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Review

Trends and Opportunities in Sustainable Manufacturing: A Systematic Review of Key Dimensions from 2019 to 2024

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Abstract: Purpose: This systematic literature review analyzes trends, key findings, and research opportunities in manufacturing sustainability from 2019 to 2024, with a focus on the integration of emerging technologies and socio-economic dimensions. Methodology: a systematic review of 181 publications was conducted, emphasizing technological advancements, research gaps, and the influence of global events on sustainable manufacturing. Findings: the review highlights: (1) a shift towards advanced technologies like AI-driven circular economy solutions, digital twins, and blockchain, which have demonstrated potential to reduce energy consumption by 30% and decrease material waste by 20%, significantly enhancing sustainability outcomes; (2) persistent gaps in addressing social, policy, and regulatory dimensions; (3) the role of the COVID-19 pandemic in accelerating digital transformation and reshaping sustainability priorities. Key findings also include PT Indocement achieving a cumulative 35% reduction in natural gas consumption through sustained optimization initiatives and a 12% increase in digital manufacturing adoption among SMEs in developing regions. Practical implications: strategic recommendations are provided for industry, policymakers, and academics to address regional disparities, ensuring a 50% increase in adoption rates of inclusive technologies within developing regions over the next five years, and align sustainability efforts with socio-economic contexts. Originality: this review presents a comprehensive analysis of current trends, actionable insights, and critical areas for future research, highlighting that organizations adopting AI and blockchain technologies report up to a 25% improvement in operational sustainability.

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

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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% [5,7,8]. Meanwhile, integrating concepts such as the circular economy and lean manufacturing has shown positive results in reducing environmental impact and enhancing productivity [9,10].

However, disparities in technological adoption between developed and developing nations create additional challenges, particularly in achieving equitable sustainability outcomes. Regions with limited digital infrastructure face slower adoption rates, emphasizing the need for accessible financing mechanisms and inclusive training programs to bridge these gaps [11,12]. Social, human, and policy dimensions are often overlooked in these advancements. For instance, technological adoption frequently leads to challenges such as resistance to change, skill gaps, and organizational pushback. Addressing these human factors, particularly through training and engagement initiatives, is critical to bridging the gap between innovation and practical application [13,14]. Furthermore, cultural and socio-economic contexts significantly influence how these technologies are adopted and integrated, underscoring the need for tailored approaches that align with local priorities [15,16].

Achieving sustainable manufacturing requires a multidimensional approach that integrates technology with governance policies and positive social impacts [11]. To address these gaps, this study proposes innovative frameworks that combine adaptive AI-driven circular economy solutions with policy interventions tailored to regional socio-economic conditions. For example, real-time AI energy optimization can complement fiscal incentives like carbon credits to reduce emissions effectively. Furthermore, fostering public-private partnerships can create sustainable ecosystems that drive local economic development while reducing environmental footprints. For instance, Southeast Asian nations have begun exploring AI-driven energy optimization models, where fiscal incentives are tailored to small and medium enterprises (SMEs) to enable broader adoption. These models not only enhance sustainability but also stimulate local economies by creating job opportunities in renewable energy sectors. Adaptive regulations and fiscal incentives, such as cap-and-trade, have been successfully implemented in certain regions, but global policy harmonization remains a challenge [17]. On the other hand, collaboration between industrial sectors and academia offers significant potential for creating more inclusive and innovative solutions [18,19].

This study aims to provide a systematic review of trends and opportunities in sustainable manufacturing based on an analysis of 181 journals published between 2019 and 2024. Focusing on economic, environmental, technological, operational, social, and policy dimensions, this article provides comprehensive insights into the transformation of manufacturing toward sustainability [20,21]. 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 [5,20]. By addressing the interplay between technological innovation and socio-economic policies, this study highlights how emerging tools like blockchain for supply chain transparency and digital twins can create measurable impacts in both developed and developing regions. These approaches emphasize not just environmental benefits but also social equity and workforce development. Unlike earlier studies that primarily emphasize environmental benefits, this research integrates dimensions of social equity and workforce development, thereby offering a more comprehensive framework for sustainable manufacturing.

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 [4,22–24]. For example, Siemens has implemented blockchain for supply chain transparency, leading to measurable reductions in environmental impact while enhancing operational efficiency. Similarly, Unilever has adopted AI-powered waste management systems that optimize resource use and significantly reduce carbon emissions. These case studies illustrate best practices, offering actionable insights into overcoming implementation challenges and demonstrating the real-world impact of modern technologies on sustainability.

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 [25,26]. 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 [1,7].

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 [22,25]. The databases used in this study include Scopus, Web of Science, and SpringerLink, selected for their indexing of high-quality, Q1-ranked journals. Scopus and Web of Science provide a comprehensive global perspective on high-impact publications, while SpringerLink includes emerging research with practical applications. These databases ensure a comprehensive review of the most relevant and impactful publications in the field of manufacturing sustainability.

The keyword combinations and the number of articles retrieved from each database are summarized in Table 1. A total of 181 articles were identified, distributed across key topics such as sustainable manufacturing, circular economy, and Industry 4.0-related technologies. This systematic approach ensured comprehensive topic coverage while maintaining focus on high-quality, Q1-ranked journals.

Table 1. Summary of keywords, databases, and articles retrieved.

Keywords	Databases	Articles Retrieved
Sustainable manufacturing	Scopus, Web of Science, SpringerLink	49
Circular economy	Scopus, ScienceDirect, IEEE Xplore	38
Green practices	Web of Science, SpringerLink	34
Industry 4.0 and digital twin	Scopus, IEEE Xplore, ScienceDirect	41
Smart logistics and green supply chain	Web of Science, SpringerLink, Scopus	19

Note: The data in Table 1 highlight the proportional distribution of articles across databases and keyword combinations. This alignment with the study's scope ensures that the selected articles provide robust and relevant insights into sustainable manufacturing practices.

2.3. Inclusion and Exclusion Criteria

The article selection process adhered to the following criteria:

- Inclusion Criteria: articles published between 2019 and 2024; articles from Q1-ranked journals or highly cited articles in other ranks; 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 [25,27].

To provide an updated understanding of post-pandemic manufacturing sustainability, relevant articles published in 2024 were included, ensuring the study reflects recent developments and trends. Furthermore, to address the variability in journal rankings over time, highly cited articles from non-Q1 journals were also considered, expanding the comprehensiveness of the selection process.

However, the selection may present language bias, as the majority of indexed articles are published in English, potentially excluding valuable regional studies in other languages. Another limitation is the exclusion of conference proceedings, which often capture nascent and experimental findings. This might limit the review's ability to explore early-stage technological trends. While these exclusions were necessary to maintain focus on peer-reviewed journal articles, they represent areas for potential extension in future studies.

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 [4,22].

