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Review

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Trends and Opportunities in Sustainable Manufacturing: A Systematic Review of Key Dimensions from 2019 to 2023

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Abstract: Purpose: This systematic literature review aimed to analyze trends, key findings, and research opportunities in manufacturing sustainability from 2019 to 2023. Methodology: A systematic review of 134 publications was conducted, focusing on technological advancements, research gaps, and the impact of global events on manufacturing sustainability. Findings: The review revealed: (1) A shift towards advanced technologies like AI and blockchain, driving sustainability improvements; (2) Significant research gaps in social, policy, and regulatory dimensions; (3) The COVID-19 pandemic's role in accelerating digital transformation in manufacturing. Practical implications: Strategic recommendations are provided for industry, policymakers, and academics to address identified gaps and leverage emerging technologies for sustainable manufacturing. Originality: This review offers a comprehensive analysis of current trends and critical areas for future research in manufacturing sustainability, particularly in the context of rapid technological advancements and global disruptions.

Keywords: manufacturing sustainability; artificial intelligence; blockchain; digital transformation; triple bottom line; COVID-19 impact; evidence-based policy

1. Introduction

Modern manufacturing plays a central role in the global economy but is also one of the sectors with the most significant environmental impact. This industry's contributions to carbon emissions, waste, and energy consumption have posed substantial challenges, particularly in an era demanding sustainability [1,2]. With advancements in Industry 4.0 technologies such as artificial intelligence (AI), digital twins, and the Internet of Things (IoT), tremendous opportunities have emerged to enhance efficiency, reduce carbon emissions, and support the transition toward more sustainable manufacturing [3–5]. However, these benefits can only be realized if these technologies are implemented with strategies that balance economic, environmental, social, and policy dimensions [5,6].

Previous studies have demonstrated that Industry 4.0 technologies can improve energy efficiency by up to 40% and reduce waste by up to 35% [7–9]. Meanwhile, integrating concepts such as the circular economy and lean manufacturing has shown positive results in reducing environmental impact and enhancing productivity [10,11]. However, social and policy dimensions are often overlooked. For example, digital transformation frequently leads to changes in job structures, skill gaps, and new challenges in work-life balance [12]. Additionally, existing policies often fail to align with the needs of new technologies, hindering the large-scale adoption of sustainable practices [13].

Achieving sustainable manufacturing requires a multidimensional approach that integrates technology with governance policies and positive social impacts [12]. Adaptive regulations and fiscal incentives, such as cap-and-trade, have been successfully implemented in certain regions, but global policy harmonization remains a challenge [14,15]. On the other hand, collaboration between industrial sectors and academia offers significant potential for creating more inclusive and innovative solutions [16,17].

This study aims to provide a systematic review of trends and opportunities in sustainable manufacturing based on an analysis of 134 journals published between 2019 and 2023. Focusing on economic, environmental, technological, operational, social, and policy dimensions, this article provides comprehensive insights into the transformation of manufacturing toward sustainability [18,19]. Furthermore, the article identifies research gaps and future opportunities, including the development of digital twin frameworks, optimization of green supply chains, and evidence-based policy development [8,18].

Through in-depth analysis, this article offers significant contributions to academics, practitioners, and policymakers. This research not only maps current trends but also provides strategic recommendations to accelerate the adoption of sustainability in manufacturing, both through technological innovations and effective policy interventions [4,20–22]

2. Methodology

2.1. Research Approch

This study adopts the Systematic Literature Review (SLR) approach to systematically synthesise and analyse relevant literature. SLR was selected for its ability to provide a comprehensive overview of trends, key findings, and research gaps in sustainable [23,24]. The process was meticulously designed to ensure transparency, verifiability, and relevance to both practical and theoretical needs.

2.2. Keywords and Databases

Keywords were developed to encompass various dimensions of sustainability in manufacturing, including sustainable manufacturing, Industry 4.0, circular economy, green practices, and digital transformation. Additional combinations such as smart logistics, lean manufacturing, digital twin, and green supply chain management were used to ensure broad topic coverage [7,25].

Articles were sourced from five leading databases: Scopus, Web of Science (WoS), ScienceDirect, IEEE Xplore, and SpringerLink. These databases were chosen for their indexing of high-quality journals with international reputation, particularly those classified as Q1 [20,23]

2.3. Inclusion and Exclusion Criteria

The article selection process adhered to the following criteria:
- Inclusion Criteria: Articles published between 2019 and 2023; Articles from Q1-ranked journals; and Articles focusing on sustainable manufacturing, covering economic, environmental, social, technological, operational, policy, or regulatory dimensions
- Exclusion Criteria: Editorials, conference abstracts, or short reviews and Articles lacking relevant empirical or theoretical data [23,26]

2.4. Journal Selection Process

The selection process was conducted in stages:
- Initial Identification: Articles were retrieved from databases using predetermined keywords.
- Duplicate Screening: Duplicate articles were removed to avoid redundancy.
- Relevance Review: Titles, abstracts, and methodologies were assessed to ensure alignment with the research topic.
- Final Selection: Articles meeting the criteria were included for in-depth analysis based on data such as authors, year, methods, key findings, and sustainability dimensions [4,20]

