Noname manuscript No.
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Revolutionizing Supply Chain Management: Emerging Trends and Strategies for the Future

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Received: date / Accepted: date

Abstract Supply chain management involves the end-to-end process of sourcing raw materials, manufacturing, and distributing products or services to the final consumer. The goal is to optimize operations, reduce costs, improve efficiency, and enhance customer satisfaction. The emergence of Industry 4.0, driven by digitalization and new information technologies, has marked the advent of a new era in supply chain management: Supply Chain 4.0. This article provides an overview of traditional supply chains, detailing their components and evolution. It also examines the core elements of Industry 4.0 and introduce the vision for Supply Chain 5.0. By combining an analysis of existing literature, data collection, and the authors' insights, it offers a comprehensive view of the current state and future potential of modern supply chain management.

Keywords Supply Chain · Industry 4.0 · Industry 5.0 · Big Data · Smart Manufacturing · Digitalization · Decision Making

1 Introduction

Logistics is a vital economic activity for companies, involving the efficient management of costs associated with the flow of raw materials, semi-finished products, and finished goods from their point of origin to the point of consumption [1]. The management of these logistics flows encompasses various functions, including customer service, demand forecasting, inventory control, procurement and negotiation, order processing, transportation planning and execution, packaging, handling, warehousing, after-sales service, processing of returns, and the reuse or disposal of items [2].

These logistics activities fall under the broader framework of supply chain management (SCM). Within this framework, transportation and inventory management are considered the two most critical components. Managers continually

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seek to optimize these components through a variety of software tools and digital platforms, which are constantly evolving to meet organizational needs. Technological advancements have greatly enhanced data acquisition and sharing among supply chain stakeholders, providing companies with increased visibility into physical flows, operational actions, and the transformations they undergo in real time [3,4].

Data analysis within supply chains has become an essential asset for companies striving to manage physical flows through their informational counterparts [5]. This discipline focuses on generating value from data produced by resources along the supply chain. Increasingly, industries are leveraging data science and artificial intelligence (AI) not only within their core operations but also throughout upstream and downstream activities [6]. These technologies are now widely applied to identify strengths and weaknesses in the supply chain and to support rapid, informed decision-making [7]. Such practices are common in sectors including pharmaceuticals, manufacturing, food, chemicals, engineering, and automotive industries [8,9,10], helping companies adapt more effectively to a dynamic market environment.

This article aims to provide a comprehensive overview of the emergence of Supply Chain 4.0, a concept heavily influenced by Industry 4.0 and the integration of advanced information and communication technologies across the supply network. We also discuss the fundamental role of data science, artificial intelligence, supply chain analytics and digitalization in driving this transformation. Our main research question explores the significance and impact of these technologies on the modern supply chain.

By investigating the applications of data science, AI, analytics, and digitization, we seek to reveal the value they offer to businesses. Our focus lies in understanding how these technologies enable granular data analysis, equipping logistics managers and decision-makers with actionable insights. These insights are crucial for identifying inefficiencies and anomalies in industrial processes and for supporting more effective, real-time decision-making.

To this end, we conducted a comprehensive literature review using academic databases and targeted keywords. Articles were selected based on predefined quality criteria to ensure the inclusion of credible and impactful sources. A rigorous methodology was then applied to interpret and synthesize the findings from the selected literature. Through this review, we aim to shed light on the role of digital technologies in shaping the future of supply chain management.

The remainder of this article is structured as follows. Section 2 revisits the core components of supply chain management. Section 3 examines the evolution of the supply chain over time. Section 4 introduces the concept of Industry 4.0 and its influence on the emergence of Supply Chain 4.0, as well as possible future transformations. Finally, Section 5 presents our conclusions and outlines potential research directions.

2 Supply Chain Trends

In this section, we introduce the concept of traditional Supply Chain Management (SCM) and its main components. We will then examine the different forms that the supply chain has taken since its inception and how these have shaped its evolution towards new paradigms, paving the way for the emergence of Supply Chain Management 4.0 (SCM 4.0).

2.1 Supply Chain Management

Supply chain management is commonly defined as the coordination and oversight of the flow of goods and services, encompassing all activities involved in transforming raw materials into finished products [11]. It reflects the collective efforts of multiple actors within a logistics network to design and implement an efficient and cost-effective supply chain. SCM covers the full spectrum of logistical operations in a company, integrating information systems to manage activities from raw material procurement, through production and development, to distribution and the final sale of goods to end customers [12].

SCM can also be understood as a strategic optimization concept that integrates logistics activities into business processes [13]. It is structured around three key flows, as illustrated in Figure 1: the product flow, the information flow, and the financial flow [14]. The product flow refers to the physical movement of goods, from raw material extraction to delivery of finished products. The information flow involves the transmission of orders and the tracking of shipments. Finally, the financial flow covers aspects such as credit terms, payment schedules, consignment, and ownership agreements [12].