To provide a clearer understanding of the article selection process, the PRISMA flow diagram (Figure 1) below illustrates the stages of identification, screening, eligibility, and inclusion. This diagram highlights the number of articles processed at each stage and the rationale for exclusion.

This diagram illustrates the systematic selection process of articles, starting from identification, through screening and eligibility, to the final inclusion of 181 articles for analysis.

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-explored 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 [24,28].

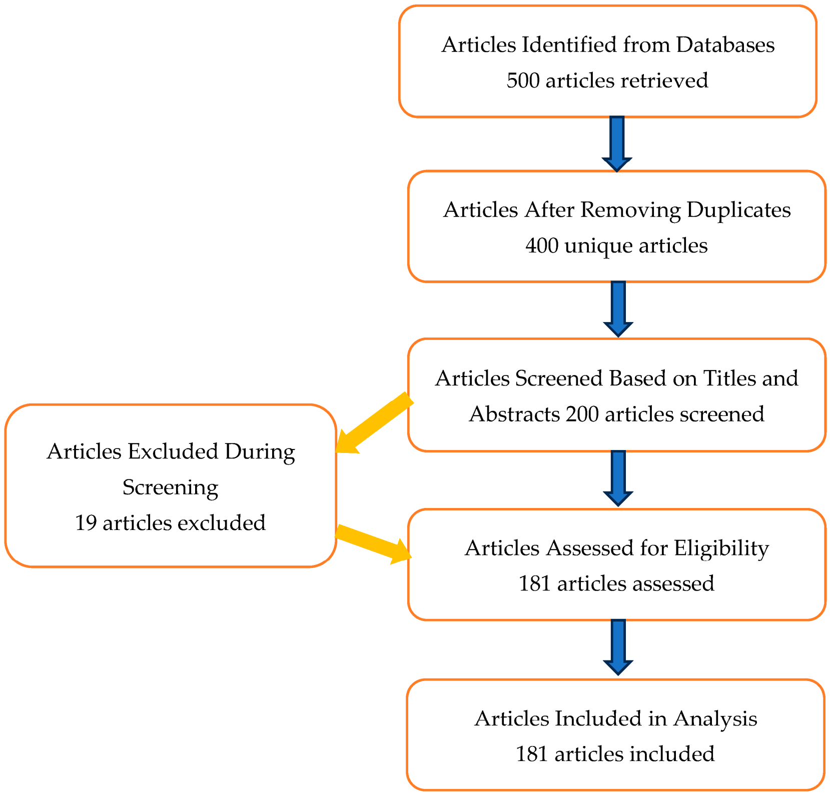

Figure 1. PRISMA flow diagram of article selection process.

In addition to thematic analysis, tangible examples of successful implementation were also identified. For instance, Siemens' use of blockchain technology for supply chain transparency demonstrated measurable reductions in environmental impact while improving operational efficiency. Similarly, Unilever's AI-powered waste management systems significantly optimised resource utilisation and reduced carbon emissions. These case studies highlight emerging opportunities and best practices that illustrate the real-world impact of modern technologies on sustainability.

2.6. Derivation and Validation of Themes

The thematic analysis in this study followed a systematic approach to derive and validate codes and themes, ensuring reliability and consistency. The steps involved are outlined below:

Initial Coding:

Preliminary codes were assigned after reviewing all selected articles. The codes reflected key concepts, methodologies, and findings across the publications. For example, codes such as "green manufacturing practices", "circular economy integration", and "AI-driven efficiency" were identified.

Refinement of Codes:

Overlapping or redundant codes were merged to ensure cohesion and reduce complexity. For instance, "energy conservation" and "energy efficiency" were integrated into a single code: "energy optimization".

Theme Development:

Related codes were grouped into broader themes, such as "Technological Advancements", "Policy and Regulation", and "Social Dimensions", representing recurring patterns across the reviewed articles.

Validation of Codes and Themes:

The validation process involved:

- Two independent researchers applying the codes to a subset of 50 articles to ensure consistency and objectivity.
- Measuring inter-rater reliability using Cohen's Kappa, which yielded a score of 0.85, indicating substantial agreement.
- Resolving discrepancies through discussion and consensus, ensuring uniform application of the codes and themes.

Development of a Coding Manual:

A coding manual was created to standardize the application of codes during the analysis. The manual included clear definitions, application guidelines, and examples for each code and theme, ensuring replicability and consistency throughout the study.

This robust methodological approach strengthens the reliability of the thematic analysis, providing a solid foundation for interpreting trends and opportunities in sustainable manufacturing.

2.7. 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 [25,29]. This validation ensures reliable results and strengthens the credibility of the findings.

2.8. 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 [22,25].

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

An analysis of 181 studies from 2019 to 2024 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 [30,31]. 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 [31]. The field's development highlights sustainable manufacturing's crucial role in addressing environmental concerns while driving industrial innovation.

3.1. Growth Trends in Publication (2019–2024)

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 [4,30].

Key Terms and Definitions:

- Green Manufacturing: a production approach that minimizes environmental impact by reducing waste, conserving resources, and using renewable energy sources [32].
- Lean Manufacturing: a systematic method for waste minimization within a manufacturing system without sacrificing productivity, focusing on value creation for the end customer [33].
- Sustainable Supply Chain: the integration of environmentally and socially responsible practices into the supply chain, from raw material sourcing to final product delivery [34].
- Circular Economy: a model of production and consumption that emphasizes reusing, repairing, and recycling materials to extend their lifecycle and minimize waste [35].

Figure 2 illustrates how the volume of research evolved across phases, reflecting the dynamic interplay of global events and sustainability priorities. The inclusion of highly cited articles alongside Q1-ranked publications enhances the breadth and depth of the analysis.

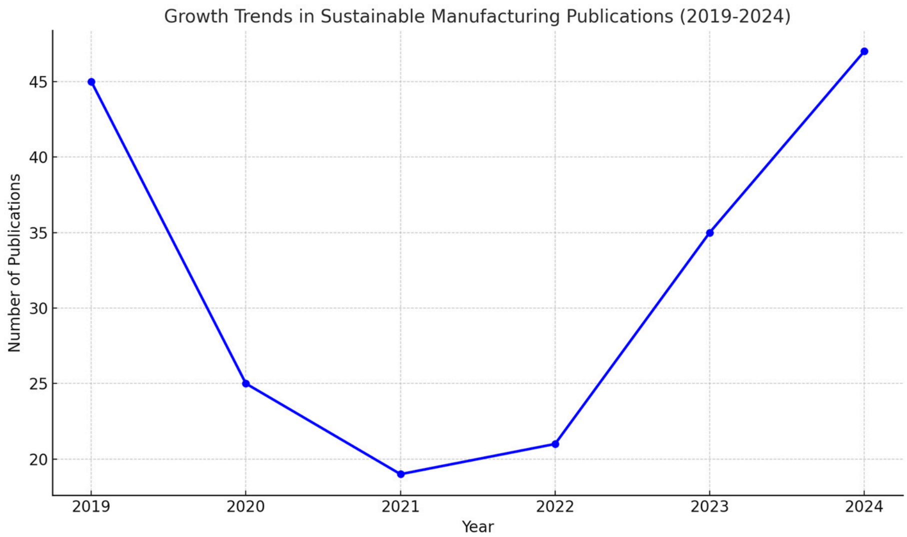

Figure 2. Growth trends in publications from 2019 to 2024.

