 5 Findings and discussion

### 5.1 Sectoral characteristics of the sample

Before presenting the content analysis, it is useful to provide descriptive information about the sample of papers reviewed. The first aspect examined is the year of publication.

As shown in Fig. 3, while no clear trend can be identified, the years with the highest number of publications were 2014, 2022, and 2023.

With respect to publication venues, three journals published more than one of the selected papers: *Journal of Cleaner Production*, *Journal of Industrial Ecology*, and *Sustainability*. This indicates the broad relevance of the topic across the academic literature. The diversity of journal scopes is also noteworthy, encompassing outlets focused on sustainability, specific industries, and disciplinary research areas.

### 5.2 Key themes in the literature

As noted earlier, the systematic literature review identified 29 papers addressing the intersection of climate change and the manufacturing sector. An inductive content analysis of these papers resulted in the development of nine thematic categories, based on the specific industries addressed. The categorisation is as follows: General manufacturing (24.1%), Automotive (17.2%), Food and Beverage (10.3%), Steel (6.9%), Cement/Concrete/Construction (17.2%), Machining Processes (10.3%), Aircraft/Aerospace (6.9%), Consumer Goods (3.4%), and Fashion (3.4%). Further details regarding the individual papers and their contributions to the climate change discourse are presented in Table 1.

In the first group of papers—those addressing general or multiple industries—several key aspects of the relationship between the manufacturing sector and climate change are highlighted. The main themes include: the influence of carbon footprint considerations on procurement decisions [96], the role of energy management in enhancing corporate sustainability [97–99], the need to reconsider product strategies [100, 101] the importance of infrastructure to support circular economy practices and increased information sharing across the supply chain [99] and the need for policies that incentivise eco-efficiency among companies [102].

In the second group of studies, which focus on the automotive industry, the studies reflect concerted efforts within the sector to reduce carbon emissions through innovations in technology [103], materials [104], and design [105]. However, the pace of change remains slow in some contexts, as illustrated by the case of the United States [103].

