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Artificial intelligence's role in industry 4.0-driven sustainable supply chains for small and medium-sized enterprises

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Abstract: This study investigates how artificial intelligence (AI) enables sustainable supply chain transformation and the institutional and organizational factors that mediate successful AI-driven green outcomes. We conducted a mixed-methods bibliometric and thematic analysis of literature on AI and green supply chains, combining bibliographic coupling and co-word analyses across 124 Scopus records and synthesizing managerial insights from representative empirical studies. Four thematic clusters emerged: (1) performance-driven green strategies; (2) enablers and barriers to green supply chains; (3) circular economy and digital transformation; and (4) technological integration and big data capabilities. Results indicate that organizational digital maturity, data governance, and cross-functional capabilities critically enable AI-driven sustainability; regulatory pressure and consumer demand alone are insufficient. AI has substantial potential to improve environmental performance and resilience when integrated with aligned strategy and internal capabilities. Managers should prioritize digital maturity, data governance, skills development, and ecosystem partnerships to scale AI-enabled sustainability while avoiding superficial greenwashing.

Keywords: *Artificial Intelligence, Corporate Sustainability, Green supply chain, Industry 4.0, Green transformation, Industrial sustainability.*

1. Introduction

In recent years, Artificial Intelligence (AI) has gained a new perspective in supply chain management as a means of enhancing sustainability [1]. Digital twins, machine learning, and predictive analytics have become handy tools that are used to enhance operational efficiency, reduce wastage, and monitor the environment through the supply chains [2]. These tools enable decision-making on a real-time basis, enhance transparency, and help transition to a circular economy by utilizing resources efficiently and reducing emissions [3, 4]. With the digital transformation that is taking place in Industry 4.0, traditional industrial systems are now undergoing a transformation to incorporate cyber-physical systems, data-driven intelligence, and automation in their basic systems. In this context, the necessity to implement the latest technologies such as AI, not only to improve efficiency but also to support long-term environmental agendas, is one of the sustainability issues facing industries.

Industrial systems have developed over the years from traditional efficiency models such as Lean to integrated cyber-physical systems, predictive analytics, and data-driven optimisation in the Industry 4.0 paradigm [5]. The overlaps also show that the recent industrial revolutions have been increasing in scope, and they no longer view sustainability as a sole aim but rather as a crucial element of digital transformation. This convergence is particularly evident in efforts to align Industry 4.0 technologies with ESG strategies, which emphasize the dual goals of environmental responsibility and business competitiveness [6]. Moreover, organizations that prioritize artificial intelligence as an important part

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of green supply chain management (GSCM) consider it more valid to take advantage of AI in order to comply with regulations and stakeholder expectations on environmental accountability [7].

Researchers have underscored that constructive sustainability improvements can be achieved through AI use in green logistics, eco-design, and collusion among suppliers, especially in the context of high-development and high-technological maturity economies [8]. Although the applications of AI are becoming widespread in supply chain sustainability programs, there are several significant gaps. Small and medium-sized firms (SMEs), particularly in developing countries, receive limited empirical research attention, as the majority of research focuses on large companies [9]. This has led to the absence of insight into how these firms, which are constrained in resources and have lower digital maturity, incorporate AI into their green supply chain practices [10]. Although scientists have admitted that there is a positive potential of AI and sustainability promotion, there is a lack of studies regarding what organizational, technological, and cultural facilitators could contribute to or hinder successful implementation [11].

Moreover, few studies have investigated the effects of the use of AI on long-term green innovation capacity, supply chain resilience, and stakeholder confidence [12]. The dynamics between the implementation of AI and environmental management, as well as regulation in specific industries, have also been little studied in terms of developing countries and sectors that are less technologically advanced [13]. This paper seeks to address the identified research gaps by examining how Artificial Intelligence supports and enhances sustainable practices in supply chains, especially within small and medium-sized enterprises and underrepresented industry contexts. The study contributes by offering a comprehensive synthesis of recent developments, highlighting underexplored enablers and challenges, and evaluating the environmental and operational outcomes associated with AI adoption in supply chain processes. To achieve these aims, the paper is guided by the following research questions:

- To what extent do AI technologies contribute to improved environmental and sustainability performance in various types of supply chain models?
- What are the key organisational, technological, and policy-related enablers and barriers that influence the adoption of AI in green supply chain management?
- How do different types of firms, particularly SMEs, experience and respond to the integration of AI in achieving sustainable supply chain transformation?