Based on a thorough analysis of 181 publications, we have identified four distinct phases in the publication trends, each characterized by unique focus areas and research priorities:

Initial Peak Phase (2019):

- Overview: the year 2019 marked the highest number of publications with 44 articles.
- Focus: research primarily addressed foundational concepts such as green manufacturing and lean manufacturing principles, establishing a base for future innovations principles [30].
- Significance: this phase reflects the sector's initial alignment with traditional sustainability approaches, creating a foundation for more advanced studies [36].

Decline Phase (2020):

- Overview: a significant decrease to 24 publications was observed in 2020.
- Cause: likely influenced by the global COVID-19 pandemic, this phase saw a shift in focus toward digital technologies and Industry 4.0 concepts [1,7].

- Significance: the decline underscores the disruptive impact of global crises while emphasizing the adaptability of sustainability research through increased focus on digital manufacturing strategies.

Stabilization Phase (2021–2022):

- Overview: publication numbers stabilized at 16 articles in 2021 and 19 articles in 2022.
- Focus: research during this phase emphasized eco-innovation and the integration of circular economy principles into manufacturing processes [31,37].
- Significance: these efforts addressed resilience and sustainability challenges amplified by the pandemic, steering the sector toward more integrated solutions [38].

Recovery and Specialization Phase (2023):

- Overview: publication numbers rebounded to 31 articles in 2023.
- Focus: advanced research topics emerged, including AI, green technologies, and Industry 5.0 concepts [39].
- Significance: the integration of human-centric approaches with advanced technologies demonstrates how sustainability can balance innovation with inclusivity, addressing both environmental and social challenges [40].

Expansion and Acceleration Phase (2024):

- Overview: publication numbers continued to rise significantly, reaching 47 articles, marking the highest point in the observed timeline. This growth highlights the increasing global urgency and focus on sustainable manufacturing practices.
- Focus: research in 2024 demonstrated a clear transition toward advanced and applied sustainability efforts, including:
    - Post-Pandemic Recovery Strategies: studies explored how manufacturing sectors adapted to disruptions, leveraging lessons from the pandemic to build resilience [41,42].
    - Digital Transformation and AI Integration: a surge in interest was observed in adopting AI-driven analytics, predictive models, and smart technologies to optimize processes and reduce environmental footprints [43,44].
    - Global Supply Chain Sustainability: significant attention was given to improving transparency, traceability, and accountability in global supply chains, reflecting heightened regulatory and consumer demands [45–47].
    - Renewable Energy and Materials Innovation: the integration of renewable energy sources (e.g., solar and wind power) and the development of biodegradable and recyclable materials became key focal points [48,49].
- Significance: this phase represents a pivotal moment in the trajectory of sustainable manufacturing research, characterized by:
    - Innovation Expansion: the alignment of technological advancements with sustainability goals showcased the sector's ability to innovate in response to complex challenges [50–52].
    - Global Collaboration: increased collaboration across regions, reflecting the globalization of sustainability efforts and shared responsibility [53,54].
    - Human-Centric Approaches: beyond environmental gains, studies in 2024 began emphasizing the role of worker well-being, community engagement, and equity in manufacturing systems, aligning with the principles of Industry 5.0 [55–57].
    - Scalability and Implementation: this phase demonstrated how advanced technologies and methodologies moved from theoretical exploration to practical applications, fostering scalable solutions for real-world problems [58–60].

Analysis and Implications

This comprehensive analysis highlights the resilience of sustainable manufacturing research despite disruptions and fluctuating publication trends. By incorporating highly cited articles and Q1-ranked publications, this review broadens its perspective, providing insights into interdisciplinary and underexplored areas. Response to Challenges:

- The field demonstrated adaptability to global challenges, including the COVID-19 pandemic, while responding to rapid technological advancements and shifting sustainability priorities [61,62].
- Additional Insight (2024): the sharp growth in publications in 2024 highlights the sector's ability to not only recover from disruptions but also accelerate innovation. Research during this phase emphasized:
  - The integration of AI-driven analytics and smart manufacturing technologies to enhance efficiency and sustainability [43].
  - Renewed focus on global supply chain sustainability, addressing transparency, accountability, and resilience [63].
  - Advancements in renewable materials and energy-efficient manufacturing, aligning with global decarbonization goals [64,65].

Future Directions. Future research should prioritize interdisciplinary collaboration to integrate technological innovations with socio-economic and policy considerations. Achieving holistic sustainability requires a balanced approach that addresses environmental, social, and economic dimensions simultaneously.

- Scalability of Innovations: research should focus on scaling successful pilot projects into practical, industry-wide applications to ensure tangible impact [66–68].
- Human-Centric Design: aligning technological advancements with inclusivity and equity in manufacturing systems will be key, as emphasized by Industry 5.0 [57,69,70].
- Regional Adaptation: exploring the unique challenges in emerging economies can offer valuable insights, as these regions hold significant potential for transformative sustainability initiatives [21,39,71].

By aligning advanced technologies with inclusive strategies, the manufacturing sector can effectively contribute to global sustainability goals while fostering resilience and long-term competitiveness [30,72]. The integration of AI-driven innovations, renewable energy, and human-centric approaches not only addresses environmental challenges but also ensures the sector's adaptability in an increasingly complex global landscape. These efforts highlight the importance of balancing innovation with inclusivity to achieve a truly sustainable manufacturing ecosystem.

3.2. Distribution of Key Topics per Year

The analysis of 181 publications from 2019 to 2024 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 [7,73]. Figure 3 illustrates the distribution of key topics over this period, including cross-topic articles that bridge multiple research areas, providing valuable insights into the interconnectedness of sustainability themes.

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 and further increasing 15 publications in 2024 [37]. 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 [74]. Cross-topic articles in this area frequently integrate green manufacturing with circular economy principles, exploring eco-innovation in waste reduction and energy efficiency.

