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Digitalization of Supply Chain Management with Industry 4.0 Enabling Technologies: A Sustainable Perspective

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Abstract: Supply chain management is one of the most prominent areas that needs to incorporate sustainability to achieve responsible consumption and production (SDG 11).It has been identified that there are limited studies that have presented the significance of different Industry 4.0 technologies from the perspective of sustainable SCM. The purpose of this study is to discuss the role of Industry 4.0 technologies in the context of sustainable SCM, as well as to identify important areas for future research. The PRISM framework is followed to discuss the role and significance of sustainable SCM and the integration of Industry 4.0-enabling technologies such as the Internet of Things (IoT), cloud computing, big data, artificial intelligence (AI), blockchain, and digital twin for sustainable SCM. The findings of the study reveal that there are limited empirical studies for developing countries and the majority are emphasized in case studies. Additionally, a few studies have focused on operational aspects, economics, and automation in SCM. The current study is able to contribute to the significance and application of IoT, cloud computing, big data, AI, blockchain, and digital twin in achieving sustainable SCM in the future. The current study can be expanded to discuss the Industry 4.0-enabling technologies in analyzing sustainability performance in any organization using environmental, social, and governance (ESG) metrics.

Keywords: supply chain management; sustainability; ESG; Industry 4.0; digital twin

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1. Introduction

The SDGs were adopted on 25 September 2015, at a meeting of global leaders held at the United Nations (UN) in New York. These 17 goals lay out a plan for the sustainable development of all countries that emphasizes social inclusion, economic prosperity, and environmental conservation [1]. The 17 SDGs are interconnected, with actions in one area influencing results in another, and the sustainability of social, economic, and environmental systems must be sustained throughout the development phase [2]. Everyone, including governments, businesses, civil organizations, and the general public, must contribute to the SDGs [3]. To some extent, the goal of economic, social, and environmental sustainability can be realized in the field of manufacturing, where manufacturing includes a variety of actions that contribute to the creation of an end product from raw materials. SCM is a field in which various manufacturing activities are regularly monitored and economic, social, and environmental factors are adequately implemented. The balancing of these factors leads to the growth of a manufacturing organization in connection with the contemporary world.

As demonstrated [4], a fully digital supply chain can be established through Industry 4.0 and digital transformation by expanding transparency in terms of activity centralization.

Additionally, Ref. [5] indicates that Industry 4.0 can greatly impact all other sustainability-related features and supply chains in an organized approach. Ref. [6] identifies all ongoing challenges that must be addressed methodically, such as categorizing appropriate Industry 4.0 technologies for the adoption of sustainable operations management decisions, fostering supply chain collaboration, and establishing performance enablers for small, attainable targets. According to [7], Industry 4.0 is mainly based on the foundation of production; however, the assimilation of SCM from the perspective of Industry 4.0 is still lacking. Furthermore, Ref. [8] discovered that research on the fourth industrial revolution's supply chain is still in its early stages. Traditional supply chains must shift quickly to effectively and efficiently adopt the principles of Industry 4.0 technologies to remain competitive in ever-changing and evolving markets, while organizations are constantly looking for ways to adapt to these new technologies [9]. Correspondingly, Ref. [10] asserted that there is a lack of evidence regarding collaboration through the notion of the digital transition.

According to previous studies, supply chain performance is measured by examining dependability, flexibility, quality, responsiveness, and asset management. Organizations are currently leveraging technological innovations to create effective communication channels and collaboration mechanisms to improve supply chain performance through increased information sharing. Since supply chain activities span functional boundaries, it has been challenging to address the issues and improve performance. To improve their process integration and analytical capacities, organizations have explored the adoption of unique and creative technologies. A new stage of SCM development known as Sustainable SCM 4.0 sees a considerable degree of automation and the integration of digital technology in the coordination of material, information, and financial flows inside business networks.

Recent advancements in information and communication technology (ICT) have demonstrated that using ICT to improve SC procedures is a promising strategy [11]. Supply chains gradually transform into supply chain ecosystems as they become more digitalized through the adoption of the Industry 4.0 strategy [12]. For the efficient adoption of supply chain practices, future supply chains should concentrate on advancing and integrating technologies such as the IoT, Cyber-Physical Systems (CPS), and blockchain. Disruptive technologies have a significant impact on supply chain practices. Organizations will benefit from making evidence-based decisions for increased sustainability performance by identifying and linking important Industry 4.0 technologies with supply chain practices [13]. These digital technologies have had a significant impact in numerous research areas due to their cutting-edge features and qualities in the process of achieving sustainability [14]. The primary areas in SCM where sustainability must be realized are economic growth, energy reduction, employment creation, pollution reduction, and living standard improvement [15–17].