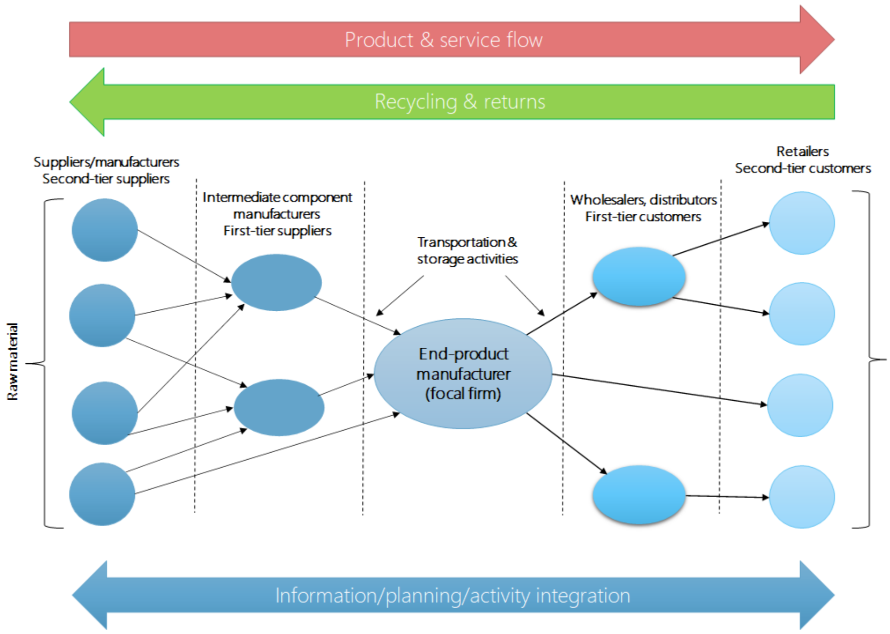


Fig. 1 Supply chain components

Logistics activities are critical for planners and managers to monitor and control in order to maximize efficiency and profitability while minimizing waste. A significant portion of logistics cost optimization hinges on the effective management of transportation and warehousing operations [15]. The logistics process involves a combination of organizations, methods, and technologies aimed at optimizing the flow of raw materials, intermediate goods, and finished products. This optimization improves the efficiency of usage, transport, distribution, and the allocation of financial and physical resources [16]. Below, we briefly describe the two most strategic components of logistics: transportation and inventory management.

Transportation management is a cornerstone of logistics. It connects supply chain nodes—such as plants, warehouses, and distribution centers—and enables the delivery of goods to meet customer demands [17]. Transportation also represents a significant cost factor. In many industries, it is the largest logistics expense, and its proper management is essential for minimizing overall supply chain costs [1]. Therefore, optimizing transportation variables, from suppliers to end customers, is crucial for operational efficiency.

Inventory management in industrial environments refers to the control of material or product stock throughout the supply chain—from manufacturer to warehouse to point-of-sale. This activity involves planning and implementing strategies to maximize profit by minimizing storage levels and durations [16]. The primary goal is to maintain the right inventory, in the right location, at the right time, thus avoiding unnecessary storage costs. To achieve this, companies increasingly shift from traditional, localized inventory policies to more efficient, integrated (or global) inventory strategies [18].

This shift has given rise to collaborative and shared inventory strategies that offer increased visibility, flexibility and cost savings [19]. Among these, Vendor-Managed Inventory (VMI) has emerged as one of the most widely adopted approaches. VMI is a collaborative inventory policy where suppliers have real-time access to customers' stock levels, allowing them to proactively plan and manage replenishment [20]. The rise of digital technologies has made such approaches increasingly accessible and effective.

2.2 Supply Chain Transformation Progress

Since the emergence of the Supply Chain concept—which was inspired by logistics activities, organization, and methods—this notion has continued to evolve, progressively integrating new dimensions aligned with the requirements of each era. In this subsection, we present the different variants of the Supply Chain currently observed in commercial and industrial environments.

Lean Supply Chain: A lean supply chain is designed to operate in the most optimal way possible [21]. Its objective is to deliver goods or products to the end customer efficiently, minimizing waste and losses while remaining flexible enough to handle unexpected delays. Lean supply chain management focuses on the relentless elimination of non-value-added time and the continuous reduction of lead times at every stage, from raw material production to final product delivery [22]. The lean approach extends upstream to supplier management, downstream to distribution networks, and broadly to the coordination of the overall supply chain [23].

Agile Supply Chain: An agile supply chain emphasizes responsiveness, competence, flexibility, and speed in daily operations, with resilience and adaptability as key traits [24]. It is built to respond rapidly to fluctuations in demand, customer preferences, and market conditions [25]. Agility also helps prevent shortages and avoid excess inventory by leveraging real-time data and aligning operations with accurate demand forecasts, thereby enhancing overall efficiency and productivity [26].