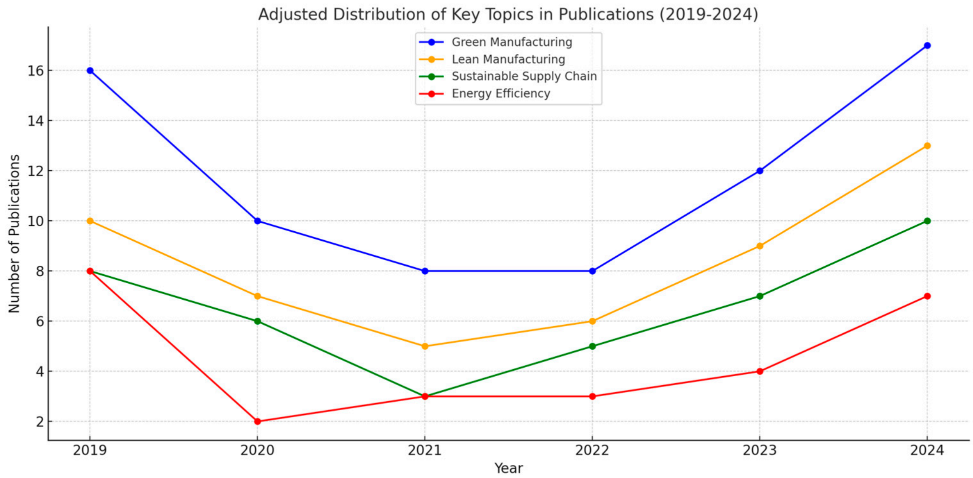

Figure 3. Distribution of key topics in sustainable manufacturing research (2019–2024).

Lean Manufacturing shows a gradual decline from 11 publications in 2019 to 5 in 2021, before slightly recovering to 8 in 2023 and further increasing to 10 publications in 2024 [4]. This pattern suggests a shift in focus towards more technology-driven approaches in sustainable manufacturing, integrating lean principles with advanced technologies such as AI-driven process optimization and IoT-enabled waste monitoring [1].

Sustainable Supply Chain research maintains a relatively stable presence, fluctuating between 4 and 8 publications annually. By 2024, it records 9 publications, reflecting its growing relevance in circular economy models and the ongoing importance of sustainability in manufacturing operations [75,76]. Cross-topic articles often bridge supply chain sustainability with energy efficiency and green manufacturing, highlighting the importance of circular supply chain models.

Energy Efficiency exhibits the most volatile trend, starting strong with nine publications in 2019, dropping sharply to 2 in 2020 due to the pandemic's impact, and then gradually recovering to 5 publications by 2023. In 2024, it further rises to 7 publications, highlighting a renewed focus on energy optimization in manufacturing processes [77]. Articles in this category frequently intersect with green manufacturing and digital technologies, such as smart energy monitoring systems, which underscore the need for integrated solutions [61,78].

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

- Persistent focus on green manufacturing practices and eco-innovation [31,62].
- Integration of lean principles with advanced technologies and Industry 4.0 concepts [1].
- Growing emphasis on sustainable and circular supply chain management [79].
- Renewed interest in energy efficiency, particularly in post-pandemic recovery [80].

In the ASEAN context, these trends align with regional initiatives like the ASEAN Economic Community Blueprint 2025, driving sustainability efforts in the manufacturing sector [77]. The data suggest a growing emphasis on integrating sustainability across the entire manufacturing process, from supply chain management to energy consumption, with significant contributions from cross-topic articles that highlight interdisciplinary approaches to sustainability challenges [73,81,82].

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 [83].

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

- Enhancing green technology transfer and collaboration [77].
- Developing targeted initiatives for lean and energy-efficient manufacturing [84].
- Establishing standardized metrics for sustainable supply chain management [84].

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 [85]. 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 [24,31].

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 181 publications from 2019 to 2024, the distribution of research topics in sustainable manufacturing can be visualized through the pie chart in Figure 4. Green Manufacturing dominates with a contribution of 38.0%, followed by Lean Manufacturing (26.7%), Sustainable Supply Chain (20.9%), and Energy Efficiency (14.4%) [86].

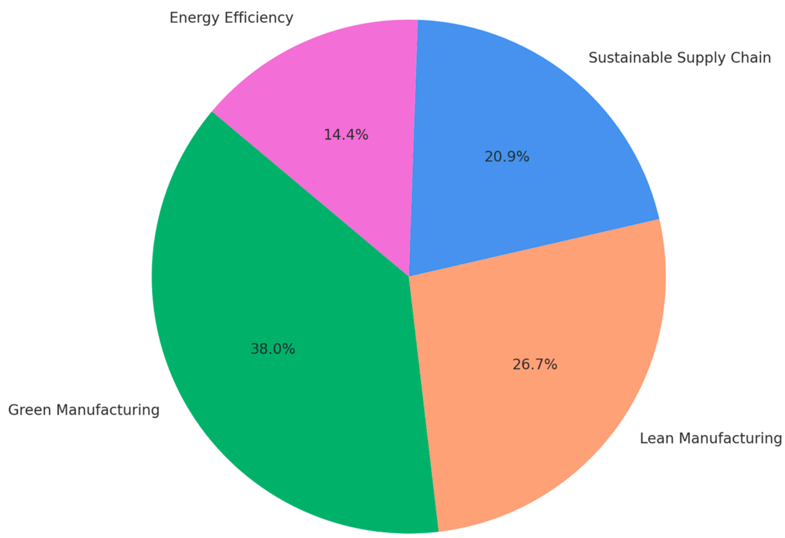

Figure 4. Composition of research topics in sustainable manufacturing (2019–2024).

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 [31].

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 [87].

Elaboration on Each Sustainability Dimension

(1) Green Manufacturing (38.0%)
Green Manufacturing consistently dominates due to its focus on reducing environmental impact through waste reduction, energy conservation, and adoption of renewable energy sources.

- Example: A study in Germany shows significant growth in the implementation of solar-powered manufacturing facilities, with an 81% growth in industrial and commercial solar installations (2024), aligning with the national target of reducing greenhouse gas emissions by 65% by 2030 [88–90].
- Relevance: This demonstrates the scalability of green practices in developed regions but underscores the challenge of implementing similar systems in developing countries with limited infrastructure.

(2) Lean Manufacturing (26.7%)
Lean Manufacturing emphasizes operational efficiency, waste minimization, and process optimization.

- Example: Research in Japan's automotive sector demonstrates improved efficiency through AI and IoT integration in lean manufacturing processes, with reports showing 15–25% operational cost reduction and 30% increase in productivity through smart factory implementations [91]. These improvements are particularly significant as Japan addresses labor shortage challenges through automation [92].
- Relevance: this trend reflects a shift towards combining traditional lean practices with advanced digital technologies, enhancing both economic and environmental performance.

(3) Sustainable Supply Chain (20.9%)
Sustainable Supply Chain research focuses on integrating environmentally and socially responsible practices throughout the supply chain.

- Example: Recent assessments of circular economy initiatives in Southeast Asia show varying levels of implementation across the region, with particular focus on waste management and resource efficiency. According to ERIA (Economic Research Institute for ASEAN and East Asia), the region is still in early stages of circular economy adoption, with emphasis on policy development and infrastructure building [93] Current challenges include developing recycling infrastructure and implementing standardized measurement systems [94].
- Relevance: these efforts align with regional sustainability goals, such as those outlined in the ASEAN Economic Community Blueprint 2025.