Based on the above motivation, this study reviews a few recent studies that have focused on SCM and Industry 4.0 technologies. A few of the studies are as follows. The first is a study that proposes a multistage implementation framework that highlights the organizational enablers, such as culture, a cross-functional approach, and continuous improvement activities [18]. The purpose of [19] was to investigate the impact of Industry 4.0-enabling technologies such as IoT, cloud computing, big data analytics, and CPS on SC performance in procurement, production, inventory management, and retailing by enabling process integration, digitization, and automation. Along with the Industry 4.0-enabling technologies in the previous study, the next study [20] has discussed the role of Industry 4.0-enabling technologies with blockchain technology. The study elaborates on a holistic perspective on the potential of Industry 4.0 for supply chain management concerning the triple bottom line. The interrelations between the dimensions of the triple bottom line are analyzed concerning potential conflicts and enabling technologies [21,22]. Another study implemented a framework for comprehending the mediating role of transparency in the relationship between new technologies and long-term sustainability [23].

From the above studies, it has been concluded that the author shave discussed the significance of Industry 4.0 technologies for enhancing supply chain performance. However, there are limited studies that have discussed all the Industry 4.0 technologies from the perspective of achieving sustainability with digitalization. This study aims to present the significance and application of a multitude of digital technologies' roles in sustainable SCM for diverse applications, as well as a prospective upgrade of SCM for the attainment of sustainability. The main contributions of the study areas follows:

- We discuss the implication of SCM in manufacturing and also address the role of Industry 4.0 digital technologies in SCM.
- We address the significance and application of IoT, cloud computing, AI, big data, blockchain, and digital twin in SCM.
- The study presents a comparative analysis, practical implications, recommendations, and future directions.

The study is structured as follows. Section 2 presents the methodology of the study; Section 3 covers the overview of SC management 4.0; Section 4 discusses the enabling technologies' assimilation for sustainable SCM; Section 5 presents the results, and Section 6 presents practical implications and suggested recommendations for future work.

2. Methodology

The present study is focused on studying the significance and application of Industry 4.0-enabling technologies for the supply chain management of an industry. In order to analyze this, this study follows the PRISM framework. To implement the PRISM framework, we framed the research questions, to collect the distinct research articles for analysis [24]. The research questions framed in this study are as follows:

- What is the progress of Industry 4.0-enabling technologies in supply chain management? (Answered in Section 3).
- What is the role of Industry 4.0 technologies in achieving sustainability in the field of supply chain management with digitalization? (Answered in Section 4).
- What future research directions can be identified based on the gaps detected? (Answered in Section 6).

After the formulation of the research questions, in the study, we searched and located studies that answer the questions. The studies were searched from high-quality and relevant research databases such as Web of Science, and Scopus. In the study, the keywords were applied along with Boolean logical operators ("AND" and "OR" for searching the articles in the research databases). The Boolean combinations are "Keyword of A AND and Keyword of B". This pattern was followed in search strings such as "industry 4.0" OR "business to business" OR "internet of things" OR "artificial intelligence" OR "blockchain" OR "digital twin" OR "digitalization" OR "digital technologies" OR "supply chain" OR "cloud computing" OR "bigdata" OR "sustainability" OR "sustainable management" OR "supply chain management" OR "sustainable development goals". After obtaining the research articles, the next stage was to filter the articles based on certain criteria, as discussed in the following.

(a) Articles such as research, reviews, and case studies that are published in the English language are included.
(b) Articles that do not have full texts and studies that do not include conducted experiments or any validation are excluded.
(c) Articles that are duplicates and also non-peer-reviewed articles are excluded.
(d) All book chapters, patents, and conferences are excluded so as to maintain quality research.

In the final phase, the complete article was reviewed by considering the framed research questions. Finally, a total of 117 papers were considered in this study for the analysis of Industry 4.0's impact on the management of finance in firms. Figure 1 illustrates the PRISM diagram of the literature considered in this study. After obtaining 117 articles, the study was categorized into four sections, in which the third section discusses the significance of sustainable SCM from the perspective of Industry 4.0. After the discussion of this aspect, in the study, the various Industry 4.0 technologies are presented for sustainable

SCM in a tabular form for better readability (Section 4). Based on the discussion in Section 4, results are presented in Section 5. In Section 6, comparison and contrast of previous studies with the proposed study, practical implications, and recommendations for future work will be presented.