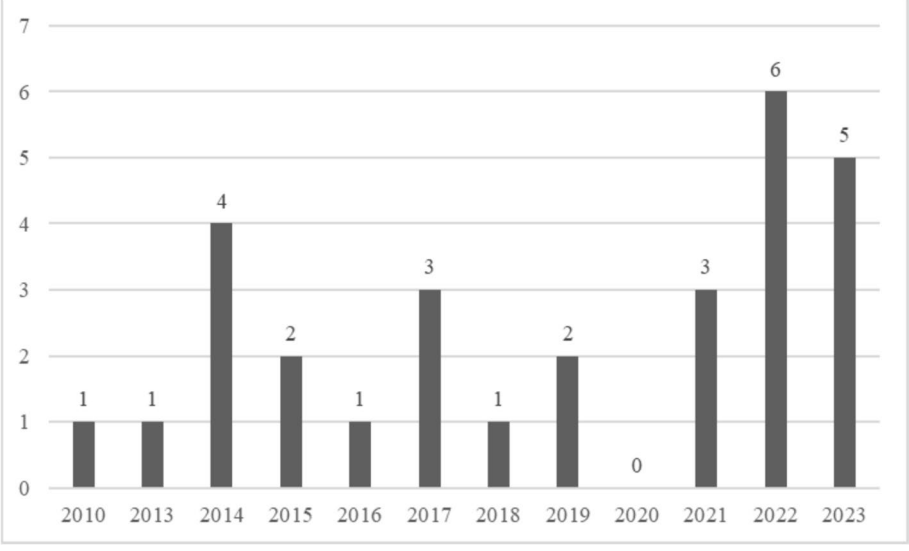


**Fig. 3** Temporal Distribution of Selected Publications (2010–2023). (Source: Authors)

**Table 1** Classification of Reviewed Studies by Industry Focus. (Source: Authors' analysis)

| Group | References |
|---|---|
| Papers addressing general themes or spanning multiple industries | Basu et al., [96] |
| | Finnerty et al., [98] |
| | Alaux et al., [97] |
| | Rios and Charnley, [100] |
| | Xu and Qu, [101] |
| | Kumar et al., [99] |
| | Suh et al., [102] |
| Studies focusing on the automotive industry | Penna and Geels, [103] |
| | Schmiedt et al., [104] |
| | Pan et al., [140] |
| | Li et al., [105] |
| | Wei et al., [141] |
| Papers related to the food and beverage industry | González-González and Zamora-Ramírez, [108] |
| | Ali et al., [106] |
| | Röös et al., [107] |
| Studies focusing on the steel sector | Priarone et al., [110] |
| | Jeong, [109] |
| Studies related to the cement, concrete, and construction sectors | Bakhoum and Mater, [111] |
| | Pedro et al., [112] |
| | Kim and Miller, [113] |
| | Zhou, [142] |
| | Pelzeter and Sigg, [114] |
| Studies focusing on machining processes | Sun et al., [115] |
| | Liu et al., [117] |
| | Tuo et al., [116] |
| Studies related to the aircraft and aerospace sector | Eckelman et al., [118] |
| | Harclerode et al., [119] |
| Studies focusing on the consumer goods sector | Theißen et al., [120] |
| Papers related to the fashion industry | Hildebrandt et al., [121] |

In the third group of papers, which focus on the food and beverage industry, the studies highlight the growing pressure on companies to reduce their carbon emissions [106, 107]. They also document measures being implemented in response to this pressure, including the monitoring and reduction of greenhouse gas (GHG) emissions [108], and the imposition and mainstreaming of more stringent environmental requirements across the supply chain [106].

In the fourth category of studies related to the steel industry, manufacturing processes are analysed to optimise energy and material use to reduce carbon emissions [109, 110]. This focus is particularly important given the high volume of greenhouse gas (GHG) emissions associated with the sector [109].

The fifth thematic group focuses on the cement, concrete, and construction industries, which are considered together due to their strong interconnection. The studies in this category highlight several good practices adopted across these sectors, including the use of waste-derived materials [111] and supplementary cementitious materials in concrete mixes [112]. Additionally, adopting alternative construction materials and implementing carbon capture and storage (CCS) technologies are noted as key strategies for reducing emissions [113]. The literature also considers the operational phase of buildings, with attention to emissions generated during their conventional use. For example, Pelzeter

**Table 2** Strategic Guidelines for Climate Change Mitigation in the Manufacturing Sector. (Source: Authors' synthesis)

| # | Guidelines | Descriptions |
|---|---|---|
| 1 | Collaborative management | Collaborative management approaches to carbon reduction in the manufacturing sector offer significant potential. Companies should actively exchange experiences and best practices to generate synergistic benefits and accelerate sector-wide sustainability gains |
| 2 | Transformative industry behaviour | Manufacturing companies must transition towards a "transformative industry" model, which involves not only adopting a sustainability-oriented organisational culture but also influencing other actors across the production chain to do the same |
| 3 | Sustainable energy and carbon capture | Sectoral case studies demonstrate the potential of energy efficiency, clean energy adoption, carbon capture, and related measures. However, their implementation remains limited, and the manufacturing sector must significantly intensify efforts in this direction |
| 4 | Carbon footprint analysis in purchases | Carbon footprint considerations should play an increasingly central role in decisions regarding the acquisition of equipment and vehicles in the manufacturing sector |
| 5 | Carbon emission analysis in product development | Product development in the manufacturing sector should increasingly prioritise low-carbon innovations that contribute to climate change mitigation—such as lightweight materials in vehicles to reduce fuel consumption, or alternative cement formulations that lower emissions |
| 6 | Eco-efficiency and low-carbon technologies detailed financial analysis | Eco-efficiency and low-carbon technologies can yield substantial financial benefits. Manufacturing firms should develop a comprehensive understanding of these concepts rather than dismissing them prematurely |
| 7 | Carbon emissions estimations for processes and products | Systematically estimating carbon emissions from manufacturing processes and products provides a valuable basis for identifying opportunities for improvement. The academic literature increasingly offers indices and decision-support tools to guide managers in these analyses |

and Sigg [114] underscore the importance of $CO_2$-optimised facility services in mitigating process-related emissions.

The sixth group of studies examines machining processes, with a particular focus on evaluating their performance in relation to carbon emissions [115, 116]. These papers also explore opportunities for reducing emissions through process optimisation and improved operational efficiency [117].