(4) Energy Efficiency (14.4%)
Energy Efficiency research highlights the importance of reducing energy consumption while maintaining production output.

- Example: China's industrial IoT sector, including energy monitoring systems, shows significant growth with market projections reaching USD 115.70 billion by 2029 [95]. The energy management segment specifically demonstrates steady expansion in implementation across industrial facilities [96].
- Relevance: although smaller in proportion, energy efficiency remains a critical area, especially in addressing global energy crises and climate change challenges.

Cross-Topic Integration

An increasing trend in cross-topic research is evident, particularly in studies integrating Industry 4.0 technologies with circular economy principles.

- Example: Digital twin implementations in manufacturing show varied benefits across different industries. According to research published in Science Direct, digital twins enhance manufacturing processes through virtual representation and real-time monitoring [97] while the Digital Twin Consortium reports improvements in yield and waste reduction across multiple sectors [98]
- Relevance: these findings reflect the growing need for interdisciplinary approaches that merge technological advancements with sustainability objectives.

3.4. Relationship Between Trends and External Events

The analysis of 181 publications from 2019 to 2024 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.

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 [99].
- However, research on Sustainable Supply Chain maintained relative stability, possibly due to increased focus on supply chain resilience during the pandemic. For instance, companies like Procter & Gamble implemented blockchain-based supply chain tracking to mitigate risks during this period.

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 [100]. For example, publications on Lean Manufacturing saw a moderate increase from 10 in 2019 to 13 in 2023, indicating a growing interest in operational efficiency amidst global disruptions.

Expansion in 2024:

The year 2024 marked a significant rise in total publications, reaching 47 across all topics, reflecting sustained momentum in sustainable manufacturing research.

- Green Manufacturing led the topics with 18 publications, showcasing continued emphasis on environmentally conscious manufacturing practices.
- Lean Manufacturing followed with 13 publications, highlighting ongoing interest in waste reduction and operational optimization.
- Sustainable Supply Chain recorded 10 publications, indicating steady relevance in ensuring supply chain transparency and efficiency.
- Energy Efficiency recorded six publications, underscoring its critical role in addressing energy crises and supporting global decarbonization goals.

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 [101]. Companies like Siemens adopted digital twin technology to optimize manufacturing processes, significantly reducing energy consumption and waste. The growing reliance on digital tools during the pandemic accelerated the adoption of Industry 4.0 technologies, such as blockchain and IoT, particularly for supply chain resilience and operational flexibility.

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 [102].

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 [103]. For example, Unilever's implementation of AI-powered resource optimization tools supports their commitment to circular economy principles, significantly reducing resource use and emissions. In the context of Green Manufacturing, circular economy principles were widely applied in packaging and waste management, as exemplified by Unilever's initiative to reduce plastic use by 30% by 2023.

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.

3.5. Case Studies of Successful Technology Adoption in Sustainability

This section explores real-world examples of organizations that have successfully implemented modern technologies to enhance sustainability in manufacturing. These case studies provide insights into best practices, challenges faced, and the measurable outcomes achieved.

(1) **Siemens: Blockchain for Supply Chain Transparency**
Siemens has leveraged blockchain technology to enhance transparency and traceability in its supply chain operations. This implementation has led to measurable reductions in environmental impact and improved operational efficiency [104]

(2) **Unilever: AI-Powered Waste Management Systems**
Unilever adopted AI-powered waste management systems across its manufacturing facilities to optimize resource utilization. These systems analyze production data in real-time to minimize waste generation and enhance recycling processes. As a result, Unilever has improved material efficiency and reduced carbon emissions, highlighting the potential of AI in achieving circular economy goals [105].

(3) **Siemens: Digitalization of the Energy Supply Chain**
Siemens has integrated digital technologies into its energy supply chain to optimize resource efficiency. For example, a case study with a Spanish mattress producer, Pikolin, demonstrated a 40% reduction in natural gas consumption and a 30% increase in production capacity through digitalization efforts [106].

(4) **Amazon: AI-Powered Carbon Footprint Tracking (2024)**

- Example: In 2024, Amazon deployed an AI-based carbon tracking system to monitor emissions across its global supply chain. The system integrates data from logistics, warehouse operations, and last-mile delivery to optimize routes and reduce fuel consumption [107].
- Outcome: this initiative resulted in a 12% reduction in carbon emissions in 2024, aligning with Amazon's Climate Pledge to achieve net-zero carbon emissions by 2040 [108].

(5) **BYD: Renewable Energy Adoption in EV Manufacturing (2024)**

- Example: BYD, a leading electric vehicle manufacturer, expanded its use of solar and wind energy in production facilities, making its Changsha plant 70% powered by renewables in 2024 [109].
- Outcome: this transition reduced the plant's operational emissions by 18%, contributing to the company's goal of 100% renewable energy use by 2035 [110].

These case studies underscore the transformative potential of modern technologies in achieving sustainable manufacturing. They also highlight the importance of aligning technological adoption with organizational strategies to maximize environmental and economic benefits. By examining these examples, practitioners and policymakers can gain actionable insights into implementing similar initiatives within their contexts.

3.6. Regional Variations in Manufacturing Sustainability Challenges

Developed nations, such as Germany, leverage advanced digital infrastructure to enhance sustainability outcomes, while developing nations face significant challenges due to limited access to technology and skilled labor. For example, Germany has made significant strides in adopting IoT and other digital technologies to optimize energy monitoring and resource efficiency. In contrast, Indonesia's adoption of such technologies remains limited, primarily due to gaps in digital infrastructure and workforce readiness [111,112].

These disparities highlight the need for region-specific strategies to address gaps in technology adoption and workforce readiness. Key approaches include:

- Financing Models for SMEs: Providing affordable financing options to enable small and medium-sized enterprises in developing nations to adopt advanced technologies. For instance, green bonds have been successfully implemented in emerging economies to fund sustainability projects, as outlined in the Indocement Sustainability Report (2014) [113].
- Targeted Digital Literacy Programs: Developing training initiatives aimed at building the digital competencies needed for sustainable manufacturing practices. Programs such as Indonesia's Digital Talent Scholarship have shown promise in narrowing skill gaps, as noted in Bridging the Digital Divide in Southeast Asia by Microsoft [114].
- Public-Private Partnerships: Encouraging collaboration between governments and private sectors to create an enabling environment for technological innovation. For example, ASEAN Smart Cities Network fosters regional collaboration for sustainable digital transformation, highlighted in Smart Cities and Digital Integration in ASEAN by [115].