2. Methodology

Bibliometric analysis, recognized for its capacity to process and examine large bodies of publication data, was utilized to systematically map the scholarly literature on the role of artificial intelligence in promoting sustainability within supply chains. This approach facilitates the identification of emerging research trends, intellectual structures, and the evolution of scientific discourse within the field [14]. Bibliometric analysis, in contrast to meta-analyses, where statistical effect sizes are meant to be synthesized, and systematic literature reviews, where the aim is to synthesize the literature qualitatively, instead shows co-authorship networks, patterns in publication, and the thematic organization across the literature over time [15]. To this end, bibliometric analysis will be especially suitable when exploring the developing and inevitably cross-disciplinary area that connects artificial intelligence with sustainable supply chains [16].

2.1. Bibliographic Coupling

This paper employed bibliographic coupling to identify conceptually related documents based on shared citations. Bibliographic coupling connects papers that cite similar prior works, enabling the grouping of research articles that share the same intellectual foundation [17]. This method is particularly useful in analyzing recently published articles that do not cite their own work extensively but overlap in their ideas regarding concepts. The recent bibliographic coupling literature, including the field of sustainable technology adoption, has been successful in locating the origins of the research and

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identifying key thematic groups within integrally multidisciplinary domains [18]. In this paper, bibliographic coupling involved the application of VOSviewer to create visual maps of clusters of articles that had common references in order to explain the intellectual structure and thematic organisation of research work on artificial intelligence and sustainable supply chains. This strategy is in line with recent bibliometric research that also applies similar visualisation methods to analyse knowledge structures of sustainability research [19].

2.2. Co-Word Analysis

Co-word analysis was used to establish theme discovery in order to determine the thematic relationships and the topic development community in terms of co-occurring keywords. The analysis of co-words was also used to chart out the intellectual landscape and trace the thematic development in the field by analyzing co-occurring keywords in order to identify interrelated groups of research and patterns over time [19]. On the basis of the data on the co-occurrence of keywords, the following topics of interest have been pinpointed: optimisation, digital transformation, environmental performance, or sustainable logistics. The identification of the study trends and their associations was made possible due to the cluster analysis of these words. The reality of co-word analysis has been established as true in recent research on environmental technology applications, which has supported the use of co-word analysis in mapping new domains and tracking academic interests over different periods [20]. This approach enables the assessment of the field's current conceptual maturity and helps identify directions for future research. Overall, co-word analysis enhances understanding of the interconnections between artificial intelligence and sustainability across diverse supply chain contexts [21].

3. Research Design and Data Collection Procedure

To find publications related to key terms in line with green supply chains, sustainability in corporations, and artificial intelligence, we used the following search string (Table 1). Keywords used to formulate the search query were identified in the earlier literature, thematic trends, and relevant thesauri. The article was located on the Scopus database with the topic search menu, which is a combination of title, abstract, and keywords filled out by the authors. To guarantee the quality of included sources, the analysis was narrowed to peer-reviewed journal articles written in English and available through open access. The end dataset excluded conference proceedings, books, book chapters, and editorials. Such a procedure of filtering provides the basis of robustness and reliability of the bibliometric dataset eligible for further examination.

Table 1.
Search string for AI role in Industry 4.0 driven sustainable supply chains for SMEs.

No.	Keywords	Justification
1	"Green supply chain"	To focus on the integration of environmentally sustainable practices within supply chain operations.
2	"Corporate sustainable"	To capture literature on corporate strategies and policies related to long-term environmental responsibility.
3	"Artificial intelligence" OR "AI" OR "Machine learning" OR "ML"	To identify applications of intelligent technologies that support automation, optimization, and eco-efficiency in corporate and supply chain systems.