The seventh group of research papers focuses on the aircraft and aerospace industry, highlighting efforts to reduce environmental impacts through material reuse and process optimisation. The use of recycled alloys is noted for its potential to lessen environmental harm [118]. Additionally, the literature addresses the social costs associated with carbon emissions in this sector, suggesting that these could be mitigated through the optimisation of remediation processes [119].

The final two groups each consist of a single paper. In the case of the consumer goods industry, the focus is on the potential of supply chain collaboration to improve environmental outcomes [120]. In the fashion industry, the highlighted study explores the use of vegan and bio-based materials as environmentally friendly alternatives. However, the authors also note that these materials can have unintended negative environmental impacts [121].

### 5.3 Strategic guidelines proposition

Following the analysis of the selected papers, a set of guidelines was developed to support the manufacturing sector in responding to climate change. These are presented in Table 2. The guidelines are intended to inform both future research and professional

practice by outlining key pathways for sustainable action. The subsequent section discusses these guidelines in relation to the broader literature.

Collaborative problem-solving fosters shared understanding, which can support collective action. These shifts in perspective may also generate broader social impacts, influencing institutional and governmental responses [122–124]. Furthermore, organisations increasingly rely on learning networks to build capabilities in complex business environments. Multi-firm collaboration facilitates the development of shared solutions to common challenges and enables economies of scale through the generation of collective knowledge and the diffusion of best practices [125]. The transition to a low-carbon economy is reshaping the business landscape, generating uncertainty across sectors. Emerging emissions regulations are expected to exert significant pressure on suppliers. As a result, competitive dynamics have shifted from individual firms to entire supply chains [126, 127].

Over the next decade, manufacturing is expected to become increasingly decentralised and interconnected. This transformation will involve smart products, collaborative robots, low-energy processes, and the seamless integration of manufacturing and logistics systems [128]. Individual products and their components will also be embedded within this digital ecosystem [128–130]. With the expansion of Internet of Things (IoT) technologies, integrated supply chains are becoming a practical reality, enabling data-driven decision-making through real-time information sharing across networks.

Collaboration across the manufacturing ecosystem enables the development of smart factories that are highly efficient and responsive to evolving industry goals [131, 132]. However, smart production systems also entail high energy and resource demands, potentially leading to adverse environmental impacts [131]. The operational efficiencies enabled by advanced computing often require substantial energy inputs to sustain integrated systems, creating unintended compensatory effects. Nevertheless, these impacts can be mitigated through sequentially implemented solutions across the supply chain, aimed at reducing the system-wide environmental footprint.

Moving beyond ad-hoc inter-firm collaborations, extended producer responsibility (EPR) policies can be implemented to hold producers accountable for the environmental impacts of their products at end-of-life. Such policies incentivise improvements in product design, including material reduction, waste minimisation, and enhanced recyclability and reusability [133]. Distributing responsibility across the supply chain can generate multiple benefits for both firms and the environment [134].

Besides inter- and intra-firm collaboration, public policies are key. The industrial symbiosis can be a bridge to meet sustainable development goals (SDGs) and circular economy objectives. The guidelines provided by intergovernmental organisations–such as the UNIDO's Industrial Decarbonization Accelerator [26]–and the European Union–above all, the EU's Net Zero Industry Act [25]–can provide a valuable framework to interpret and navigate the industrial green growth, suggesting policies, strategies, infrastructures, sustainable finance, and practical guidelines to reach these objectives. Following these measures will create new green jobs, income, opportunities, and competitiveness, especially in the energy sector and other critical industries.

Energy production and demand constitute a critical focus for public policy. Rising electricity consumption has significantly increased global demand. However, renewable energy policies often face implementation challenges due to insufficient research on

context-specific barriers. Among the most significant obstacles are policy and political constraints, followed by economic, administrative, geographic, technical, and social factors [64].

Purchasing decisions can play a significant role in reducing a company's carbon footprint. Emissions can be lowered without substantial cost increases by optimising ordering strategies. Collaboration among firms within the same supply chain—focusing on minimising total system costs rather than individual firm costs—can lead to greater overall efficiency and reduced emissions [135]. Although purchasing strategies have considerable impact, focusing on them alone is insufficient,a comprehensive assessment of emissions across all industrial activities is essential.