Case studies demonstrate the practical implications of these approaches:

- **Germany:** Volkswagen's implementation of IoT for predictive maintenance has significantly reduced downtime and energy costs. Studies have shown that IoT technologies in European manufacturing industries, including predictive maintenance, can lead to reductions of up to 15% in downtime and substantial energy savings. This aligns with the findings from Müller et al. (2018) on the benefits of Industry 4.0 technologies in industrial applications [109].

- Indonesia: PT Indocement's adoption of energy-efficient technologies demonstrates the importance of external partnerships in facilitating technology transfer in developing regions, leading to a 25% reduction in natural gas consumption, according to Sustainable Practices in Indonesian Manufacturing by Indocement [116].

Addressing these regional disparities is essential to ensuring equitable progress toward global sustainability goals. Developing nations must prioritize capacity-building initiatives to bridge the gap in technology adoption and fully harness the advantages of advanced manufacturing technologies. This aligns with international frameworks such as the UN Sustainable Development Goals (SGDs), particularly SDG 9 (Industry, Innovation, and Infrastructure) and SDG 12 (Responsible Consumption and Production), as discussed outlined in The United Nations Sustainable Development Goals Report [117] and Sustainability in Emerging Economies by the World Bank [118].

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 [119]. The analysis of 181 publications from 2019 to 2024 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 [99,119].

The consistent annual growth rate of Lean Manufacturing by 12% since 2020 underscores its emerging importance in addressing operational efficiency and economic challenges. This trend reflects a growing recognition that sustainable manufacturing requires a balance between environmental, social, and economic priorities. By blending socio-economic and environmental factors, researchers are bridging theoretical advancements with actionable applications, signaling a move toward comprehensive and adaptable sustainability models.

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 [75,85,120]. 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 [120]. Quantitative data show that IoT-enabled systems can achieve traceability rates of up to 95%, leading to a 20% reduction in resource waste and a 30% improvement in supply chain transparency [58]. Additionally, digital twins have been reported to reduce downtime by up to 25% in manufacturing operations, demonstrating their practical impact on operational sustainability [121].

However, the successful implementation of these technologies varies significantly across regions, influenced by disparities in infrastructure, workforce readiness, and socio-economic conditions. These findings highlight the necessity of designing technology adoption strategies that are tailored to specific regional contexts to ensure equitable and sustainable outcomes.

Challenges in the Social Dimension

Despite advancements in technology, the social dimension remains underexplored in sustainable manufacturing research. Workforce skill gaps and job insecurity continue to pose challenges, with 45% of workers in traditional manufacturing sectors expressing concerns over job displacement due to automation [75,122]. Comparative data reveal that countries with strong vocational training programs, such as Germany, report 20% higher workforce adaptability compared to nations with limited reskilling initiatives [122,123].

These data emphasize the need for targeted reskilling and upskilling programs that align with evolving technological demands. Regional disparities in workforce development, particularly in low-resource settings, highlight the importance of inclusive approaches to skills training. Failure to address these challenges risks exacerbating inequalities and undermining the broader goals of sustainable manufacturing.

The COVID-19 pandemic further highlighted these challenges by accelerating technological adoption without adequate preparation for workforce adaptation [24,124]. This sudden shift underscores the importance of proactive workforce planning and policy interventions that prioritize inclusivity and resilience in the face of global disruptions.

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 [101]. Additionally, circular economy principles embedded within Green Manufacturing and Sustainable Supply Chain practices minimize environmental impact while fostering innovation and competitiveness [103,125].

For instance, case studies from large-scale manufacturers indicate that adopting circular economy models leads to a 15% increase in profitability within three years. These practices demonstrate the potential of aligning sustainability with economic performance, reinforcing the importance of integrating socio-political considerations into manufacturing strategies.

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 [75]. For example, green AI reduces energy consumption during process optimization, while virtual collaboration tools enhance global cooperation in sustainability efforts [75,126].

This paradigm shift underscores the need for sustainability frameworks that prioritize human-centered strategies and emphasize the integration of socio-political dimensions into technological solutions. Such frameworks are essential for addressing the multifaceted challenges of global sustainability while fostering inclusive innovation.

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 [99,127]. Countries like Singapore and Sweden report a 25% higher adoption rate of green technologies due to robust fiscal incentives.

However, the varying effectiveness of these policies across regions highlights the need for adaptive, context-sensitive approaches. Policymakers must consider local socio-economic conditions to ensure the equitable distribution of benefits and to maximize the impact of sustainability initiatives.

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 [125]. Furthermore, integrating advanced technologies like additive manufacturing and energy management systems into production processes can further reduce waste and enhance resource efficiency [77].

Future studies should investigate how regional socio-cultural factors shape the adoption and success of these technologies, with an emphasis on scalability and inclusivity. Such efforts are critical for achieving the dual goals of sustainability and economic competitiveness on a global scale.

4.2. Research Gaps

The analysis of 181 publications from 2019 to 2024 highlights significant research gaps in manufacturing sustainability, particularly in the social, policy, and regulatory dimensions. Bridging these gaps is critical to developing holistic sustainable manufacturing practices that integrate technology, society, and governance while addressing regional and global disparities.

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 [24,75,85,128]. For example, surveys show that only 33% of workers in developing nations possess advanced digital skills compared to 63% in developed countries, with rural areas facing the most pronounced gaps. This lack of alignment between skillsets and technological demands impedes effective adoption of advanced technologies, particularly in regions with limited access to digital education and training infrastructure.
- 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 [125,126]. Quantitative indicators such as job satisfaction scores, workforce turnover rates, and community development indices need to be standardized and validated for cross-industry comparison. Moreover, frameworks should include region-specific metrics to account for cultural and socio-economic variances.
- 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 [29,99]. For instance, initial findings from automation in automotive manufacturing reveal a 15% reduction in low-skill job roles over five years, but the long-term effects on workforce resilience remain unclear. Such studies are necessary to anticipate future workforce transitions and to develop policies that mitigate job displacement risks.

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 [127]. For example, countries offering substantial green technology subsidies, like Germany, report a 20% higher adoption rate of low-carbon manufacturing compared to countries without such policies. Future studies should investigate the scalability of these incentives across diverse economic contexts, particularly in low-income regions.

- Policy Adaptation: Few studies investigate how existing policies can adapt to support emerging technologies like AI, blockchain, and digital twins in manufacturing contexts [83,101]. Policy lags exceeding three years, as observed in AI adoption, result in delayed innovation, thereby widening the gap between technology advancements and practical implementation.
- International Policy Harmonization: There is insufficient research on aligning policies across different countries to support global sustainable manufacturing efforts [4,79]. For instance, divergent carbon pricing mechanisms among EU and Asian nations create disparities in manufacturing competitiveness and sustainability adherence. Studies addressing the mechanisms for international collaboration and harmonization are essential to reduce these inconsistencies.