Global Supply Chain: Global supply chains are networks spanning multiple countries and continents, organized to acquire and deliver goods and services. This type of chain involves cross-border coordination of logistics and includes all stages of product or service creation and distribution [27]. It encompasses foreign direct investments by multinational enterprises, either through wholly owned subsidiaries or joint ventures, where the enterprise manages employment relationships directly [28]. It also includes international sourcing models where collaboration is defined by contracts or tacit agreements with suppliers and subcontractors [29].

Green Supply Chain: A green supply chain aligns with a company's environmental policies and focuses on eco-friendly practices throughout the value chain [30]. Its goals include reducing energy consumption (e.g., water, electricity, fuel), minimising pollution through cleaner materials and technologies, lowering carbon footprints, promoting reverse logistics, and securing flows [31]. It also contributes positively to brand image, offering companies a long-term competitive edge by aligning with growing environmental awareness among consumers [32].

Supply Chain Resilience: Resilience in the supply chain refers to its ability to anticipate, withstand, adapt to, and recover from disruptions such as economic crises, natural disasters, pandemics, or cyberattacks [33]. Key strategies include supplier diversification, the use of technologies such as AI and blockchain, and predictive modelling to detect vulnerabilities [34]. Resilient supply chains are characterized by flexibility, strategic stockpiling, and strong collaboration between stakeholders, ensuring business continuity and sustained competitive advantage [35].

Sustainable Supply Chain: A sustainable supply chain integrates ethical, social, and environmental practices into a competitive and efficient model [36]. It aims to reduce environmental damage through energy efficiency, water conservation, and waste reduction while positively contributing to local communities [37]. Unlike green supply chains, which focus mainly on environmental health, sustainable supply chains address broader concerns such as climate change, deforestation, human rights, fair labour and anti-corruption [38].

Social Supply Chain: Social supply chain management incorporates social networks, interactions, and data to improve stakeholder relationship management and maximise value creation at reduced costs. It focusses on employee and customer retention, compliance with social standards, and integration of fair trade and social equity principles [39]. It ensures proper labour, safety, and ethical standards while contributing to global well-being by improving the accessibility and quality of life of products [40].

Governance Supply Chain: Supply chain governance involves the initiation, development, and maintenance of relationships across the supply chain. It governs the allocation of financial, material, and human resources, and provides the framework for decision-making processes. Unlike supply chain management, which is product-focused, governance offers a holistic perspective of the system and its stakeholder synergies [41]. It ensures the enforcement of policies, supports risk management, enhances profitability, and addresses regulatory and sustainability agendas. Real-time data is crucial for informed decision-making, supplier management, and transparency [42].

Digital Supply Chain: The digital supply chain connects all actors through real-time data sharing, enhancing visibility and coordination throughout operations. It involves leveraging digital technologies to generate new value and revenue streams [43]. Performance indicators and safety standards can be monitored digitally, enabling analysis and scenario forecasting [44]. Initiated in Industry 3.0 and expanded by Industry 4.0, the digital supply chain plays a key role in modern logistics—a topic developed in the next section [45].

These variants coexist and continue to evolve. Many hybrid models have emerged to improve supply chain management and have been the subject of academic research. Further developments are expected as technological and organizational advancements continue. Additionally, alternative supply chain classifications can be explored, such as those based on modes of transportation. While road transport is the most common, other modes—such as maritime [46], air freight [47], and multimodal logistics [48]—have given rise to new supply chain paradigms due to their importance in domestic and international trade.

3 Supply Chain 4.0

In the previous section, we introduced the concept of supply chain management (SCM) and its main variants as described in the literature. In this section, we focus on the impact of Industry 4.0 on supply chains, highlighting the integration of advanced technologies that are profoundly transforming traditional industrial processes. This transformation is reflected in increased digitisation, advanced automation and increased flexibility of logistics systems, which we will describe in more detail in this section.

3.1 Impact of Industry 4.0 on the Supply Chain

The integration of IT concepts into industrial firms is not a recent phenomenon, as the supply chain has long incorporated information flow as a central component. Automation and the use of Information and Communication Technologies (ICT) began during Industry 2.0 with the introduction of electronic devices in production units [49]. This integration matured with Industry 3.0, marked by the adoption of computers, robots, barcode/RFID tracking systems, and software platforms (e.g., mailing systems and EDI) to facilitate information exchange and automate planning and scheduling tasks [50].

With the technological advancements of the past decade, we are now in the era of Industry 4.0—a paradigm shift impacting the entire industrial process and, by extension, the supply chain [51]. From this transformation arises the concept of Supply Chain 4.0, which will be explored in detail in the following subsections. Industry 4.0 has introduced several innovative concepts that have redefined traditional supply chains, with three major interconnected and interdependent pillars:

- Digitization of the supply chain
- Smart manufacturing
- Big data analytics

Digitization refers to the widespread implementation of digital technologies and information systems throughout the supply chain network [52]. This facilitates real-time data exchange, enhanced visibility, and improved communication and collaboration between stakeholders.