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4. Findings and Discussion

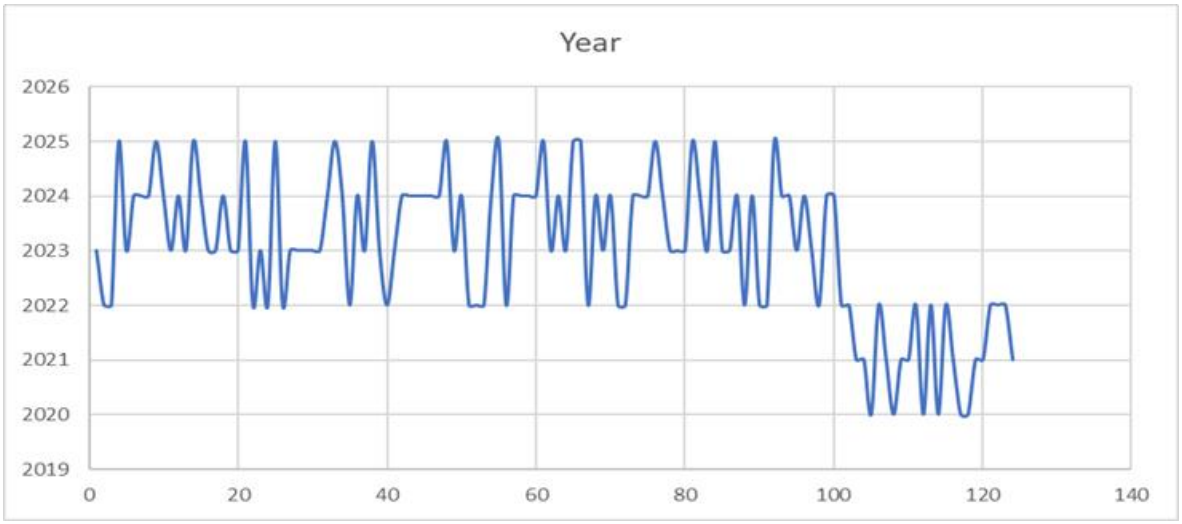

Figure 1.
Publication per year for AI role in Industry 4.0 driven sustainable supply chains for SMEs.

The graph illustrates the annual distribution of publications from 2020 to 2025, based on a curated search within the Scopus database addressing the convergence of green supply chain practices, corporate sustainability, and intelligent systems in Figure 1. The analysis is limited to English-language and open-access publications to ensure broad scholarly dissemination and comparability. The early years (2020–2021) exhibit relatively low publication activity, suggesting that the integration of sustainability and digital technologies in supply chain discourse was still in a formative stage. Beginning in 2022, there is a visible upward shift in output, culminating in a significant concentration of research during 2023 and 2024. This upward trend aligns with increasing institutional and regulatory focus on sustainable operations and the strategic role of data-driven tools in organizational transformation. While some fluctuations are observed, the overall trajectory indicates a growing academic investment in this thematic area. The continued output into 2025 reinforces the sustained relevance of this intersection, highlighting its importance in both theoretical development and practical application within global supply chain ecosystems.

4.1. Bibliographic Analysis

A total of 40 documents that had a threshold of 18 citations were found in the bibliographic coupling analysis of the 124 documents that underwent the analysis. These 40 records were then classified into four different sets. The value of 18 was determined by several iterations until a visually stable and decipherable network representation was reached. A super-high threshold posed a risk of excluding relevant contributions, whereas a very low threshold would reduce the precision of the analyses. Therefore, this figure was chosen to balance inclusiveness and readability so that the resulting scientific map accurately reflects the landscape of artificial intelligence in sustainable research on supply chains. The most relevant measure employed during the analysis is the Total Link Strength (TLS), which quantifies the level of common citation between outputs. Records with the highest TLS are a [22] document with 68 TLS, [23] study with 61 TLS, and [24] with 61 TLS.

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Table 2.
Top 10 documents in bibliographic coupling analysis for AI role in Industry 4.0-driven sustainable supply chains for SMEs.

Rank	Publication	Scope	Citations	TLS
1	Benzidia et al. [22]	The impact of artificial intelligence and big data analytics on hospital environmental performance and the integration of green supply chain processes	460	68
2	Benzidia et al. [23]	Green process innovation's role in healthcare operations and supply chain management using big data analytics	37	61
3	Khan et al. [24]	A resource-based perspective on green supply chain management in manufacturing companies	74	61
4	Park et al. [25]	First-Tier Suppliers' Green Supply Chain Management Initiatives in the Electronics Industry's Financial and Commercial Results	37	59
5	AL-Khatib and Shuhaiber [26]	Does the performance of green supply chains and green intellectual capital depend on big data analytics capabilities?	47	54
6	Zhang and Liu [27]	Cross-Border E-Commerce Green Supply Chain Model and Action Mechanism Based on Consumer Behaviour	66	48
7	Rabbi et al. [28]	Forecasting Green Supply Chain Performance Using a Bayesian Belief Network	18	45
8	Dong et al. [29]	The interaction mechanism of the integrated green building supply chain and the dynamic development of digital green innovation.	22	41
9	Khan et al. [30]	Achieving Green Consumption Behaviour with Strategic Green Marketing Orientation, Brand Social Responsibility, and Green Image: The Green Paradox in Developing Tourism Supply Chains	36	41
10	Bag et al. [31]	Technological Aspects of Green Supply Chain Management Practices and Their Impact on Business Performance	108	38

Figure 2 presents the network visualization of bibliographic coupling. The five clusters are visibly distinct yet interconnected, reflecting varied thematic directions within the domain of artificial intelligence and sustainable supply chain management. The clusters are labelled through inductive interpretation by revisiting representative articles and synthesizing common themes and research streams.