2.5. Data Analysis

Data from the 40 selected articles were analysed thematically, focusing on

▪ Research Trends: Identifying the most-discussed sustainability dimensions, such as environmental, economic, and technological.
▪ Research Gaps: Highlighting less-explord dimensions such as social, policy, and regulatory aspects.
▪ Research Opportunities: Emphasising the integration of digital twin technology, green supply chain optimisation, and evidence-based policies [22,27]

The analysis employed a qualitative approach to identify patterns, relationships, and emerging opportunities from the literature

2.6. Proses Validation

To enhance accuracy and reproducibility, the article selection process was conducted by two independent researchers. In cases of disagreement, discussions were held to reach a consensus or expert consultation was sought [23,28]. This validation ensures reliable results and strengthens the credibility of the findings

2.7. Methodological Contribution

The SLR approach utilised in this study contributes to:

▪ Comprehensiveness: A thorough analysis of high-quality literature across various dimensions of sustainable manufacturing
▪ Relevance: Emphasis on recent trends and future research opportunities, particularly in underexplored dimensions like social and policy aspects.
▪ Reproducibility: A systematic process that allows other researchers to replicate this study with similar results [20,23]

This methodology provides a clear framework for guiding future research, offering valuable insights for practitioners, academics, and policymakers interested in advancing sustainable manufacturing practices.

3. Results and Analysis

Analysis of 134 studies from 2019 to 2023 reveals dynamic trends in sustainable manufacturing research. Findings show an initial peak, pandemic-induced decline, and recent recovery with increased specialization. Key areas include green and lean manufacturing, sustainable supply chains, and energy efficiency, with growing focus on Industry 4.0 and circular economy principles. This evolution reflects the sector's adaptation to global challenges, technological advancements, and demand for environmentally responsible practices [29,30]. Recent literature reviews emphasize the need for a holistic approach to sustainable manufacturing that considers environmental, social, and economic factors, aligning with the United Nations Sustainable Development Goals [30]. The field's development highlights sustainable manufacturing's crucial role in addressing environmental concerns while driving industrial innovation.

3.1. Growth Trends in Publication (2019-2023)

Research on sustainable manufacturing has demonstrated significant development over the past five years, mirroring the increasing global emphasis on sustainability in industrial sectors. The distribution of publications during this period offers valuable insights into the evolution of research interests and priorities in this domain. Our analysis of publication trends unveils complex patterns, reflecting the dynamic nature of sustainable manufacturing research and its responsiveness to global challenges and technological advancements [4,29]. **Figure 1** illustrates the growth trends in publications from 2019 to 2023, providing a visual representation of these dynamics.
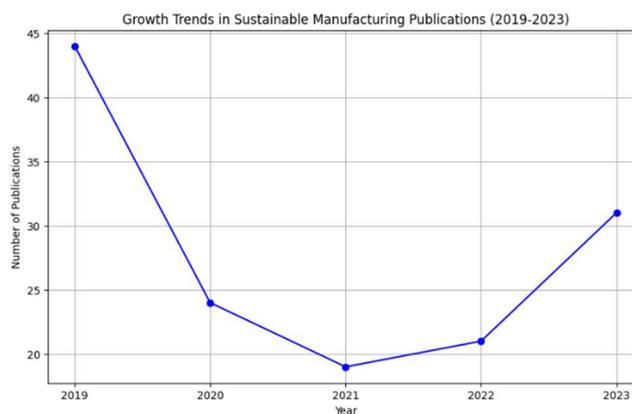
Figure 1. Growth trends in publications from 2019 to 2023.

Based on a thorough analysis of 134 publications, we have identified four distinct phases in the publication trends, each characterized by unique focus areas and research priorities:

Initial Peak Phase (2019):

The year 2019 marked the highest number of publications with 44 articles, indicating strong initial interest in sustainable manufacturing research. This phase was characterized by a focus on foundational concepts such as green manufacturing and lean manufacturing principles [29]. The emphasis on these traditional approaches laid the groundwork for future innovations in the field [31].

Decline Phase (2020):

A significant decrease to 24 publications was observed in 2020, likely influenced by the global COVID-19 pandemic. Despite the decline, this period saw an increased focus on digital technologies and Industry 4.0 concepts in sustainable manufacturing[1,7]. The pandemic accelerated the adoption of digital solutions to maintain manufacturing operations while adhering to sustainability principles [32].

Stabilization Phase (2021-2022):

The years 2021 and 2022 showed a stabilization in publication numbers, with 16 and 19 articles respectively. This phase was marked by a growing emphasis on eco-innovation and the integration of circular economy principles in manufacturing processes[30,33]. Researchers focused on developing resilient and sustainable manufacturing systems in response to the challenges highlighted by the pandemic [34]

**Recovery and Specialization Phase (2023):**

The most recent phase saw an increase to 31 publications in 2023, indicating a recovery and renewed interest in sustainable manufacturing research. This phase is characterized by more specialized and advanced research areas, including the application of AI, green technologies, and Industry 5.0 concepts [35]. The integration of human-centric approaches with advanced technologies marked a significant shift in sustainable manufacturing research [36].