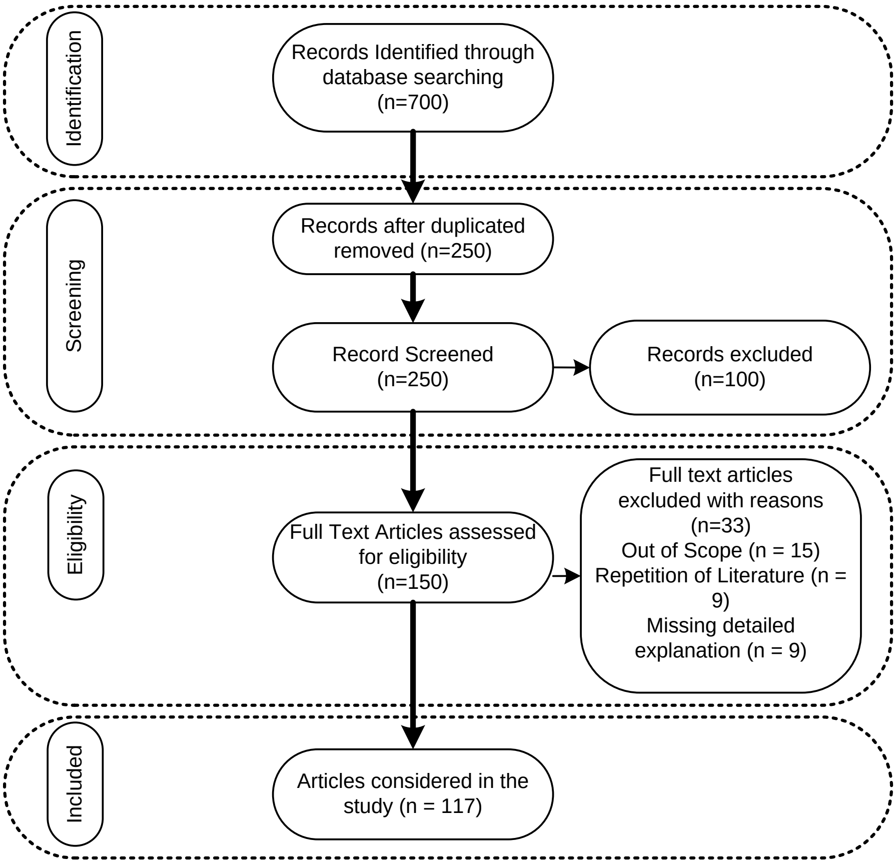

Figure 1. PRISM framework.

Figure 2 illustrates the number of articles that have been obtained after applying the PRISM framework. Here, it represents the number of articles that have been selected year-wise, such as 2014–2022. There are 9 articles from the years 2001, 2008, 2009, 2012, and 2013, and one reference is a web link. Of the remaining articles, 108 are from the years 2014–2022. The details of articles year-wise are presented: 2014 (5%), 2015 (4%), 2016 (4%), 2017 (11%), 2018 (7%), 2019 (9%), 2020 (17%), 2021 (19%), and 2022 (14%).

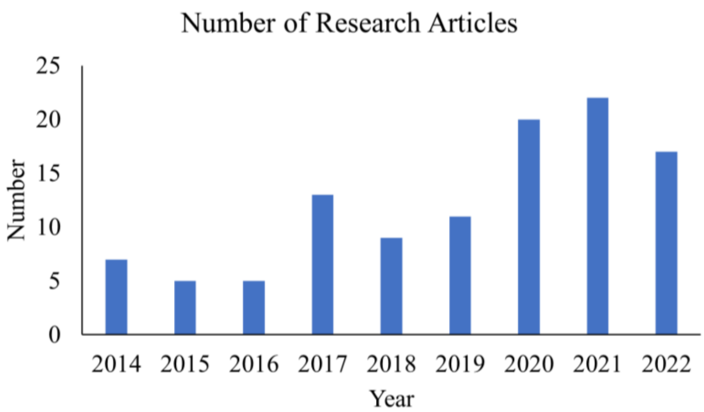

Figure 2. Graphical representation of the number of articles.