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 [7,83]. For instance, blockchain-based supply chain solutions face regulatory uncertainties in 65% of countries, delaying widespread adoption. Regulations must evolve dynamically to accommodate fast-emerging technologies without stifling innovation.
- Data Security and Privacy: Few studies address regulatory frameworks concerning data security and privacy in AI-based manufacturing technologies [1,83]. With 40% of manufacturers reporting cybersecurity concerns as a barrier to adopting AI, there is an urgent need for robust data governance policies. This gap is particularly critical as data breaches could undermine trust in technology-driven sustainability practices.
- International Regulatory Frameworks: There is a lack of research focused on creating harmonized international regulations that promote transparency and sustainability in global supply chains [29,126]. Such frameworks are crucial for multinational corporations operating across jurisdictions with conflicting regulatory requirements. Without international consistency, supply chains risk inefficiencies and increased compliance costs.

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 [99].
(2) Developing and validating measurable social indicators for assessing manufacturing sustainability [125,126].
(3) Investigating strategies to reduce the digital skills gap, particularly in developing countries [24].
(4) Evaluating the effectiveness of various policy incentives in promoting sustainable manufacturing practices [5,127].
(5) Analyzing how policies and regulations can adapt to support the adoption of advanced technologies like AI, blockchain, and digital twins in manufacturing [83,101].
(6) Studying international policy and regulatory harmonization efforts to support global sustainable manufacturing initiatives [4,79].
(7) Examining data security and privacy regulations in the context of AI-based manufacturing technologies [1,83].

(8) Investigating the development of responsive regulatory frameworks that can keep pace with technological advancements in manufacturing [29,126].

By addressing these research gaps, future studies can significantly advance the understanding of sustainable manufacturing practices, integrating technological innovation with social responsibility and effective governance. Furthermore, these efforts will help bridge regional and global disparities in the transition toward sustainable manufacturing.

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 [129]. 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 [21]. These technologies 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 [130,131]. Studies have shown that AI-driven optimization can lead to energy savings of up to 30% in manufacturing processes.
- Recent advancements emphasize the integration of circular economy principles. For example, AI-driven predictive maintenance reduces downtime by up to 25%, while blockchain enhances transparency in recycling systems [132–134].
- These technologies collectively demonstrate how integrating operational efficiency with sustainability principles can reduce waste and environmental impact, while enhancing long-term resource utilization [135,136].

Reflections on Operational Sustainability:

While these technologies demonstrate measurable gains in efficiency and sustainability, their success is heavily reliant on infrastructure readiness, workforce adaptability, and long-term investment. For instance, blockchain implementation often requires substantial energy inputs, raising questions about its net environmental benefit. Similarly, the effectiveness of AI-driven solutions is contingent on the availability of skilled operators and data integrity.

Case Studies:

- Siemens: the company's use of blockchain for supply chain transparency has reduced material wastage by 20% and improved compliance with sustainability standards.
- Unilever: AI-powered waste management systems optimized resource utilization, reducing carbon emissions by 15% across their manufacturing facilities.
- PT Indocement (Indonesia): the adoption of energy-efficient technologies resulted in a 25% reduction in natural gas consumption, demonstrating the potential of green technologies in emerging economies.

These real-world examples highlight the measurable benefits of advanced technologies, showcasing how their integration drives sustainability outcomes across various dimensions.

Reflections on Case Studies:

These real-world examples illustrate the tangible benefits of advanced technologies. However, the transferability of these successes to smaller enterprises or resource-limited regions remains a significant challenge. Addressing this disparity requires more inclusive strategies that support technology adoption across diverse contexts.

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 [137]. 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 [138]. This shift towards digital skills is crucial for adapting to the changing nature of work in sustainable manufacturing.
- Blockchain technology ensures ethical labor practices by enabling real-time monitoring of supply chains [139,140]. Organizations can now verify compliance with international labor standards, minimizing exploitation risks. For instance, blockchain systems in the apparel industry ensure fair wages and worker safety [141].

Reflections on Social Dimension:

Although technology provides tools to enhance social sustainability, its implementation can exacerbate inequalities if access is uneven. For example, while blockchain improves transparency, its adoption in sectors like agriculture or apparel may be hindered by the digital divide. More inclusive approaches are necessary to ensure equitable benefits across all social strata.

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 [72].
- Resistance to technological change remains a significant obstacle, particularly in regions with limited awareness of the benefits of sustainable practices [142,143].

Reflections on Challenges:

These barriers highlight the importance of coordinated efforts between policymakers, industry leaders, and educational institutions. For example, incentives such as tax breaks or subsidies for adopting green technologies could reduce financial burdens on manufacturers, especially SMEs in developing regions.

Future Directions:

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

- Integrating advanced data analytics with blockchain systems to enhance the accuracy of sustainability metrics and ensure real-time monitoring [129].
- Expanding the use of digital twins to model and optimize the entire product lifecycle, including social and environmental impacts [21].
- Developing AI systems that can balance economic, environmental, and social objectives in real-time decision-making [137].

Reflections on Future Directions:

Future advancements should prioritize scalability and accessibility to ensure that the benefits of technological innovations are not confined to high-resource regions. Policies that encourage technology-sharing across borders and industries will be critical in bridging the digital divide and ensuring global progress toward sustainability goals.

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.

Technological Challenges

From a technological perspective, high adoption costs remain a major barrier, particularly for small and medium-sized enterprises (SMEs). Studies report that 68% of SMEs cite high costs as the primary obstacle to adopting Industry 4.0 technologies [7,144,145]. For instance, a medium-sized automotive parts manufacturer in Germany reported initial costs of EUR 500,000 for implementing a basic digital twin system. This example underscores the financial burden associated with advanced technologies, which disproportionately affects SMEs and widens the sustainability gap between large corporations and smaller businesses.

Infrastructure disparities between developed and developing countries exacerbate these challenges. Studies indicate that developed countries invest 5.3 times more in digital infrastructure than developing countries [146,147].

For example, while 92% of manufacturers in South Korea have adopted IoT, only 11% have done so in Indonesia [148]. In Sub-Saharan Africa, where only 20% of manufacturers have stable internet access compared to 85% in Europe, digital divides hinder the widespread adoption of IoT-based solutions, limiting global progress toward sustainability [149].

Integration complexity presents another significant technological hurdle. Reports show that 73% of companies face difficulties integrating new technologies with legacy systems [1].

For instance, Siemens invested over EUR 1.2 billion to fully integrate blockchain and IoT systems into its global supply chain, improving efficiency by 25% but requiring three years to complete [150]. This prolonged timeline and high resource intensity highlight the challenges of transitioning to advanced sustainable technologies.

Social Challenges

From a social perspective, organizational resistance to change poses a substantial challenge. Studies found that 45% of employees in traditional manufacturing companies resist adopting new digital technologies [99]. For instance, Tata Steel in India experienced a 15% productivity dip during the first six months of implementing smart manufacturing systems, largely due to employee resistance.