Globally, the steel and cement industries are among the largest contributors to $CO_2$ emissions, exerting a significant impact on climate change [136–138]. Several countries and economic blocs have already established targets and regulatory frameworks to mitigate the environmental impact of high-emission industries such as steel and cement. The European Union, for instance, implemented its cap-and-trade scheme through Directive 2003/87/EC, which has become a widely adopted model for regulating $CO_2$ emissions. Similar policies have been introduced in India (since 2001) and Brazil (since 2008). China, currently the world's largest emitter of $CO_2$, has also committed to reducing its emissions through the introduction of binding targets, fuel efficiency standards, and increased investment in cleaner technologies [139].

The proposed guidelines can be interpreted through the dual lens of industrial ecology and systems thinking, which together provide conceptual coherence to the framework. From an industrial ecology perspective, guidelines such as eco-efficiency and low-carbon technologies (G6), carbon emission estimation (G7), and carbon analysis in product development (G5) operationalise life-cycle thinking by optimising material and energy flows, minimising waste, and embedding circularity into design and production processes [87, 94].

At the same time, systems thinking underscores that these technical measures must be embedded within broader organisational and inter-organisational structures: collaborative management (G1) and transformative industry behaviour (G2) illustrate the importance of feedback loops, knowledge exchange, and cultural change in scaling climate solutions [84, 85]. Similarly, sustainable energy and carbon capture (G3) and carbon footprint analysis in procurement (G4) exemplify systemic leverage points that require coordinated action across supply chains and governance levels [93, 95].

By grounding the guidelines in these two complementary theories, the framework proposes that decarbonisation strategies address not only technological efficiency but also the systemic, organisational, and cultural transformations required for long-term sustainability in the manufacturing sector.

## 6 Conclusion

This paper has examined the nexus between climate change and the manufacturing sector. Globally, manufacturing remains a major contributor to greenhouse gas emissions, largely due to its reliance on fossil fuels. Addressing these impacts presents significant challenges and demands a multifaceted response. Given the sector's intensive resource use and waste generation, the adoption of circular economy principles—such as reducing resource consumption, reusing materials, and recycling waste—is increasingly

critical. In parallel, the implementation of lean manufacturing techniques can support these efforts by minimising inefficiencies and reducing waste throughout production processes.

The novelty of the paper lies in the fact that it focuses on more than just energy efficiency. It proposes a new framework that directly incorporates circular economy principles into production lines. It shows how tracking resources in real time and turning waste into valuable materials can separate manufacturing growth from its environmental effects. This approach offers a scalable way to achieve a truly sustainable industry.

### 6.1 Policy and practical implications

Based on the new ideas in this paper, several important policy implications arise. Policymakers should go beyond focusing only on carbon regulations. They need to encourage circular and material-efficient production. This means implementing real-time reporting on resource use, providing tax credits for industrial partnerships, and funding research and development for closed-loop technologies. Additionally, procurement policies must focus on products that have proven low material footprints. This comprehensive approach would drive a change from just improving energy efficiency to achieving real resource independence. It would also connect industrial policy with larger climate and circular economy objectives.

Overall, the transition to greener manufacturing demands substantial investment in innovative technologies and sustainable processes. To support this transformation, targeted government incentives and funding mechanisms are essential, both to enhance the attractiveness of green investment and fast-track sector-wide mainstreaming. Strategic collaboration among firms and key stakeholders, including universities, research institutions, and industry associations, will also be essential for sharing costs, driving innovation, and enabling critical knowledge transfer. Collectively, these coordinated efforts can help position the manufacturing sector as a catalyst for climate resilience and long-term sustainable economic growth.

Beyond carbon pricing, governments can speed up the adoption of low-carbon technologies by using focused innovation and demand-side policies. This includes direct public funding for research and development, as well as pilot projects to reduce the risks associated with technologies like green hydrogen or carbon capture. Implementing Green Public Procurement rules for low-carbon materials in infrastructure projects creates immediate market demand. In addition, establishing Product Carbon Standards and Material Passports sets clear technical guidelines and promotes circularity, offering long-term regulatory certainty for investors and producers in these difficult-to-reduce sectors.