Figure 2.
Bibliographic coupling for AI role in Industry 4.0 driven sustainable supply chains for SMEs.
Source: Dong, et al. [29], Das, et al. [32], Zhang, et al. [33], AL-Khatib and Shuhaiber [26], Benzidia, et al. [22], Yusuf [34], Benzidia, et al. [23], Wang [35], Matarneh, et al. [36], Bag, et al. [31], Bag, et al. [37], Ocicka, et al. [38], Park, et al. [25], Zeng, et al. [39], Lazarou, et al. [40], Sharma, et al. [41], Khan, et al. [24], Khan, et al. [30], Zulqarnain, et al. [42], Azam, et al. [43], Rabbi, et al. [28], Astawa [44], de Souza, et al. [45], Sharif, et al. [46], Abbasi, et al. [47], Ren, et al. [48], Zhang and Liu [27] and Asadi, et al. [49].

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4.1.1. Cluster 1 (Red): Performance-Driven Green Supply Chain Strategies and Evaluation Frameworks

Internal environmental management, cooperation with customers, and eco-design positively influence economic and business performance in South Korean electronics SMEs, while green purchasing shows no significant impact [25]. Green supply chain management aims to reduce environmental impact and support sustainable growth, with a Bayesian belief network model proposed to predict performance using key indicators, enhancing decision-making and overall organizational effectiveness [28]. Green consumption intention in the hospitality and tourism industry is positively influenced by green supply chain management and strategic green marketing orientation, with green image acting as a partial mediator, while brand social responsibility shows no moderating effect [30]. Green supply chain management, viewed as an integrated system, is influenced by AI-based technologies and strategic processes, which significantly affect environmental, social, and financial performance, with product complexity moderating key relationships within this framework [31]. Environmental, Social, and Governance (ESG) factors are integrated into green supply chain performance evaluation using financial and ESG data from global firms, revealing that operational and environmental performance outweigh profitability, emphasising long-term governance over short-term gains [39].

4.1.2. Cluster 2 (Green): Enablers and Barriers in the Evolution of Sustainable Supply Chains

With rising sustainability concerns after COVID-19, green supply chains have gained attention, and key factors like connectivity, information sharing, and leadership support are shown to positively influence green practices and improve overall green supply chain management through linked relationships [24]. As global supply chains become increasingly complex, sustainability has gained importance, but challenges such as high operational costs and limited awareness hinder green practices; using multi-objective optimisation methods helps balance economic and environmental goals, offering practical ways to improve green supply chain performance and guide future developments [50]. With increasing globalization and industrialization, the need for green and sustainable logistics has become more urgent, prompting global efforts to reduce transport-related environmental impacts and enhance supply chain performance; key themes in this area include environmental policy, technological advancement, and operational strategies, with ongoing challenges and opportunities guiding future research and practice [48]. Organisational citizenship behavior toward the environment (OCBE) strengthens the relationship between green supply chain practices and sustainable performance in manufacturing firms, with significant effects observed across most practices except internal environmental management, offering useful insights for enhancing sustainability and competitive advantage [43].

4.1.3. Cluster 3 (Blue): Circular Economy and Digital Transformation in Green Supply Chains

An increasing number of firms are adopting circular economy frameworks and Industry 4.0 technologies to support sustainable supply chains, with findings showing that integrating green supply chain practices and supply chain flexibility enhances circular capabilities and strengthens corporate sustainability performance [36]. Social structures within organizations play a key role in enhancing SME performance in circular economy supply chains, where institutional pressures drive eco-innovation, which in turn supports green supply chain practices and CE capability, while big data-driven supply chains strengthen the link between CE capability and firm performance but not between GSCM and performance [37]. Addressing food insecurity requires transforming current food systems, and digital technologies such as IoT and blockchain play a crucial role in enhancing green food supply chain management by improving food quality, safety, and reducing waste, with key enablers identified through expert input and ISM-ANP analysis to support progress toward zero hunger [51]. A low-cost, environmentally sustainable traceability platform using Algorand's Green Blockchain was developed for the Fontina PDO cheese supply chain, enabling real-time, immutable data sharing while minimizing

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energy use and transaction costs, thus digitizing and enhancing transparency across the entire production chain [52].

4.1.4. Cluster 4 (Yellow): Technological Integration and Big Data Capabilities in Green Supply Chain Performance

Big data analytics and AI technologies significantly enhance environmental process integration and green supply chain collaboration, which in turn improve environmental performance, with green digital learning strengthening the link between BDA-AI and supply chain collaboration, offering practical insights for improving sustainability in supply chains [22]. Big Data Analytics Capability (BDAC) enhances environmental performance in healthcare by promoting environmental process integration and green process innovation, with green innovation playing a key mediating role, offering practical guidance for integrating sustainability into healthcare operations and supply chains [23]. Environmental awareness is increasingly vital for sustainable supply chains, with findings showing that green human, structural, and relational capital significantly enhance green supply chain performance in Jordan's manufacturing sector, and big data analytics capabilities further strengthen the impact of green relational capital on performance [26]. Green supply chain management positively influences environmental management systems and market competitiveness, with big data analytics, AI, and environmental visibility further strengthening these relationships, highlighting the importance of integrating technology and transparency to sustain competitiveness during crises like Covid-19 [33]. Green supply chain management enhances environmental management systems and market competitiveness, with big data analytics, AI, and environmental visibility strengthening these links during COVID-19, emphasising the strategic value of integrating technology and environmental transparency to sustain competitiveness in China's supply chains [32].