3. Overview of Sustainable SCM 4.0

Industry 4.0 is transforming the way in which companies achieve, improve, and distribute their products. Manufacturers are incorporating new technologies into their manufacturing facilities and processes. Organizations are required to embrace this impending change in their operations, as well as in the larger supply, due to the shifting business trends in network chains [25]. Industry 4.0 seeks to deliver real-time information on production, machines, and component flow by combining smart manufacturing, smart goods, and the IoT. These data are combined to help managers to make decisions, track performance, and track materials in real time [26]. Figure 3 illustrates the Industry 4.0-enabling technologies that have already shown an impact in the various study areas for digitalization and sustainability.

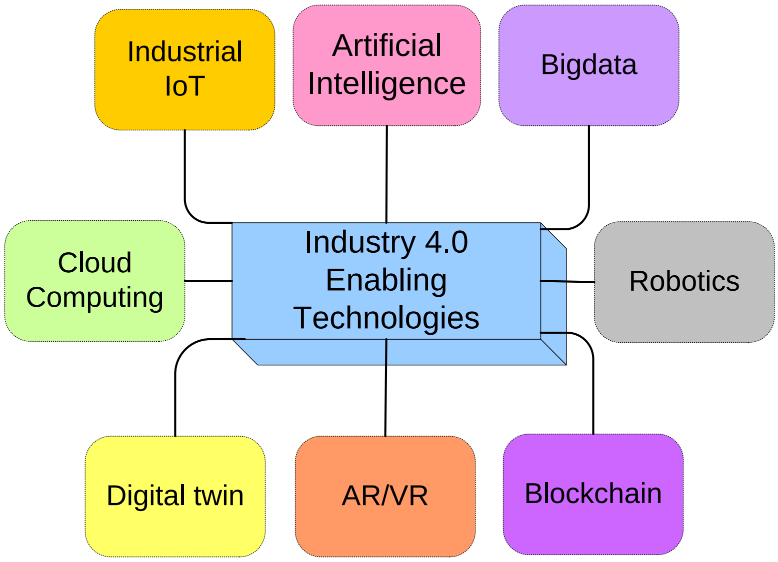

Figure 3. Enabling technologies of Industry 4.0.

SCM, which is now more complex than ever, will gain a great deal from becoming digital. According to studies, an interconnected, digital SC can increase business speed, agility, granularity, accuracy, and efficiency while reducing operational costs by more than 30%, reducing the chances of missing sales by more than 60%, and even reducing the amount of inventory needed by more than 70%. Furthermore, SCM has a significant environmental impact, emitting 33 billion tons of CO_2 into the atmosphere. According to McKinsey, consumer-packaged goods businesses' supply chains account for more than 80% of greenhouse gas emissions and more than 90% of the impact on air, land, water, biodiversity, and geological resources [27].

Figure 4 illustrates the mapping of SDGs concerning the activities involved in SCM. In SCM activities, the SDG goals are mapped for suppliers (SDG 6), inbound logistics and distribution (SDG 11), company operations (SDG 8), product use (SDG 12), and product end life (SDG 13). These goals empower SCM to support sustainability in terms of social, economic, and environmental perspectives. In order to achieve the SDGs, Industry 4.0 has a significant impact because it enables the monitoring, analyzing, predicting, securing, and transmitting of every activity of SCM with its enabling technologies. The benefits of moving to a completely automated, digital, and networked supply chain are enormous, even if it will take a lot of work and time. Supply chain optimization can help businesses to achieve a higher level of operational excellence and experience in the reduction of costs. The industries of the future will enable connectivity between machines and people in CPS in the context of Industry 4.0. These new systems concentrate their efforts on the development of intelligent goods and industrial procedures that will enable the sector to adapt to quick changes in consumer behavior [28].