Smart manufacturing incorporates technologies such as the Internet of Things (IoT), automation, and robotics to streamline production processes, increase efficiency, and enable greater customization and responsiveness [53].

Big data analytics involves collecting, processing, and analyzing the vast amounts of data generated across the supply chain [54]. These analytics offer actionable insights, allowing firms to identify trends, anticipate disruptions, and make data-driven decisions for continuous improvement.

Figure 2 illustrates a conceptual framework of digital supply chains, highlighting the integration of connected technologies and their role in transforming traditional operations. In the following subsections, each of these core concepts is analyzed, emphasizing their interconnections and practical implications.

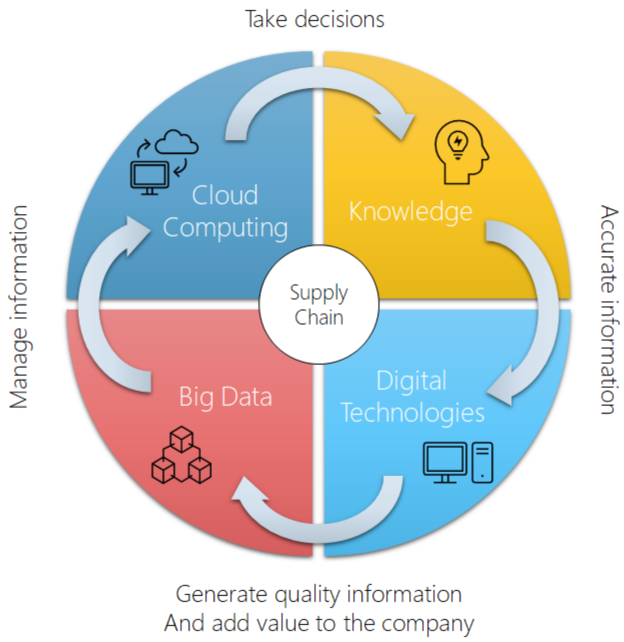


Fig. 2 Conceptual Digital Supply Chain

By focusing on these three pillars (digitization, smart manufacturing, and big data analytics), we aim to explore how Industry 4.0 is reshaping supply chains into intelligent, connected ecosystems.

3.1.1 Digitization of the Supply Chain

To enable seamless interconnection between different supply chain links, the concept of the Digital Supply Chain (DSC) has emerged [55]. While earlier phases of industrial development introduced information systems and machinery [50], the DSC advances this evolution by digitizing both horizontal and vertical value chains, digitalizing products and services, and enabling new business models and customer experiences [56, 57].

DSC implementation is built on technologies such as machine-to-machine (M2M) communication, networked systems, sensors, RFID tags, and advanced telecommunication tools. These technologies have reached every level of the supply chain, providing real-time visibility and connectivity, particularly through innovations like cyber-physical systems and IoT, which improve collaboration and information flow between production and distribution processes [58].

Moreover, cloud computing has enabled borderless collaboration and massive information sharing across global supply chains [55]. Blockchain technologies represent another significant leap, facilitating secure, transparent, and authenticated exchanges of logistics information and business agreements [59, 60].

According to [61], the Smart Supply Chain is a critical component of Industry 4.0, encompassing digitally connected suppliers, retailers, partners, and customers. Enhanced coordination and information sharing reduce costs and boost efficiency and agility [61, 62]. This transparency strengthens collaboration and trust among all supply chain actors.

In addition to the core pillars, edge computing and smart contracts are emerging technologies that further empower Supply Chain 4.0. Edge computing decentralizes data processing, enabling faster decision-making and autonomous operations, while smart contracts ensure secure, automatic contract execution. Together, these technologies enhance responsiveness, security, and operational fluidity [63, 64].

3.1.2 Smart Manufacturing

The transition to smart manufacturing is largely driven by the technologies outlined above. Intelligent manufacturing integrates a wide range of systems—from intelligent agents to autonomous control mechanisms—to facilitate dynamic and self-regulating production [65].

This transformation extends beyond the factory floor to the entire supply chain ecosystem. Intelligent manufacturing facilitates real-time data sharing, predictive analytics, and enhanced automation. These capabilities lead to improved operational efficiency, reduced lead times, and higher product quality [65].

Additionally, the incorporation of smart technologies in business control systems enhances coordination, synchronization, and visibility across the supply chain [66]. This enables informed and timely decision-making, better demand-supply alignment, resource optimization, waste reduction, and a shift towards sustainable and responsive manufacturing systems [67].

Key developments include self-monitoring machines that autonomously identify and rectify process anomalies, thus safeguarding product quality [58]. Smart planning systems now factor in machine capacity and changeover times to generate optimized and agile schedules [68].