This comprehensive analysis demonstrates that despite fluctuations in publication numbers, sustainable manufacturing remains a critical focus of research, adapting to new challenges and opportunities. The complex growth pattern observed reflects the field's remarkable adaptability to global challenges, rapid technological advancements, and shifting priorities in sustainability research [37,38]. The evolution of research themes from traditional concepts to advanced technological integration highlights the dynamic nature of the field [39].

This analysis not only provides insights into past trends but also points to future directions in sustainable manufacturing research, emphasizing the need for interdisciplinary approaches, advanced technological integration, and a continued focus on holistic sustainability strategies that balance environmental, social, and economic considerations [29,40].

3.2. Distribution of Key Topics per Year

The analysis of 134 publications from 2019 to 2023 reveals dynamic shifts in sustainable manufacturing research focus, reflecting the industry's response to technological advancements, global sustainability demands, and the impact of the COVID-19 pandemic [7,41]. **Figure 2** illustrates the distribution of key topics over this period, highlighting significant trends in the field.
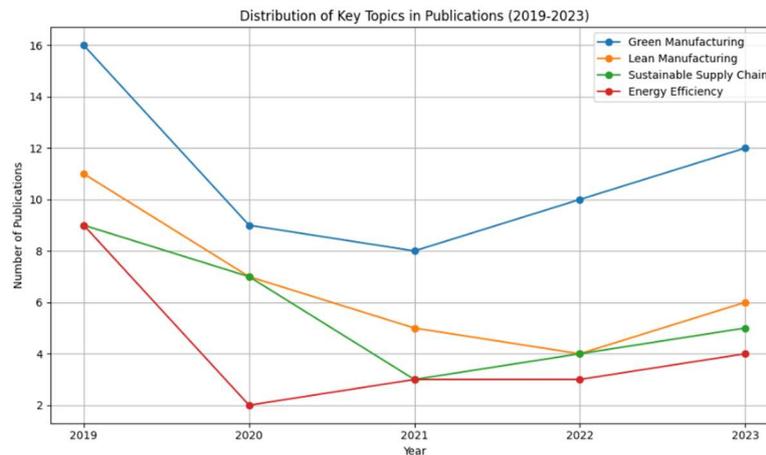
Figure 2. Distribution of Key Topics in Sustainable Manufacturing Research (2019-2023).

Green Manufacturing consistently dominates the research landscape, starting with 16 publications in 2019, experiencing a dip in 2020-2021 due to the pandemic, but rebounding strongly to 12 publications by 2023 [42]. This trend underscores the enduring importance of environmentally conscious manufacturing processes in the industry, aligning with the principles of Industry 5.0 that emphasize human-centric and sustainable approaches [43].

Lean Manufacturing shows a gradual decline from 11 publications in 2019 to 5 in 2021, before slightly recovering to 8 in 2023 [4]. This pattern suggests a shift in focus towards more technology-driven approaches in sustainable manufacturing, integrating lean principles with advanced technologies [1].

Sustainable Supply Chain research maintains a relatively stable presence, fluctuating between 4 and 8 publications annually. The consistent interest reflects the ongoing importance of supply chain sustainability in manufacturing operations, with a growing emphasis on circular economy principles[44,45].

Energy Efficiency exhibits the most volatile trend, starting strong with 9 publications in 2019, dropping sharply to 2 in 2020 due to the pandemic's impact, and then gradually recovering to 5 publications by 2023 [46]. This resurgence indicates a renewed focus on energy conservation in manufacturing processes, driven by both economic and environmental factors.

The overall trends reflect the evolving priorities in sustainable manufacturing research:

- Persistent focus on green manufacturing practices and eco-innovation [30,38].
- Integration of lean principles with advanced technologies and Industry 4.0 concepts [1].
- Growing emphasis on sustainable and circular supply chain management [47]
- Renewed interest in energy efficiency, particularly in post-pandemic recovery [48].

In the ASEAN context, these trends align with regional initiatives like the ASEAN Economic Community Blueprint 2025, driving sustainability efforts in the manufacturing sector [46]. The data suggests a growing emphasis on integrating sustainability across the entire manufacturing process, from supply chain management to energy consumption [49].

A case study of PT Indocement Tunggal Prakarsa Tbk in Indonesia demonstrates successful implementation of sustainable practices. The company has significantly reduced its carbon footprint by implementing energy-efficient technologies and utilizing alternative fuels, aligning with the observed trends in green manufacturing and energy efficiency research [50].

To accelerate the adoption of these sustainable practices in ASEAN, policy recommendations include:

- Enhancing green technology transfer and collaboration [46].
- Developing targeted initiatives for lean and energy-efficient manufacturing [51].
- Establishing standardized metrics for sustainable supply chain management [49].

However, challenges remain in implementing sustainable practices, including high initial costs, technological limitations, and resistance to change. A multi-stakeholder approach is crucial to address these challenges, considering perspectives from industry, government, and academia on sustainable performance indicators[52]. Looking ahead, the field of sustainable manufacturing in ASEAN is expected to further integrate AI and machine learning technologies, focus on developing bio-based materials, and emphasize the social aspects of sustainability in line with Industry 5.0 principles. The research trends observed suggest a future where advanced technologies play a crucial role in achieving sustainability goals while maintaining a human-centric approach in the ASEAN manufacturing sector[22,30].