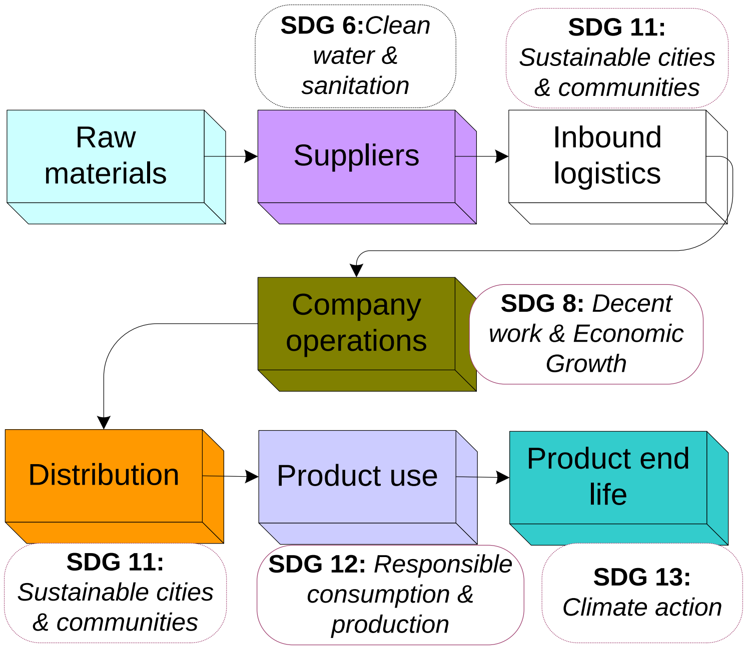

Figure 4. Mapping of SCM with SDGs.

Acceleration through exponential technologies: employing cutting-edge technologies gives businesses the ability to lower costs, enhance flexibility, and customize their products. AI, drones, nanotechnologies, and a range of inputs are automated systems that facilitate customization, quick production, and flexibility [29]. To apply the CPSs within the smart factory, strategies, networks, and business models must be put in place. This horizontal integration achieves high levels of flexibility, allowing the corporation to react more quickly [30]. The manufacturer can recognize changes in clients' demand and account for them in all production processes, from development to distribution, thanks to the transparency inside the value chain [31].

4. Enabling Technologies' Assimilation for Sustainable SCM

In this section, we discuss the implementation and progress of enabling technologies for sustainable SCM. Based on this motivation, the individual technologies in sustainable SCM are presented in detail.

4.1. IoT

IoT has modern roots in logistics. It has been possible to track items using technology with various information and communication technologies. As a result, the developments brought about by IoT in the logistics domain might be seen as an extension of earlier advancements. Transporting "the right items in the right quantity and right quality at the right time to the right place for the right price" is one of the core logistics functions [32]. Large businesses and their subsidiaries are not the only ones using IoT in the industry. It is a commonly utilized and readily accessible tool for a variety of SCM tasks [33], such as creating real-time quality/maintenance data, inventory tracking, information sharing, joint ordering, quality supervision, quality-controlled logistics, enabling enhanced reverse logistics, collecting product data while in use, and providing visibility on parts and raw materials to increase operational efficiencies and revenue opportunities [34].

It has been made known that different IoT forms offer further possibilities in the auto-capture of data, visibility, intelligence, and sharing of information for better integrating retail SC. This improves the cost, quality, delivery, and flexibility of the SC, which benefits the firm's stability concerning finance, society, and the environment [35]. Through increased transparency and flexibility throughout the supply chain, the Internet of Things offers new options to reduce risks, manage complexity, and create actual economic benefits [36].

Figure 5 indicates that IoT can be used by various stakeholders, such as manufacturers, inspection departments, warehouses, transporters, and retailers, for the sharing of information related to items among themselves. This makes information available in real-time to all the stakeholders connected to the SC. The integration of radio frequency identification (RFID) tags, sensors, barcodes, and communication protocols enables them to obtain real-time data. IoT assists with real-time tracking and tracing with the assistance of global positioning systems (GPS) and other identification technologies. Recently, there has been rapid progress in wireless communication technologies and sensors, which enable the adoption of IoT-based systems to monitor items from any remote location through internet connectivity.