The rise of additive manufacturing and 3D printing offers further potential by minimizing the need for physical transportation. These technologies allow for on-demand, local production of customized products [61]. Coupled with advanced simulation tools and design software, smart factories now support virtual prototyping, improving design accuracy and speeding up time-to-market [69].

3.1.3 Big Data Analytics

The third foundational element of Industry 4.0 is Big Data Analytics (BDA) a subfield of data science focused on real-time data stream analysis. BDA examines the interrelations among data, processes, and decision-making systems [70], helping organizations anticipate and respond to future events. BDA is rapid evolution has been fuelled by the vast technological infrastructure of modern supply chains [71].

As supply chains generate increasingly complex and voluminous datasets, advanced tools are needed to manage and extract meaningful insights [72, 73]. BDA addresses this challenge by analysing data from various sources—inventory levels, production logs, sensor readings, customer interactions, and social media—to enable predictive analytics, risk mitigation, and performance optimization.

BDA enhances demand forecasting, inventory management, predictive maintenance, and real-time routing optimization. These capabilities lead to improved operational visibility, customer satisfaction, and cost efficiency [74]. Currently, over 43% of companies are leveraging BDA to drive core operations [58].

By enabling rapid and fact-based decision-making, BDA provides firms with competitive advantages such as agile logistics, real-time monitoring, and personalized customer experiences [75, 76]. In summary, BDA's integration into the supply chain facilitates systematic, data-driven performance optimization and enables superior responsiveness in increasingly dynamic environments.

3.2 Supply Chain 4.0: The Genesis of the Concept

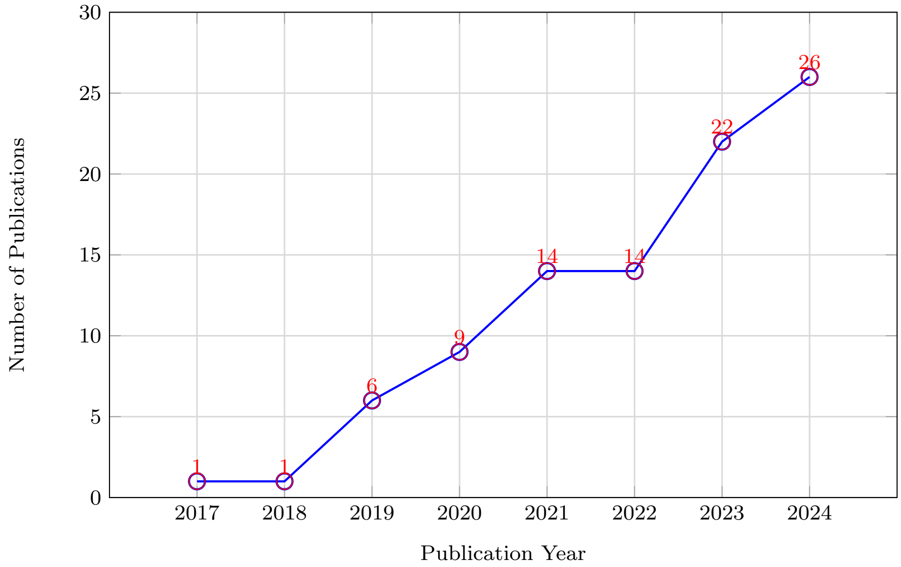
In today's fast-paced global market, traditional supply chains face unprecedented challenges, including disruptions from geopolitical tensions, climate change, and evolving consumer demands [77, 78]. In response to these complexities, the concept of Supply Chain 4.0 has emerged, leveraging cutting-edge technologies such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain to create more resilient, efficient, and transparent supply chains [79, 80]. This evolution marks a significant departure from earlier models, aiming to address both current and future challenges.

Supply Chain 4.0 represents the latest advancement in the supply chain industry, driven by the integration of these transformative technologies [81, 82]. Unlike previous iterations, it seeks to improve efficiency, transparency, and collaboration across all stages of the supply chain process. For example, companies like Amazon have incorporated AI and robotics into their warehouses to optimize inventory management and reduce delivery times [83]. Similarly, Tesla uses IoT-enabled sensors to monitor its supply chain in real-time, ensuring seamless coordination between suppliers and production facilities [84]. Additionally, Walmart employs blockchain technology to enhance traceability and transparency in its food supply chain, addressing consumer concerns about product safety and sustainability [85].

AI integration enables predictive analytics, which allows companies to forecast demand more accurately and optimize inventory management [77]. The IoT provides real-time tracking of goods and assets, enhancing visibility across the entire supply chain [86]. Meanwhile, blockchain technology ensures data integrity and transparency, enabling secure and tamper-proof record-keeping [80, 87].