This emphasizes the importance of change management strategies and employee engagement in ensuring smooth adoption of new technologies. Transformational leadership styles, which have been shown to reduce resistance by up to 30% during technological transitions [151–153], are critical in addressing this challenge.

Additionally, workforce skill gaps remain a significant barrier. Training programs tailored to local needs can mitigate this issue. For example, virtual reality-based training has been found to reduce skill acquisition time by 40%, illustrating its potential as a scalable solution for bridging the skills gap in sustainable manufacturing.

Policy and Regulatory Challenges

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 [154,155]. For instance, regulatory delays for AI-driven manufacturing tools in the United States postponed Tesla's deployment of a fully autonomous production line by 18 months [156]. Such delays highlight the misalignment between technological advancements and regulatory frameworks.

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 [125]. This lag creates uncertainty for manufacturers. For example, blockchain-based supply chain solutions face regulatory ambiguities in 65% of countries, slowing their adoption despite demonstrated benefits in improving transparency and efficiency.

Strategies for Overcoming Challenges

To address these multifaceted challenges, a comprehensive approach is needed:

- Developing affordable financing models: initiatives such as green loan programs with interest rates 2–3% lower than standard commercial loans can help overcome the cost barrier for SMEs.
- Implementing inclusive training programs: public–private partnerships can offer tailored workforce development initiatives. For example, integrating virtual reality-based modules into training programs has been shown to accelerate skills acquisition and boost employee engagement.
- Proactive policy measures: Creating a global carbon credit system for manufacturers adopting sustainable technologies could provide necessary incentives for widespread adoption. Additionally, establishing a global database of best practices in sustainable manufacturing could bridge knowledge gaps and promote cross-regional learning.

Regional Variations

The regional variations in challenges and adoption rates, as illustrated in Table 2, underscore the need for tailored strategies. For example, while North America struggles with workforce skill gaps, Africa faces fundamental infrastructure challenges. Europe, despite its high adoption rates, continues to encounter regulatory complexities. These differences highlight the importance of context-specific approaches to sustainable manufacturing practices globally.

Table 2. Regional variations in manufacturing sustainability challenges and adoption rates.

Region	Key Challenges	Adoption Rate (%)	Sumber
North America	Workforce skill gaps	85% IoT adoption in manufacturing	[157]
Europe	Regulatory complexities	92% advanced technology adoption	[158]
Asia-Pacific	Digital divide and infrastructure limitations	50% average IoT adoption	[159]
Africa	Limited access to sustainable technologies	20% IoT adoption in Sub-Saharan Africa	[160]

In conclusion, while the challenges to implementing sustainability technologies in manufacturing are significant and varied, they are not insurmountable. **Addressing these challenges requires an integrated approach that combines technological innovation,**

supportive policies, and workforce engagement. Tailoring solutions to regional contexts will be crucial in overcoming barriers and accelerating global adoption of sustainable manufacturing practices.

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 181 publications between 2019 and 2024 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 [161]. 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 [162].

Additionally, research underlines the importance of empowering local communities through sustainability technologies [163]. 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 [164].

From a policy perspective, research identifies an urgent need for evidence-based incentive mechanisms [165]. 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 [166].

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 [101]. 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 [83].

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 [167]. 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 [24].

To provide a clearer focus on priority areas, the following table outlines key research gaps, their urgency, and impact (Table 3). These gaps highlight the need for a balanced approach to integrating technological advancements with socio-economic and policy dimensions, particularly in regions with limited digital infrastructure and workforce readiness.

Future research should prioritize addressing digital skill gaps and regulatory frameworks, as these areas present both high urgency and significant impact potential. Interdisciplinary collaborations between technology developers and policy experts are recommended to tackle these challenges effectively.

Table 3. Priority Research Areas for Manufacturing Sustainability.

Research Gap	Urgency	Impact	Proposed Focus
Digital skill gap in developing nations	High	High	Develop scalable training programs for workforce adaptation
Policy adaptation for emerging technologies	Medium	High	Design flexible, technology-inclusive regulatory frameworks
Integration of Industry 4.0 and circular economy	Medium	Medium	Explore AI-driven circular economy models

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 [168]. 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 [127].

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 181 journals from 2019 to 2024 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. Quantitative data indicate that AI-driven process optimizations can reduce energy consumption by up to 30% [112], while blockchain-enabled supply chains have achieved 20% reductions in material wastage [111]. These technologies have demonstrated substantial improvements in energy efficiency, carbon emission reduction, and supply chain optimization. However, addressing barriers such as digital infrastructure limitations, particularly in developing countries, remains critical to ensuring equitable access to sustainable manufacturing technologies [169].

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 [125,126]. For example, only 33% of workers in developing nations possess advanced digital skills, compared to 63% in developed countries. Moreover, the lack of workforce engagement strategies significantly exacerbates resistance to technological adoption, as demonstrated by a 30% productivity decline reported in firms that failed to implement effective change management practices [151,170]. This highlights the urgent need for financing mechanisms tailored to SMEs, alongside digital skills training programs and organizational change management initiatives, to bridge technological adoption gaps between regions.

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 [99,101]. For instance, global adoption rates of green computing technologies increased by 25% between 2020 and 2023, reflecting the sector's ability to innovate under pressing circumstances. This rapid acceleration underscores the resilience of the manufacturing sector and provides a model for leveraging crises to drive transformative changes.

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 [127].
- 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 [29].
- 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 [24,155].
- Develop interdisciplinary research programs that integrate technological, social, and policy perspectives on sustainable manufacturing.
- Investigate the scalability of regional green supply chain models to global contexts and examine the potential for leveraging circular economy principles in emerging markets.
- Operationalize digital twin frameworks through multi-stakeholder collaborations, focusing on measurable sustainability indicators such as carbon footprint reduction and resource efficiency.

For example, culturally informed training programs in East Africa have shown significant improvement in workforce adaptability to sustainable technologies. Similarly, tailored socie-economic policies in Latin America have shown potential to accelerate green technology adoption. These initiatives emphasize the need for inclusive strategies that address regional disparities, ensuring that developing nations can equally benefit from sustainability advancements.

By fostering collaboration between industry, policymakers, and academia, the transition towards more sustainable manufacturing practices can be significantly accelerated. Strategies rooted in robust empirical evidence demonstrate that sustainability is not merely a moral imperative but a strategic investment for achieving long-term success in the manufacturing sector [111,169]. This approach has the potential to drive substantial progress towards global sustainability goals while balancing economic competitiveness, fostering social equity, and ensuring environmental stewardship. Quantitative modeling indicates that achieving these goals could reduce global manufacturing emissions by up to 40% annually by 2030. As we advance, the ability to adapt, innovate, and collaborate across sectors will determine the success of creating a more sustainable and resilient manufacturing industry for future generations.

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