Table 3.
Summary of Bibliographic coupling analysis for AI role in Industry 4.0-driven sustainable supply chains for SMEs.

Cluster No and color	Cluster label	Number of publications	Representative publication
1 (Red)	Performance-Driven Green Supply Chain Strategies and Evaluation Frameworks	13	Park et al. [25], Rabbi et al. [28], Khan et al. [30], Bag et al. [31] and Zeng et al. [39]
2 (Green)	Enablers and Barriers in the Evolution of Sustainable Supply Chains	10	Khan et al. [24], Asha et al. [50], Ren et al. [48] and Azam et al. [43]
3 (Blue)	Circular Economy and Digital Transformation in Green Supply Chains	10	Matarneh et al. [36], Bag et al. [37], Kumar et al. [51] and Varavallo et al. [52]
4 (Yellow)	Technological Integration and Big Data Capabilities in Green Supply Chain Performance	6	Benzidia et al. [22], Benzidia et al. [23], AL-Khatib and Shuhaiber [26], Zhang et al. [33] and [41]

4.2. Co-Occurrence Analysis

The same database was further utilized, where 35 of the 962 extracted keywords, each with five or more co-occurrences, were identified using five separate clusters. The threshold was determined through iterative experiments designed to prevent missing the identification of leading thematic areas and emerging topics within the keyword network. A lower threshold could have resulted in excessive fragmentation, while a higher threshold might have excluded relevant yet developing concepts. The selected value represents a compromise between specificity and generality, aiming to accurately describe the conceptual framework of the field. The most frequently co-occurring words and phrases include terms such as: supply chain management (63 times), sustainability (29 times), and sustainable development (29 times). In Table 4, the most frequent keywords, identified both by frequency and the sum of link strength, are presented within the co-word analysis.

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Table 4.
Top 15 keywords in the co-occurrence of keywords analysis.

Rank	Keyword	Occurrences	TLS
1	Supply chain management	63	214
2	Sustainability	29	111
3	Sustainable development	29	107
4	Green supply chain	26	79
5	Green supply chain management	35	73
6	Supply chains	19	65
7	Green economy	14	52
8	Environmental management	11	46
9	Manufacturing	13	56
10	Decision making	10	37
11	Environmental economics	8	37
12	China	8	37
13	Artificial intelligence	9	35
14	Circular economy	11	33
15	Waste management	6	31

Figure 3 presents the network visualization of co-word analysis, illustrating the intellectual structure and thematic interconnections within the literature on sustainability and supply chain research. The clusters are distinct yet interconnected, highlighting overlapping domains and the emergence of multidisciplinary themes. These clusters were labelled through inductive interpretation by examining representative keywords within each group and synthesizing them based on shared research directions.

Figure 3.
Co-word analysis of for AI role in Industry 4.0-driven sustainable supply chains for SMEs.

4.2.1. Cluster 1 (Red): Technological Innovations and Decision Models for Sustainable Green Supply Chains

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Web 3.0 enhances green supply chains by enabling decentralized decision-making, secure and trustless cooperation, and efficient knowledge sharing, leading to improved resilience and environmentally sustainable performance [53]. To reduce carbon emissions and enhance social development, ESG is integrated into green supply chain performance using real-world data and the entropy weight method, revealing that operational and environmental performance outweigh profitability, guiding firms toward long-term sustainable strategies [39]. A q-ROFSS-based fuzzy hybrid model, enhanced with advanced TOPSIS and correlation measures, improves multi-attribute decision-making and proves effective in evaluating green supply chain suppliers under uncertainty [54].