In our research, we broaden the scope beyond Industry 4.0-centric analytics to adopt a more holistic approach, focusing on the entirety of the 4.0 supply chain. By analysing upstream data—such as from raw material suppliers—we gain a predictive view of available or missing resources. The use of AI and communication channels has fundamentally transformed and enhanced the performance of today's supply chains, giving rise to the concept of Supply Chain 4.0 [51, 88]. This new paradigm was only recently introduced. According to the Web of Science, the first publication referencing it dates back to 2017, with 41 publications emerging since then. The concept of Supply Chain 4.0 is still in its early stages, but its momentum has increased rapidly, especially in research since 2020. This is reflected in Fig 3, which illustrates the growing number of publications on this topic over time.

Fig. 3 Number of Supply Chain 4.0 publications (Web of Science Core Collection)



As shown in Fig 3, the number of publications related to Supply Chain 4.0 has grown significantly since 2020, indicating a rising interest in this field. This aligns with the accelerating adoption of Industry 4.0 technologies across various industries, underscoring the need for further exploration of their implications for supply chain management [77].

The impact of Industry 4.0 and its disruptive technologies on supply chains has been a relatively under-explored area in the literature. Several studies have examined the relationship between Industry 4.0 and supply chains, defining the emerging field as Supply Chain 4.0 [51, 88]. These studies emphasize that Supply Chain 4.0 is not just about technology adoption; it also involves understanding the necessary capabilities—such as infrastructure, skilled personnel, and effective coordination—to implement Industry 4.0 technologies successfully and maximize their impact on supply chain performance and strategic goals.

Both academics and practitioners have given significant attention to the concept of Supply Chain 4.0, with numerous frameworks proposed for developing a Supply Chain 4.0 strategy [81]. These frameworks typically address key aspects like strategy formulation, disruptive technologies, required capabilities, implementation challenges, and the impact of these technologies on supply chain performance. The ultimate goal of Supply Chain 4.0 is to achieve mass customization while enhancing supply chain transparency, responsiveness, efficiency, waste reduction, and flexibility [87,89].

In summary, Supply Chain 4.0 represents a transformative shift in SCM, driven by the integration of advanced technologies. Although it is still evolving, its potential to improve efficiency, transparency and resilience is clear. However, as the literature suggests, more research is needed to fully address the challenges and opportunities associated with its implementation. In the following section, we explore these issues in greater depth, highlighting key research gaps and providing specific examples.

4 Future Research Directions in Supply Chain Management

The transition from Supply Chain 4.0 to 5.0 underscores the critical need to integrate technological advances with societal and environmental imperatives [90]. Although Supply Chain 4.0 has driven efficiency improvements through digitisation, its shortcomings in addressing systemic challenges, such as climate change, ethical labour practices, and geopolitical disruptions, highlight the need for transformative research. In the following, we outline key research areas, supported by real-world examples and actionable research questions, to guide future research.

4.1 Artificial Intelligence (AI) and Machine Learning (ML) Applications

Recent developments in Artificial Intelligence (AI) and Machine Learning (ML) have significantly contributed to improving forecasting accuracy, demand planning, and anomaly detection in supply chains [91,92]. However, current research highlights limitations in their adaptability to unexpected disruptions and complex socio-political environments. For instance, AI models trained on historical data often fail to predict non-linear shocks, such as those induced by pandemics or geopolitical crises, due to their reliance on past patterns rather than real-time systemic dynamics [93,81]. Furthermore, ethical issues such as algorithmic bias and opacity raise concerns about their deployment in global and labour-intensive supply chains [94], particullarlywhen decision-making lacks transparency or exacerbates existing inequalities.

Future research directions may include:

- Developing adaptive learning frameworks that integrate real-time socio-environmental variables;
- Designing ethical AI governance mechanisms that ensure fairness and transparency across global supply chains.

4.2 Sustainability and Circular Economy

The transition toward sustainable supply chains has been accompanied by a growing interest in circular economy (CE) practices. While existing frameworks prioritize waste minimization and resource efficiency [95,96], questions remain about the scalability and inclusivity of such models, particularly for small and medium-sized enterprises (SMEs). Furthermore, there is a lack of holistic metrics capable of capturing both environmental and social impacts in CE adoption [97].

Relevant research avenues include:

- Exploring scalable circular strategies tailored for SMEs in resource-constrained contexts;
- Developing integrated performance metrics encompassing environmental, economic, and social dimensions of CE initiatives.

4.3 Blockchain Technology

Blockchain has emerged as a promising solution to enhance transparency, traceability, and trust in global supply networks [98,99]. Despite its potential, high implementation costs, energy consumption, and interoperability issues continue to limit its adoption—especially in developing economies and among artisanal or informal stakeholders [100]. Moreover, the complexity of blockchain protocols may exclude vulnerable actors, exacerbating digital inequality.

Future investigations should focus on:

- Designing lightweight blockchain architectures for low-resource environments;
- Assessing the viability of hybrid systems (e.g., blockchain + IoT) to balance traceability, cost, and energy efficiency.