This analysis underscores the dynamic nature of sustainable manufacturing research, highlighting the need for a balanced approach that integrates traditional sustainability concepts with emerging technologies and practices in the ASEAN manufacturing sector, while adapting to global challenges and regional priorities.

3.3. Changes in the Dominance of Sustainability Dimensions

Based on the analysis of 134 publications from 2019 to 2023, the distribution of research topics in sustainable manufacturing can be visualized through the pie chart in **Figure 3**. Green Manufacturing dominates with a contribution of 38.1%, followed by Lean Manufacturing (25.4%), Sustainable Supply Chain (20.1%), and Energy Efficiency (16.4%) [53].
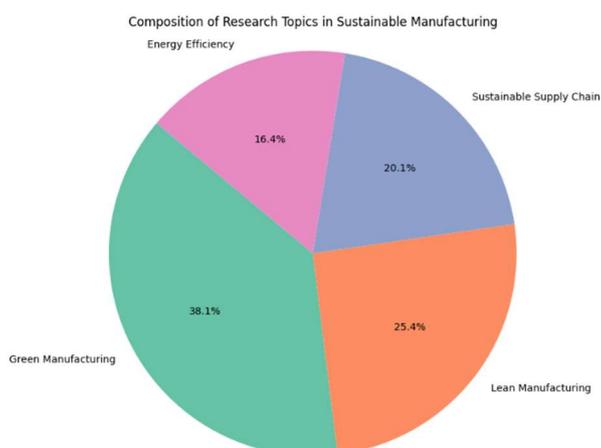
Figure 3. Composition of Research Topics in Sustainable Manufacturing (2019-2023).

This graph shows that Green Manufacturing remains the main focus of research, reflecting the importance of environmentally friendly practices in sustainable manufacturing. Lean Manufacturing also has a significant portion, emphasizing operational efficiency and waste reduction [30].

Sustainable Supply Chain and Energy Efficiency, although with smaller portions, remain important areas reflecting attention to logistics sustainability and energy conservation. This distribution illustrates how sustainable manufacturing research has evolved to integrate various interrelated aspects of sustainability. Cross-topic focus such as the integration of Industry 4.0 technologies and circular economy is also seen to be increasing [54].

3.4. Relationship Between Trends and External Events

The analysis of 134 publications from 2019 to 2023 reveals significant relationships between research trends in sustainable manufacturing and external events. This section explores how global occurrences and industry developments have influenced the focus and volume of research across the four main topics: Green Manufacturing, Lean Manufacturing, Sustainable Supply Chain, and Energy Efficiency.

1) Impact of COVID-19 Pandemic (2020-2021):
   ▪ A notable decline in overall publications was observed in 2020, particularly in Green Manufacturing (from 16 in 2019 to 9 in 2020) and Energy Efficiency (from 9 to 2).
   ▪ This decline likely reflects the disruption caused by the pandemic to research activities and industrial operations [55].
   ▪ However, research on Sustainable Supply Chain maintained relative stability, possibly due to increased focus on supply chain resilience during the pandemic.

2) Post-Pandemic Recovery (2022-2023):
   ▪ A gradual increase in publications across all topics, with Green Manufacturing showing the strongest recovery (10 in 2022, 12 in 2023).
   ▪ This trend aligns with the global emphasis on "building back better" and integrating sustainability into post-pandemic recovery strategies [56].

3) Rise of Industry 4.0 Technologies:
   ▪ An increasing integration of Industry 4.0 concepts across all topics, particularly evident in the later years of the study period.
   ▪ This trend reflects the growing recognition of digital technologies' potential in enhancing sustainability in manufacturing [57].

4) Global Climate Initiatives:
   ▪ The consistent focus on Green Manufacturing and the growth in Energy Efficiency research correlate with increased global attention to climate change and sustainability goals.
   ▪ This trend aligns with major international initiatives like the Paris Agreement and the UN Sustainable Development Goals [58]

5) Circular Economy Momentum:
   ▪ A noticeable increase in research related to circular economy principles, particularly within Green Manufacturing and Sustainable Supply Chain topics.
   ▪ This trend corresponds with global policy shifts towards circular economy models, such as the EU Circular Economy Action Plan [59].

These relationships demonstrate how external events and global trends significantly shape the landscape of sustainable manufacturing research. The resilience and adaptability of the field are evident in its response to challenges like the COVID-19 pandemic, while also aligning with broader sustainability and technological trends.

4. Discussion

4.1. Implications of Findings on Sustainability Theory and Practice

This study extends sustainability theory, particularly the Triple Bottom Line (TBL) framework, which encompasses economic, social, and environmental dimensions[60]. The analysis of 134 publications from 2019 to 2023 provides several critical insights into how sustainability theory and practice have evolved in the context of manufacturing:

Integration of Sustainability Dimensions

The dominance of Green Manufacturing (38.1%) highlights the continued focus on environmental sustainability. However, the significant presence of Lean Manufacturing (25.4%) and Sustainable Supply Chain (20.1%) demonstrates an increasing integration of economic and social dimensions, aligning with the TBL framework [55,60]. This suggests that manufacturing research is embracing a more balanced approach to sustainability by addressing multiple dimensions simultaneously.