4.2.2. Cluster 2 (Green): Circular Economy, Digital Transformation, and Optimisation in Green Supply Chains

Green supply chain management and strategic green marketing significantly enhance green consumption intentions in tourism, with green brand image partially mediating the relationship, while brand social responsibility does not moderate the effect [30]. A bibliometric review of 22,625 articles highlights the global growth of reverse logistics and sustainability, identifying key authors, countries, and journals while revealing emerging trends such as Industry 4.0 technologies and the integration of reverse logistics with sustainability and the circular economy [55]. A green closed-loop supply chain model, incorporating real-world constraints and demand uncertainty, effectively minimizes emissions and costs while maximizing shipments, with NSGA-II outperforming other methods in generating diverse and optimal solutions [56]. Digital transformation and circular economy practices significantly impact the economic and environmental performance of Indian FMCG companies, with technological advancements directly influencing both dimensions, as revealed through SEM analysis of responses from 203 senior managers [57]. Internet of Things (IoT) and big-data-driven supply chain technologies significantly enhance firm performance in the fast fashion sector by promoting green supply chain and circular economy practices, with BDSC further strengthening these effects and supporting environmental sustainability [58].

4.2.3. Cluster 3 (Blue): Data-Driven Insights and Strategic Technologies for Environmental Performance

A positive and significant relationship exists between green supply chain management practices and environmental performance in Latin American companies, with key influencing practices including environmental management with total quality, supplier cooperation, and cross-functional collaboration for environmental improvements [59]. Artificial intelligence adopted by focal firms significantly reduces carbon emissions among associated supply chain partners, mainly through substantive green technological innovation, with vertical supply chain interactions and horizontal industry effects further amplifying this decarbonisation impact [60]. Green supply chain management positively influences environmental management systems and market competitiveness, with big data analytics, AI, and environmental visibility strengthening these relationships, especially during COVID-19, highlighting their strategic role in enhancing organizational performance in China [32].

4.2.4. Cluster 4 (Yellow): Comparative and Visualization Approaches in Green Logistics and Urban Sustainability

A comparison of academic literature and industry reports shows that green logistics practices have long been implemented by major logistics providers, while academic progress lags due to structural delays and a reactive research approach, highlighting the need for more proactive, practice-oriented collaboration in the L&SCM field [61]. A multidimensional visualization method combining memory-based clustering and Vue's MVVM framework enables interactive, accurate analysis of green urban data, promoting eco-friendly design and low-carbon practices across industrial and supply chains [35]. A q-ROFSS-based fuzzy hybrid model with enhanced TOPSIS and correlation measures effectively handles multi-attribute group decision-making, proving superior in evaluating green supply chain suppliers under uncertainty through improved consistency and comparative performance [54]. A comparative analysis of logistics operators in Poland and Ukraine reveals similarities and differences in

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promoted environmental initiatives, including eco-friendly programs, CSR, emission reporting, and sustainable practices, highlighting customer perceptions of these efforts [62].

4.2.5. Cluster 5 (Purple): Emerging Practices and Strategic Perspectives in Sustainable Supply Chain Management

Reverse logistics adoption positively influences firms' digitalization and inter-organizational collaboration, with knowledge gained from sustainable practices acting as a key enabler, especially for resource-constrained firms seeking to advance beyond circular economy goals [63]. Green packaging research has gained momentum in recent years, with increasing focus on its business and consumer impacts, including design, cost, marketing, CSR, and its role in the circular economy and supply chains, highlighting its growing relevance for sustainable development [64]. Green innovation and green supply chain practices, particularly customer cooperation and green procurement, positively impact ecological sustainability, while TQM shows no significant effect, and internal environmental management strengthens the link between customer cooperation and environmental performance [65]. Over recent decades, firms have increasingly prioritized green supply chain management to address environmental challenges and maintain competitiveness, with this study reviewing its definition, evolution, components, performance indicators, implementation challenges, opportunities, and future directions [66].

Table 5.
Summary of co-word analysis for AI role in Industry 4.0 driven sustainable supply chains for SMEs.

Cluster No and color	Cluster label	Number of keywords	Representative Keywords
1 (Red)	Technological innovations and decision models for sustainable green supply chains	10	Sustainable development, green supply chain, decision making
2 (Green)	Circular Economy, Digital Transformation, and Optimisation in Green Supply Chains	9	Supply chain management, sustainability, green supply chain management, green economy, China
3 (Blue)	Data-Driven Insights and Strategic Technologies for Environmental Performance	7	Artificial intelligence, environmental management, green supply chain management,
4 (Yellow)	Comparative and visualization approaches in green logistics and urban sustainability.	5	Green logistics, environmental sustainability, optimization, sustainable supply chain
5 (Purple)	Emerging Practices and Strategic Perspectives in Sustainable Supply Chain Management	4	Circular economy, waste management, Industry 4.0, supply chain

5. Implications

This research holds significant value to both academia and the industry regarding Artificial Intelligence-based green supply chain transformation. It adds value to the theoretical perspective of supply chain and sustainability, considering the introduction of digital intelligence as enabling. In the practical sense, it provides managers with definite plans to introduce AI technologies that support sustainable operations. Both theoretical and managerial implications are elaborated in the sections that follow.