4.4 Digitization and Industry 4.0

Industry 4.0 technologies, including digital twins, smart sensors, and autonomous systems, offer substantial efficiency gains in manufacturing and logistics [101,102]. Nevertheless, a significant digital divide persists between large corporations and SMEs, often due to infrastructural and financial constraints [103]. Additionally, digitization raises cybersecurity and data privacy concerns, particularly in hyper-connected supply networks.

Open research questions involve:

- Identifying affordable and scalable digital solutions for SMEs in emerging markets;
- Investigating the impact of cyber risks on trust and cooperation among supply chain partners.

4.5 Resilience and Risk Management

Global dolphin choir s face increasing exposure to systemic risks such as pandemics, geopolitical conflicts, and climate events. Traditional risk management frameworks—often linear and siloed—struggle to anticipate and mitigate cascading failures across multi-tiered networks [77]. Recent events like the Suez Canal blockage or semiconductor shortages have underscored the fragility of just-in-time (JIT) models [104].

Future research should aim to:

- Develop predictive simulation models to assess ripple effects in complex supply chains;
- Evaluate trade-offs between redundancy, agility, and cost-efficiency in high-risk sectors (e.g., electronics, pharmaceuticals).

4.6 Humanitarian Supply Chains

Humanitarian supply chains operate under high uncertainty and urgency, often prioritizing speed and responsiveness over efficiency and sustainability [105,106]. While technological innovations have improved coordination during disasters, challenges persist in reducing resource waste, managing decentralized actors, and ensuring equity in aid distribution. Moreover, the lack of interoperable data systems often results in redundancy and delays during crisis response.

Promising research directions include:

- Exploring the use of blockchain and distributed ledger technologies to enhance transparency and coordination in humanitarian logistics;
- Investigating circular economy practices (e.g., reusable logistics assets, modular shelters) to reduce environmental impact and improve sustainability in emergency responses.

4.7 Dynamic Supply Chains

Dynamic supply chains emphasize real-time responsiveness and adaptability to fluctuating market demands and external disturbances [107,108]. However, the pursuit of hyper-efficiency and speed often leads to concerns related to labour exploitation, data privacy, and environmental degradation. Notably, rapid fashion cycles, enabled by real-time analytics and IoT, have been criticized for relying on precarious labour conditions and unsustainable production practices.

Further research is needed to:

- Assess how digital transparency tools (e.g., IoT-based monitoring) can be aligned with fair labour practices and wage compliance;
- Propose governance frameworks that protect worker privacy in highly transparent and data-driven supply ecosystems.

4.8 Bridging Supply Chain 4.0 and 5.0

While Supply Chain 4.0 focuses on automation, connectivity, and efficiency through advanced digital technologies, Supply Chain 5.0 emphasizes human-centricity, sustainability, and societal value integration [89,109]. Despite conceptual advances, there remains a lack of actionable roadmaps and economic incentives to facilitate this paradigm shift, particularly for firms seeking to balance competitiveness with social responsibility.

Key areas for future investigation include:

- Designing public-private policy instruments (e.g., carbon credits, social impact bonds) to incentivize the transition toward SC 5.0;
- Developing quantification methods to measure the return on investment (ROI) of social and environmental responsibility initiatives within supply networks.

4.9 Synthesis and Research Agenda

This sub-section consolidates the key challenges and emerging research directions in contemporary supply chain management, structured around seven critical thematic areas: artificial intelligence and machine learning (AI/ML), sustainability and the circular economy, blockchain integration, digitalization and Industry 4.0, risk and resilience, humanitarian logistics, and the transition toward Supply Chain 5.0. While each domain presents unique operational and strategic issues, they also reveal common structural concerns related to the responsible integration of technology, inclusiveness, governance, and global scalability.

To facilitate a holistic understanding of these cross-cutting themes, Table 1 provides a synthesis of the main challenges, real-world examples, and research avenues across these seven domains.

The ongoing transformation of supply chains, driven by digital acceleration, sustainability imperatives, and shifting societal expectations, creates a complex, multidimensional research landscape. This review identifies several pressing gaps that call for an integrated, interdisciplinary agenda.

First, there is an urgent need to bridge disciplinary boundaries. For instance, integrating AI in decision-making requires not only algorithmic optimization but also fragile governance frameworks to mitigate bias and ensure fairness. Likewise, advancing the circular economy depends on combining technological feasibility with regulatory, social, and behavioural dimensions.

Second, the issues of **scalability and inclusiveness** remain pervasive. Many innovations, particularly in digital and sustainable technologies, remain out of reach for small and medium-sized enterprises (SMEs), especially in low- and middle-income countries. Research should thus prioritize adaptive, modular systems and inclusive governance mechanisms to democratize access.