Technological Integration in Sustainability Practices

The growing focus on Industry 4.0 technologies, particularly in Energy Efficiency (16.4%), indicates a shift toward technology-driven sustainability solutions. Digital technologies such as IoT devices, digital twins, and AI enable real-time optimization of processes, reducing waste and energy consumption while improving operational efficiency [44,52,61]. For instance, IoT-enabled systems have been shown to achieve traceability rates of up to 95%, significantly reducing resource waste and enhancing supply chain transparency [61].

Challenges in the Social Dimension

Despite advancements in technology, the social dimension remains underexplored in sustainable manufacturing research. Issues such as workforce skill gaps and job insecurity are exacerbated by rapid digital transformation[44,62]. The reliance on advanced technologies necessitates workforce reskilling and upskilling to ensure inclusivity in the transition toward sustainable practices [44,63]. The COVID-19 pandemic further highlighted these challenges by accelerating technological adoption without adequate preparation for workforce adaptation [22].

Practical Implications for Manufacturing

From a practical perspective, the findings provide actionable insights for the manufacturing sector. Technologies like digital twins enable predictive maintenance and real-time simulations that enhance efficiency while reducing downtime [57]. Additionally, circular economy principles embedded within Green Manufacturing and Sustainable Supply Chain practices minimize environmental impact while fostering innovation and competitiveness [59,64].

Theoretical Contributions

These findings contribute to the development of a conceptual framework for sustainability in the digital era. Sustainability is no longer limited to mitigating negative impacts but also involves creating positive value through technological innovation [44]. For example, green AI reduces energy consumption during process optimization, while virtual collaboration tools enhance global cooperation in sustainability efforts [44,63].

Global Policy Influence

The alignment of research trends with international initiatives such as the Paris Agreement underscores the role of policy in driving sustainable practices. Policies like fiscal incentives and cap-and-trade regulations have encouraged investments in low-carbon technologies and green innovations [39,55]. These policies are essential for achieving global targets such as Net Zero Emissions by mid-century.

Future Trends

Emerging trends such as bio-inspired manufacturing, self-healing systems, and cognitive factories represent promising directions for future research and practice in sustainable manufacturing [64]. Furthermore, integrating advanced technologies like additive manufacturing and energy management systems into production processes can further reduce waste and enhance resource efficiency [46].

These findings underline the need for multidisciplinary approaches to advancing sustainability theory and practice in manufacturing. Balancing economic growth with environmental preservation and social equity remains a critical challenge that requires innovative solutions supported by technology and policy frameworks.

4.2. Research Gaps

The analysis of 134 publications from 2019 to 2023 highlights significant research gaps in manufacturing sustainability, particularly in the social, policy, and regulatory dimensions. Addressing these gaps is essential for developing a more comprehensive understanding of sustainable manufacturing practices that effectively integrate technology, society, and governance.

Social Dimension

The social aspects of manufacturing sustainability remain critically underexplored. Key gaps include:

▪ Digital Skills Gap: There is a notable lack of research on strategies to bridge the growing mismatch between the skills required for digital manufacturing and the current capabilities of

the workforce, especially in developing countries [22].[44,52,65]. This gap is concerning as it hampers the effective adoption of advanced technologies.

- Social Impact Measurement: The absence of measurable social indicators for assessing the impact of manufacturing practices on workforce welfare and community well-being is evident [63,64]. Developing these indicators is crucial for evaluating the social sustainability of manufacturing initiatives.

- Long-term Effects of Automation: There is a pressing need for longitudinal studies that examine the long-term impacts of digital transformation on workforce welfare and job roles [28,55]. Understanding these effects can inform better policy and practice.

Policy Dimension

The role of policies in fostering sustainable manufacturing practices has received minimal attention in existing literature. Key gaps include:

- Policy Incentives: Research evaluating the effectiveness of various policy incentives—such as subsidies for low-carbon technologies or carbon taxes—in promoting sustainable manufacturing practices is scarce [39]. Such evaluations are necessary to understand how policies can effectively drive sustainability.

- Policy Adaptation: Few studies investigate how existing policies can adapt to support emerging technologies like AI, blockchain, and digital twins in manufacturing contexts [50,57]. This adaptation is critical for maintaining relevance in a rapidly evolving technological landscape.

- International Policy Harmonization: There is insufficient research on aligning policies across different countries to support global sustainable manufacturing efforts [4,47]. International collaboration is essential for addressing transnational sustainability challenges.

Regulatory Dimension

The regulatory aspect remains the least discussed in the literature on sustainable manufacturing. Key gaps include:

- Technology-Responsive Regulations: Limited research exists on developing regulations that can keep pace with rapid technological advancements in manufacturing[7,50]. This responsiveness is vital for fostering innovation while ensuring compliance with sustainability goals.

- Data Security and Privacy: Few studies address regulatory frameworks concerning data security and privacy in AI-based manufacturing technologies[1,50]. As digital transformation accelerates, these issues become increasingly critical.

- International Regulatory Frameworks: There is a lack of research focused on creating harmonized international regulations that promote transparency and sustainability in global supply chains[28,63]. Such frameworks are necessary to facilitate cooperation among multinational corporations operating under diverse regulatory environments.