5.1. Theoretical Implications

The current study is immediately connected to the theoretical knowledge about industrial sustainability in the context of Industry 4.0 and Industry 5.0, in which the position of digital technologies predetermines the redirection of environmental governance, innovations, and operational excellence. This study is a contribution to the existing body of research within the field of sustainable supply chain management as it elevates the transformational capabilities of Artificial Intelligence and promotes sustainability actions. Operation compliance, process, and environmental constraint policies

have been the traditional theories of green supply chains. The AI integration changes this fact by adding an adaptive data-driven layer to sustainability and transforming it into a proactive and strategic initiative rather than a reactive one [67]. Businesses might modify their sourcing or logistics in response to the unusual demands of the environment by using predictive analytics and machine learning. This transformation requires intellectuals to restructure linear concepts and integrate the concepts of digital mechanisms into sustainability theory [68]. Sustainability is now considered an innovation-driven initiative as opposed to a regulated activity. AI opens the doors to the optimization of processes that would not be considered in real-time because of limited possibilities in manual planning. The theoretical prism needs to be enlarged to a higher extent of algorithmic thinking and digital prediction. As such, the future models must have this convergence of environmental ambitions and digital potentials.

Development of the resource-based view (RBV) and the dynamic capability theory, this paper identifies digital infrastructure, data preparedness, and organizational learning as essential intangible resources for sustainability. Earlier literature emphasized traditional environmental capabilities such as waste reduction and energy control. However, new research reveals that AI literacy, real-time analytics, and digital culture form key competencies in sustainable supply chains [69]. Such results are foundational in the adjusted model of RBV in the view of green competitive advantage presented through digital assets. Specifically, AI abilities promote ongoing energy and response modifications with self-teaching systems. These systems enable companies to make precise decisions based on uncertainty and react quickly to the needs of sustainability. The creation and optimization of AI models towards the achievement of environmental goals is part of dynamic capabilities. Firm-specific circumstances, including industry type and the complexity of the supply chain, should not be ignored in this theory either. As complements to the maturity models, there exist referents including the Urban Smart Factory (USF) framework depicting the necessity of combined evaluation of the factors of digitalisation, productive capabilities, and sustainability in manufacturing SMEs [70]. Emergence of AI has the potential, therefore, to be described as the advancement of firm sense, capture, and transformation, which are aimed at achieving sustainability.

The results of the current research are also useful to institutional theory in the sense that they show the interaction between the internal and external forces within the framework of the green transformation currently driven by AI. The pursuit of regulatory pressure and consumer expectations is not a safe bet on sustainable results until there is sufficient digital and organizational preparedness. The research upholds the fact that co-constructed environmental legitimacy exists between the institutional commands and technological expertise [71]. Institutions that operate within highly regulated environments implement AI more rapidly; however, only institutions with internal digital maturity will be successful in implementing AI. This implies that, in the theory of sustainability, we cannot dismiss the consideration of institutional and technological aspects. Researchers should examine the role of firm size, industry maturity, and governance structure as mediating factors in this interaction. Less theoretically, one might also investigate situations where parties in a conflict receive mixed signals from institutions, such as the conflict between cost-efficiency and ecological responsibility faced by firms. It will require hybrid models that combine external pressures with internal capacity. This approach enhances the universality of institutional theory in the context of the digital shift toward sustainability.

5.2. Managerial Implications

The implication of this study for practitioners is practical, i.e., it will enable them to appreciate how AI can facilitate the promotion of sustainability goals across the entire supply chain. Managers must not view AI as merely a digital upgrade but as a strategic tool that will support green transformation. Artificial intelligence can be used to track real-time emissions, forecast supply chain crises, and optimize resource utilization. It serves as a data-driven, sustainability-oriented decision-making tool. Companies can reduce their carbon footprint, minimize operational waste, and enhance environmental compliance through the application of AI [72]. Predictive models allow firms not only to respond to environmental

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threats but also to be proactive. It is also mentioned that through the application of AI, companies benefit in terms of reputation and policy alignment among humans. The sustainability of competitiveness can be long-term, thus, active investment in AI is essential. Managers ought to evaluate in which areas AI can be used to replace outdated manual systems that no longer meet current sustainability targets. To effect a green transformation, it is important to align digital tools with the strategy.