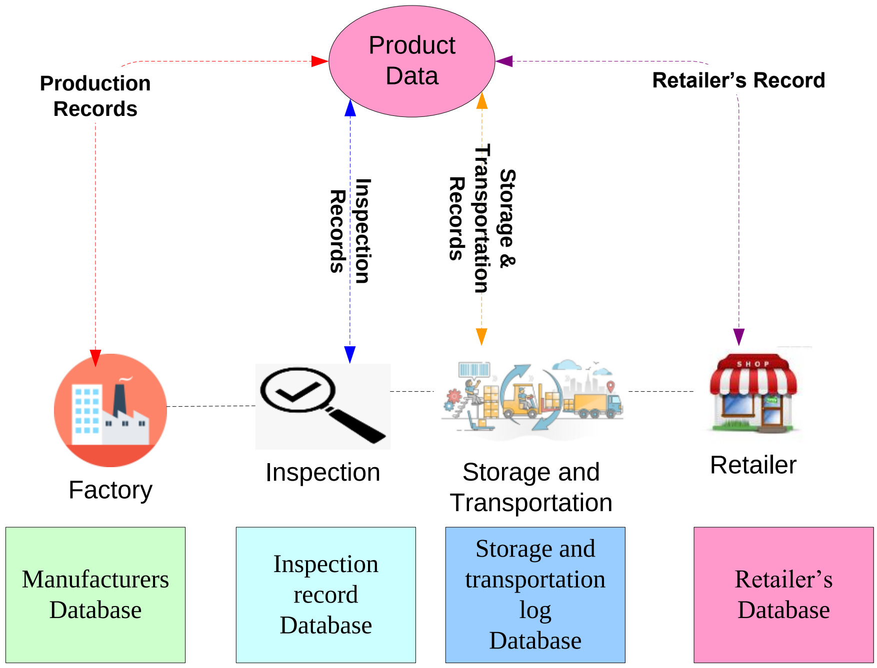

Figure 5. Application of IoT in sustainable SCM.

Cloud computing is the delivery of on-demand services and resources over the internet by distributed computer networks such as data centers and servers [37]. For a variety of applications within SC management procedures and related enterprise information systems (ISs), cloud computing services are offered. For instance, these services provide constant platforms for international networking and the sharing of real-time data. Additionally, they facilitate rapid decision-making and guarantee efficiency, which may improve the competitive edge concerning digital SC activities [38].

The main reasons that small and medium enterprises (SMEs) choose to use the cloud are its simplicity and convenience. The second reason that SMEs choose the cloud after cost savings is improved security and privacy. As a result, they can use ERP, CRM, SCM, etc.—applications that would be exceedingly costly to operate internally [39]. It was discovered that cloud computing technology has enormous promise in delivering effective collaboration solutions in precast construction [40]. The emergence of cloud computing presents the clear potential to enhance the sharing of information, allow the better utilization of modern analytical methods, and better control security and limited access [41]. Figure 6 depicts all the stakeholders connected in the supply chain cloud. They can share information and resources among themselves. As discussed earlier, the cloud server empowers participants to connect physical items in the virtual world through communication protocols. Table 1 provides the recent studies on the implementation of IoT for sustainable SCM.

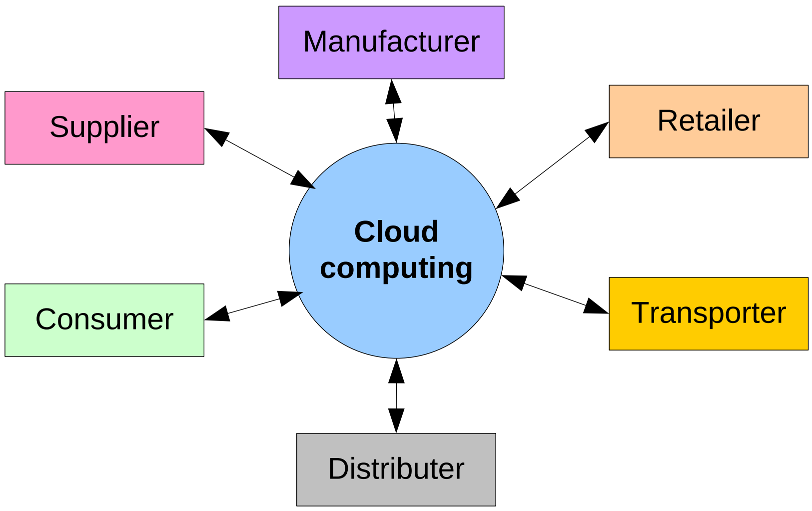

Figure 6. Application of cloud computing in sustainable SCM.

Table 1. IoT for sustainable SCM.