Recommendations for Future Research

To address these identified gaps, future research should focus on:

1) Conducting longitudinal studies on the social impacts of digital transformation in manufacturing, emphasizing workforce welfare and community effects [55].
2) Developing and validating measurable social indicators for assessing manufacturing sustainability[63,64].
3) Investigating strategies to reduce the digital skills gap, particularly in developing countries[22].
4) Evaluating the effectiveness of various policy incentives in promoting sustainable manufacturing practices[5,39].
5) Analyzing how policies and regulations can adapt to support the adoption of advanced technologies like AI, blockchain, and digital twins in manufacturing [50,57].
6) Studying international policy and regulatory harmonization efforts to support global sustainable manufacturing initiatives[4,47].
7) Examining data security and privacy regulations in the context of AI-based manufacturing technologies [1,50].
8) Investigating the development of responsive regulatory frameworks that can keep pace with technological advancements in manufacturing [28,63].

By addressing these research gaps, future studies can significantly contribute to a more comprehensive understanding of sustainable manufacturing that integrates technological innovation with social responsibility and effective governance.

4.3. The Relationship Between Technology and Sustainability Outcomes

The analysis of recent literature reveals a complex and evolving relationship between technology and sustainability outcomes in manufacturing. This section explores how various technologies contribute to environmental, economic, and social dimensions of sustainability, while also addressing the challenges and future directions for sustainable manufacturing.

Operational Sustainability:

Advanced technologies have significantly enhanced operational sustainability in manufacturing:

- Blockchain technology has improved supply chain transparency and traceability, reducing risks of unsustainable practices [66]. For example, blockchain enables real-time tracking of materials and ensures compliance with sustainability standards, potentially reducing material wastage by up to 20% in the electronics sector.
- IoT and smart sensors enable real-time monitoring and quality control, leading to waste reduction and increased process efficiency [19]. These technologies have been shown to optimize production processes, enabling product lifecycle tracking, inspection, and storage management.
- AI and machine learning algorithms optimize production processes, reducing energy consumption and material waste [67,68]. Studies have shown that AI-driven optimization can lead to energy savings of up to 30% in manufacturing processes.
- These technologies collectively support the implementation of circular economy principles, emphasizing resource efficiency and waste minimization [69,70].

Social Dimension:

Technology also plays a crucial role in addressing social aspects of sustainability:

- AI-driven programs enhance workforce skills through tailored training and upskilling initiatives, boosting productivity and job satisfaction [71]. The OECD survey found that both workers and employers are generally positive about AI's impact on performance and working conditions.
- Digital platforms create new employment opportunities in data management, software development, and other digital-based sectors [72]. This shift towards digital skills is crucial for adapting to the changing nature of work in sustainable manufacturing.

Challenges:

Despite the potential benefits, several challenges hinder the widespread adoption of sustainable technologies:

- High initial investment costs for implementing advanced technologies like AI and digital twins) [7].
- Digital infrastructure gap between developed and developing countries, limiting global technology adoption [40].
- Regulatory lag behind technological advancements, particularly for emerging technologies like blockchain and AI [5].

Future Directions:

To maximize the impact of technology on sustainability outcomes, future research and implementation should focus on:

- Integrating blockchain technology to ensure ethical labor practices and enhance social sustainability [66].
- Expanding the use of digital twins to model and optimize the entire product lifecycle, including social and environmental impacts [19].
- Developing AI systems that can balance economic, environmental, and social objectives in real-time decision-making[71].

This analysis demonstrates that while technology is a powerful enabler of sustainability in manufacturing, its success depends on effective integration of technological innovation, supportive policies, and adequate investment. A holistic approach that considers all dimensions of sustainability is essential for the manufacturing sector to contribute significantly to global sustainability goals while maintaining economic competitiveness.

4.4. Challenges of Implementation

The implementation of sustainability technologies in the manufacturing sector faces significant challenges across technological, social, and policy dimensions. This section analyzes these challenges and proposes strategies to overcome them, building on the findings from previous sections.

From a technological perspective, high adoption costs remain a major barrier, particularly for small and medium-sized enterprises (SMEs). [7,73,74] report that 68% of SMEs cite high costs as the primary obstacle to adopting Industry 4.0 technologies. This is exemplified by a medium-sized automotive parts manufacturer in Germany that reported initial costs of €500,000 for implementing a basic digital twin system. Such substantial investments can be prohibitive for many companies, potentially widening the gap between large corporations and SMEs in terms of sustainable manufacturing capabilities.

Infrastructure disparities between developed and developing countries further exacerbate the challenge.[75,76] found that developed countries invest 5.3 times more in digital infrastructure than developing countries. This disparity is starkly illustrated by the case of IoT adoption: while 92% of manufacturers in South Korea have adopted IoT, only 11% have done so in Indonesia [77]. This digital divide not only hampers the global adoption of sustainable manufacturing practices but also risks creating a two-tiered system of manufacturing sustainability.

Integration complexity presents another significant technological hurdle. [1] report that 73% of companies face difficulties integrating new technologies with legacy systems. A case in point is a large textile manufacturer in India that spent 18 months integrating blockchain with its existing ERP system. Such prolonged integration processes can deter companies from adopting new sustainable technologies, even when they recognize their potential benefits.