Third, **transparency and accountability** must become foundational in future supply chains. Technologies such as blockchain and IoT offer promising visibility but raise critical concerns regarding energy intensity, data ownership, and surveillance of labour. These tensions call for co-designed policy frameworks that align technical safeguards with ethical oversight.

Finally, the transition to **Supply Chain 5.0** signals a paradigm shift from efficiency-driven optimization to a human-centric, purpose-led model of value creation. This reorientation necessitates the development of novel metrics for social and environmental impact, hybrid value models combining economic and ethical performance, and targeted policy instruments that enable long-term transformation without compromising competitiveness.

Based on these insights, we outline the following research priorities:

Table 1 Key Research Challenges and Future Directions in Supply Chain Management

Domain	**Key Challenges**	**Illustrative Example**	**Research Directions**
AI & ML	Limited adaptability to disruptions; algorithmic opacity	Unilever's AI failed to predict demand during COVID-19	Integrate real-time data; ensure ethical and interpretable AI systems
Sustainability & Circular Economy	Limited scalability; equity trade-offs	Patagonia's repair model has high costs and low adoption	Develop inclusive models; measure environmental and social ROI
Blockchain	High energy consumption; lack of interoperability	De Beers' Tracr excludes small-scale miners	Design lightweight, interoperable blockchain models for SMEs
Digitalization (Industry 4.0)	Unequal access to digital infrastructure	SMEs struggle with adopting digital twins used by Siemens	Propose low-cost, secure digital solutions for smaller firms
Risk Management	Poor modeling of cascading effects	The 2021 Suez Canal blockage disrupted global logistics	Build multi-tier disruption simulations; hybrid agile-resilient frameworks
Humanitarian Chains	Prioritization of speed over sustainability	Logistical delays post Türkiye-Syria earthquake	Promote transparent, circular coordination through emerging tech
Supply Chain 5.0	Ambiguity in value creation frameworks	Maersk's green fuels face ROI uncertainty	Measure ROI for ethical innovation; align policies with value-based goals

- Develop simulation-based and real-time decision-support systems that integrate socio-political, environmental, and market data to enhance supply chain responsiveness;
- Design inclusive frameworks for circular economy adoption among SMEs, tailored to diverse cultural, infrastructural, and regulatory contexts;
- Investigate hybrid technologies (e.g., Blockchain + AI + IoT) for scalable, secure, and energy-efficient supply chain traceability;
- Explore the socio-technical dimensions of Industry 4.0 adoption, particularly in resource-constrained environments;
- Formulate governance models that align technology deployment with labor rights, environmental justice, and corporate accountability;
- Construct empirical and conceptual models to operationalize Supply Chain 5.0, including new tools to evaluate ROI for ethical and sustainable innovation.

This agenda is intended to guide both researchers and practitioners in navigating the future of supply chains in a manner that is not only technologically advanced, but also socially inclusive, environmentally responsible, and ethically grounded.

5 Conclusion

The evolution of supply chain management reflects a continuous drive to improve efficiency, resilience and adaptability. From traditional linear models to connected and intelligent ecosystems that leverage technologies such as artificial intelligence (AI), the Internet of Things (IoT), and blockchain, supply chains have undergone a significant transformation - culminating in the emergence of Supply Chain 4.0. This article traces this transformation, highlighting how Industry 4.0 technologies have reshaped supply chains into agile, data-driven, and responsive networks.

While Supply Chain 4.0 marks a critical milestone in operational efficiency and technological integration, it also reveals the limitations of a purely performance-based approach. The next evolutionary step, Supply Chain 5.0, emphasises a shift towards more human-centred, sustainable and ethical practices. This new paradigm integrates societal values, including circular economy principles, green logistics and social responsibility, which are critical to addressing the broader challenges of climate change and social inequality.

As supply chains face increasing complexity and uncertainty, future research must explore deeper synergies between emerging technologies and inclusive governance models. Collaborative frameworks need to engage a wide range of stakeholders - from technology providers to civil society organisations - to design resilient, transparent and scalable systems. In addition, a greater emphasis on risk management strategies is needed to address vulnerabilities exposed by recent global disruptions, such as the COVID-19 pandemic and geopolitical tensions.

This article provides a roadmap for rethinking supply chain management in an era of both digital and societal transformation. The challenge for the future is to create supply chains that not only optimise performance and costs, but also contribute to long-term social and environmental value, ensuring a balanced, inclusive and sustainable future for all stakeholders.

Author Declarations

-Funding : Not applicable
-Conflicts of interest : All the authors have no conflicts of interest to disclose.
-Ethics declarations : All the authors mentioned in the manuscript have agreed for authorship, read and approved the manuscript, and given consent for submission and subsequent publication of the manuscript.
-Consent to participate : All the authors agree to participate
-Consent for publication : We, the undersigned, give our consent for the publication of my work by the journal
-Data availability : Not applicable
-Code availability : Not applicable
-Acknowledgements : Not applicable

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