Transitioning to climate-compatible manufacturing also depends on a well-prepared workforce, supported by sustained employee training and upskilling investment. In parallel, educational institutions should design relevant curricula and programmes that respond proactively to the evolving competencies demanded by low-carbon and resource-efficient production systems.

It is also important to notice that a fair and effective climate framework must reflect the principle of Common But Differentiated Responsibilities. Developed nations, with their significant historical emissions and greater economic capacity, must take the lead in making deep, absolute emissions cuts. They should also provide substantial financial and

technological support to developing nations. For developing countries, the focus should be on low-carbon development pathways. This aims to separate economic growth from emissions. Their expectations should be linked to improved support, enabling them to industrialize in a clean way and respond to climate impacts. They should not be held to the same immediate absolute reduction targets as developed economies.

### 6.2 Theoretical implications

The paper provides a set of theoretical contributions, such as extending socio-technical transition theory by providing sector-specific decarbonisation pathways; it also sharpens the practical relevance by reframing the seven guidelines into a prioritised Roadmap. The key insights cut across various sectors (e.g., lock-in, supply chain vulnerability, rebound effects), which increases its contribution to the literature.

## 7 Research limitations

This paper has some limitations. First, it focuses specifically on the manufacturing sector and does not examine other climate-relevant sectors, such as transportation and the long-distance movement of goods, which are known to contribute significantly to emissions. Second, the analysis is based on a review of 29 papers, representing a selective rather than comprehensive scope. Nonetheless, the paper offers a valuable contribution to the literature by illustrating how climate change can disrupt supply chains, particularly through its impact on the availability of raw materials and components. It also highlights the importance of diversifying supply sources and developing more localised supply chains, supported by investments in resilient infrastructure and predictive analytics to anticipate and mitigate future disruptions.

### 7.1 Future research proposals

Addressing the challenges presented in this paper is essential not only for mitigating climate change but also for positioning the manufacturing sector as a leader in sustainable and competitive innovation. Further research is needed in areas such as carbon pricing and the design of market-based mechanisms that not only reduce emissions but also drive strategic advantage. In addition, advancing sustainable manufacturing methods and the development of low-carbon products can help set global benchmarks, reducing environmental footprints while fostering long-term industrial leadership.

**Acknowledgements**

Acknowledgments: This study is part of the "100 papers to accelerate the implementation of the UN Sustainable Development Goals" initiative, led by the Inter-University Sustainable Development Research Programme (IUSDRP). This work was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), under the grant 304145/2021-1, and 308354/2021-4, and by the Internal Faculty Start-Up Research Grant of Wenzhou-Kean University Project No. ISRG2023014.

**Author contributions**

Conceptualization, WLF; methodology, WLF, YAA, AG, ISR, TFACS, RA, RLFB, OLGQ, CRPV; validation, WLF, YAA, AG, ISR, TFACS, RA, RLFB, OLGQ, CRPV; formal analysis, WLF, YAA, AG, ISR, TFACS, RA, RLFB, OLGQ, CRPV; writing—original draft preparation, WLF, YAA, AG, ISR, TFACS, RA, RLFB, OLGQ, CRPV, JML; writing—review and editing, WLF, YAA, AG, ISR, TFACS, RA, RLFB, OLGQ, CRPV, JML; supervision, WLF; project administration, WLF.

**Funding**

This study is part of the "100 papers to accelerate the implementation of the UN Sustainable Development Goals" initiative, led by the Inter-University Sustainable Development Research Programme (IUSDRP). This work was supported by the Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq), under the grant 304145/2021-1, and 308354/2021-4, and by the Internal Faculty Start-Up Research Grant of Wenzhou-Kean University Project No. ISRG2023014.

**Data availability**
Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

## Declarations

**Competing interests**
The authors have no conflict of interest to declare. Walter Leal Filho is the Editor-in-Chief of Discover Sustainability and confirms he was not involved in the handling or decision-making of his own submission. Rosley Anholon is an Editorial Board Member of Discover Sustainability and confirms he was not involved in the handling or decision-making of his own submission.

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Received: 6 August 2025 / Accepted: 1 October 2025
Published online: 04 November 2025

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