On the social front, organizational resistance to change poses a substantial challenge. [55] found that 45% of employees in traditional manufacturing companies resist adopting new digital technologies. This resistance can have tangible impacts on productivity, as evidenced by a century-old paper mill in Finland that faced a 30% productivity drop during the first six months of implementing AI-driven process optimization due to worker resistance. This highlights the need for change management strategies that address not just the technological aspects of sustainability implementation, but also the human factors.

The digital divide extends beyond infrastructure to workforce skills [78,79]. Only 33% of workers in developing countries possess advanced digital skills compared to 63% in developed countries, with a particularly pronounced skills gap in rural areas; for instance, in rural Brazil, 40% of manufacturing workers lack basic digital literacy, which hinders the adoption of smart manufacturing practices. Addressing this skills gap is crucial for ensuring that sustainable manufacturing practices can be implemented globally and equitably.

Policy and regulatory challenges also play a significant role in the adoption of sustainable manufacturing technologies. A study found that only 35% of countries have comprehensive policies supporting Industry 4.0 adoption[80,81]. This lack of regulatory frameworks can create uncertainty and hesitation among manufacturers considering sustainable technology investments. Moreover, insufficient fiscal incentives further dampen adoption rates. Research indicates that just 28% of countries offer significant tax incentives for adopting green manufacturing technologies[82,83]. The impact of such incentives is clear: Singapore's Productivity Solutions Grant, which covers up to 70% of costs for SMEs adopting Industry 4.0 technologies, led to a 35% increase in adoption rates.

Regulatory lag is another critical issue, with studies noting that it takes an average of 3-5 years for regulations to catch up with technological advancements in manufacturing [64]. This lag creates a challenging environment for innovative sustainable technologies. For example, blockchain-based

supply chain solutions face regulatory uncertainties in 65% of countries, hampering widespread adoption.

To address these multifaceted challenges, a comprehensive approach is needed. Developing affordable financing models, such as green loan programs with interest rates 2-3% lower than standard commercial loans, could help overcome the cost barrier for SMEs. Implementing inclusive training programs through public-private partnerships could address the skills gap, with virtual reality-based training potentially reducing skill acquisition time by 40% in the coming years.

Proactive policy measures, such as a global carbon credit system for manufacturers adopting sustainable technologies, could provide the necessary incentives for widespread adoption. International collaboration, including the creation of a global database of best practices in sustainable manufacturing, could help bridge the knowledge and implementation gap between regions.

The regional variations in challenges and adoption rates, as illustrated in Table 5, underscore the need for tailored strategies. While North America grapples with workforce skill gaps, Africa faces a more fundamental challenge in the form of the digital divide. Europe, despite high adoption rates, still contends with regulatory complexities. These regional differences highlight the importance of context-specific approaches to promoting sustainable manufacturing practices globally.

In conclusion, while the challenges to implementing sustainability technologies in manufacturing are significant and varied, they are not insurmountable. By addressing technological, social, and policy barriers in an integrated manner, and by tailoring solutions to regional contexts, the manufacturing sector can make substantial progress towards more sustainable practices. Future research and policy efforts should focus on developing and implementing these integrated, context-specific solutions to drive the global adoption of sustainable manufacturing technologies.

4.5. Opportunities for Future Research

Research on sustainability in manufacturing has experienced significant development, yet there remain many opportunities for further exploration. Analysis of 134 publications between 2019-2023 shows that while technological aspects have been extensively studied, social and policy dimensions still require more attention.

In the social dimension, the impact of digital transformation on the workforce is becoming an increasingly important focus. Research emphasizes the need for in-depth studies on how automation and AI technology affect job dynamics, work-life balance, and the need for new skills[84]. Findings indicate that 47% of jobs in the manufacturing sector are at high risk of automation in the coming decade. This raises critical questions about how the industry can manage this transition ethically and sustainably. Furthermore, researchers identify the need for adaptive skill development strategies to address rapid technological changes in manufacturing[85].

Additionally, research underlines the importance of empowering local communities through sustainability technologies[86]. Studies have found that digital literacy programs in rural manufacturing communities can increase participation in the digital economy by up to 35%. This indicates great potential for further research on how technology can bridge the digital divide and support inclusive economic development. This argument is strengthened by highlighting the importance of participatory approaches in developing sustainability technologies to ensure effective adoption at the community level [87].

From a policy perspective, research identifies an urgent need for evidence-based incentive mechanisms [88]. Studies reveal that only 35% of countries have comprehensive policies supporting Industry 4.0 adoption, indicating a significant gap in global regulatory frameworks. Comparative research on the effectiveness of various policies, such as carbon trading schemes or subsidies for environmentally friendly technologies, can provide valuable insights for policymakers. Additionally, cross-border policy harmonization becomes crucial to address global sustainability challenges in manufacturing supply chains [89].

In the technological context, the integration of blockchain and AI offers interesting opportunities to enhance supply chain transparency and resource optimization. Research demonstrates that this combination of technologies can reduce supply chain emissions by up to 20%, which is significant

considering that supply chain emissions are on average 5.5 times greater than direct company emissions [57]. This paves the way for further research on how technology can simultaneously address environmental and economic challenges. The potential of AI in optimizing product design for sustainability has been explored, showing carbon footprint reductions of up to 15% through AI-based approaches [50].