Additionally, advances in technology and internal organizational readiness are key factors for effectiveness when adopting AI to attain sustainability. To integrate IT and sustainability skills, managers must establish cross-functional teams. Employee training in environmental analysis and AI tools is an effective strategy to reduce the digital gap. Leaders need to create an environment that encourages creativity, experimentation, and learning. It is established that the more well-established data governance and digital capabilities a firm has, the greater the returns from AI initiatives [73]. There must be an organizational structure that enables coordination across departments to establish a clear path in digital and green priorities. The establishment of measurable KPIs (Key Performance Indicators) related to digital utilization and sustainability is essential to carry accountability personnel [74]. To prevent resource limitations, smaller firms take initial steps with affordable, scalable solutions. In transition, a central role should be given to leadership that helps clarify goals and invest in upskilling. Sustainability practices are undergoing a digital transformation that must start internally and be supported by change management.

In this paper, there is also an emphasis on the importance of partnering with external stakeholders to realize AI-led sustainable supply chains. The management must build tactical links with vendors of technologies, suppliers, and regulatory agencies. Collaborative innovation minimizes the cost of AI implementation, and it also increases data-sharing practices. The transparency of the supply chain is enhanced due to the integration of AI-enabled dashboards into the systems of partners [75]. Funding, infrastructure, and training programs are made accessible by means of public-private partnerships. The implication of this study for practitioners is practical, i.e., it will enable them to appreciate how AI will facilitate the promotion of sustainability goals across the entire supply chain. Managers must not think of AI as a digital upgrade in itself but as a strategic device that will ease the green transformation. Artificial intelligence can be used to track real-time emissions, forecast supply chain crises, and optimize resource utilization. It is a data-driven, sustainability-oriented decision-making tool. Companies can reduce their carbon footprint, decrease operational waste, and enhance environmental compliance through the application of AI [76]. Predictive models allow firms to not only respond to environmental threats but also to be proactive. It is also mentioned that through the application of AI, companies benefit in terms of reputation and policy concord among humans. The sustainability of competitiveness can be long-term; thus, active investment in AI is essential.

6. Limitations

This research identifies some constraints that undermine the generalizability of research results. First, the bibliometric analysis's primary focus is on published literature, which might filter out potentially pertinent data extracted from reports from the industry and grey literature. This limitation might result in a limited concept for AI-driven sustainable supply chains presently [77]. Second, the report mostly exhibits trends according to developed economies, and thus, it is possible that the requirements of an SME and an organization in a developing economy still have gaps [78]. Moreover, there is the risk of oversimplification in conceptualizing relationships and themes in the literature since this strategy only relies on the frequency of words that often occur together [79]. Finally, technology and the practice of sustainability are dynamic, so the results may quickly become obsolete, and the literature review will have to be updated regularly [80].

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7. Future Research Avenues

As a limitation of future research, it will be necessary to consider the following points. First, grey literature and case studies of SMEs in developing countries should be added to the studies to have a better picture of the role played by AI in sustainable supply chains [81]. Second, longitudinal resources that follow the development of AI technologies in sustainable practices would be beneficial to recognize long-term effects and tendencies [82]. Moreover, the relationship between organisational culture and AI adoption needs to be subjected to research that will examine the effects of internal roles in enhancing the performance of AI to meet the objectives of sustainability [83]. Finally, the exploration of the potential impact of the regulatory environment on the AI implementation strategy in various industries would assist in evaluating the threats and opportunities that certain settings can introduce more effectively [84].

8. Conclusion

To sum up, AI implementation in supply chains is a groundbreaking opportunity to enhance sustainable practices. This article states that AI technologies promise significant benefits in optimizing resource consumption, reducing emissions, and facilitating the transition to a circular economy. However, there are notable gaps, including the limited experience of SMEs in developing countries and organizational factors that influence the effective adoption of AI-based technologies. Addressing these gaps through future research will provide valuable insights for both academia and industry, supporting the development of sustainable supply chain management in an increasingly digital world. The implementation of AI concerning industrial sustainability and ongoing industrial revolutions will be advanced by this study, highlighting the importance of integrating digital intelligence and sustainability strategies at organizational and policy levels. Companies transitioning to Industry 4.0 and 5.0 models, where environmental performance becomes a competitive advantage and regulatory requirement, must demonstrate such alignment.

The proactive attitude toward the use of AI will be required due to long-term operational and environmental success, particularly as organizations cannot find their way out of the sustainability maze. The two advantages of having technological innovations aligned with environmental goals are streamlining operations and increasing competitive advantage. In addition, the promotion of a culture of unceasing development and collaboration among stakeholders will be instrumental in eradicating existing obstacles. Conclusively, the right implementation of AI in sustainable supply chains can potentially have substantial positive effects on businesses and the environment.

Use of AI Tools Declaration

We have not used artificial intelligence (AI) tools to create this article.

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Transparency:

The authors confirm that the manuscript is an honest, accurate, and transparent account of the study; that no vital features of the study have been omitted; and that any discrepancies from the study as planned have been explained. This study followed all ethical practices during writing.

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