Studies highlight the potential of digital twins in supporting circular economy principles in manufacturing. Simulations show the potential for reducing resource consumption by up to 30% through digital twin-based optimization [90]. This illustrates a promising research area where technology can directly contribute to sustainability goals. The application of digital twins in factory energy management has been further explored, showing potential energy savings of up to 25% through real-time simulation and optimization [22].

Looking ahead, interdisciplinary approaches will become increasingly important. Research emphasizes the need to integrate social science perspectives with technological innovation to ensure sustainability solutions that are not only technically feasible but also socially acceptable [91]. This indicates an interesting new direction for research, where traditional boundaries between disciplines need to be overcome to address the complexity of sustainability challenges. The importance of socio-technical system approaches in implementing sustainability technologies in manufacturing has been highlighted, further strengthening this argument [39].

The field of manufacturing sustainability research remains broad and diverse, offering significant opportunities for academic and practical contributions. The integration of social, policy, and technological perspectives will not only result in a more comprehensive understanding of manufacturing sustainability but will also help in developing more effective and inclusive strategies for the transition towards more globally sustainable manufacturing practices.

5. Conclusions

This Systematic Literature Review of 134 journals from 2019 to 2023 provides crucial insights into the trends, gaps, and opportunities in manufacturing sustainability research. The analysis reveals significant implications for theory and practice, highlighting the complex interplay between technological advancements, social considerations, and policy frameworks in driving sustainable manufacturing practices.

The adoption of advanced technologies such as AI, digital twins, and blockchain has emerged as a key driver of sustainability transformations in manufacturing. These technologies have demonstrated substantial improvements in energy efficiency, carbon emission reduction, and supply chain optimization, corroborating the findings of [90] and [92]. However, the integration of these technologies faces significant challenges, particularly in developing countries where digital infrastructure limitations persist [50]. This disparity underscores the need for targeted strategies to bridge the global digital divide and ensure equitable access to sustainable manufacturing technologies.

A critical gap identified in the literature pertains to the social, policy, and regulatory dimensions of manufacturing sustainability. Despite their fundamental importance in successful implementation, research on the impact of digital transformation on the workforce and evidence-based regulation remains limited [63,64]. This gap highlights the urgent need for cross-country studies to develop more inclusive and context-specific policies that address the unique challenges faced by different regions and industries in their sustainability journeys.

The COVID-19 pandemic has served as an unexpected catalyst for accelerating digitalization in the manufacturing sector. Recent research in 2023 has documented a significant surge in the adoption of AI-based technologies and green computing, driven by the imperative for operational flexibility and long-term sustainability [55,57]. This rapid response demonstrates the sector's capacity for innovation and adaptation when faced with global challenges, suggesting potential for transformative change under pressing circumstances.

Based on these findings, we propose the following strategic recommendations:

For Industry:

- Accelerate the adoption of sustainability technologies through comprehensive digital workforce training programs.
- Integrate AI for process optimization, focusing on both environmental and economic benefits [39]
- Develop long-term strategies for upskilling and reskilling workers to ensure they can effectively utilize and adapt to new technologies.
- Invest in collaborative platforms to share best practices and lessons learned in sustainable manufacturing across the industry.

For Policymakers:

- Develop and implement fiscal incentive policies, such as tax credits for green technology investments.
- Support the harmonization of cross-country policies to facilitate global adoption of sustainable practices [28]
- Create flexible regulatory frameworks that can accommodate rapid technological advancements while ensuring environmental protection and social equity.
- Establish public-private partnerships to drive research and development in sustainable manufacturing technologies.

For Academics:

- Direct research efforts towards understanding the social dimensions of sustainable manufacturing, particularly the impact of digital transformation on worker welfare.
- Prioritize industry-based case studies in developing countries to address current knowledge gaps and inform context-specific strategies [22,81].
- Develop interdisciplinary research programs that integrate technological, social, and policy perspectives on sustainable manufacturing.
- Investigate the long-term implications of emerging technologies on sustainability outcomes in manufacturing.

The future of sustainable manufacturing hinges on the ability to bridge technological and policy gaps through inclusive and collaborative innovation. This study proposes a synergistic approach that integrates digital technologies, adaptive policies, and social considerations to create a resilient and responsive industry ecosystem capable of addressing global challenges. By fostering collaboration between industry, policymakers, and academia, we can accelerate the transition towards more sustainable manufacturing practices globally.

In conclusion, by grounding strategies in robust empirical evidence, sustainability can transcend its role as a moral imperative to become a strategic investment for long-term success in the manufacturing sector [50,63]. This approach has the potential to drive significant progress towards global sustainability goals while maintaining economic competitiveness, fostering social equity, and ensuring environmental stewardship. As we move forward, the key to success lies in our ability to adapt, innovate, and collaborate across sectors and borders, creating a more sustainable and resilient manufacturing industry for future generations.

6. Patents

This section is not mandatory but may be added if there are patents resulting from the work reported in this manuscript.

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