Ref	Objective	Supply Chain	Findings
[42]	To achieve intelligently perception and access to various manufacturing resources	Manufacturing resources and services	For data collection via IoT, effective and reliable data mining and processing technologies must be implemented.
[43]	A framework for assessing the security of proposed systems is introduced, which combines the neutrosophic Decision Making Trial and Evaluation Laboratory technique with the Analytic Hierarchy Process (AHP).	Suppliers and managers	Neutrosophic DEMATEL–AHP technique can be implemented in areas including project management and scheduling.
[44]	Proposed an ecosystem for the realization of IoT services in SCM	Logistics service providers	The proposed ecosystem assists companies to understand the implementation of IoT services, to find the right partners with which to cooperate, and to establish their ecosystem.
[45]	RFID adoption strategies are implemented for a decentralized supply chain with two competing suppliers and a dominant retailer facing inventory inaccuracies	Suppliers and a dominant retailer	Supplier adopts RFID and the profit of the powerful supplier that forgoes RFID increases as the inventory availability rate increases.
[46]	Improvement in minimizing environmental pollution in the logistics industry to a certain extent	Logistics	Effectively reduce costs in all aspects of the logistics industry, and the first to develop green logistics will undoubtedly take the initiative in the development of the logistics industry.

4.2. Big Data

Big data is a popular enterprise system or platform that appears to provide additional functions for gathering, storing, and analyzing massive amounts of generated data from various sources to achieve value addition [47]. SCM, which provides a fertile environment for big data production, collects massive amounts of data from a variety of operations, such as the use of sensors, RFID, and tracking devices. The concept of big data contributes to increased visibility and risk reduction. SC disruption and failures are avoided by providing an integrated framework for monitoring customer performance and engagement through the analysis of real-time data and critical decision-making scenarios [48]. The prevalence of mobile computing and the amount of data produced have created new opportunities for process improvement, as well as new gateways for monitoring demand, enhancing problem understanding, and making plans [49]. The results show how demand management, vendor rating, IoT, analytics, and data science have an impact on operational excellence, cost savings, customer satisfaction, visibility, and closing the communication gap between demand management and SC management. Big data technology adoption can result in significant value addition and financial gains for businesses and will soon become the norm in the sector [50].

A significant opportunity exists for SC management based on information systems in the planning of construction projects and the design of buildings. These findings support the assumption that SC management systems and the idea of big data can significantly impact the sustainable design of buildings. These technologies are anticipated to increase economic sustainability by lowering prices and reducing the time it takes to distribute materials and build structures [51]. The concept of "big data" (BD) opens up new opportunities for developing SCM and customer relationship management (CRM) plans that will support and customize client sales, services, and logistics [52]. According to [53], big data has significant potential to benefit the fields of engineering, construction, and architecture. Big data plays an important role in managing the huge amount of data generated in various processes of the supply chain. Figure 7 indicates that big data analytics may be utilized for the optimization of the supply chain. It may be used in analyzing demand, inventory, procurement, transportation, and production. Table 2 illustrates the recent studies on big data implementation for sustainable SCM.

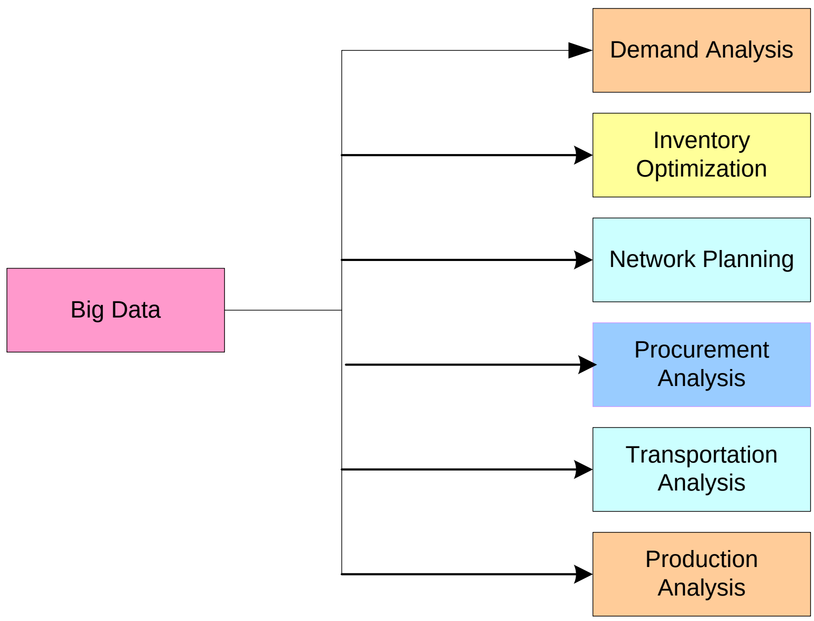

Figure 7. Application of big data in sustainable SCM.

Table 2. Big data for sustainable SCM.

Ref	Objective	Supply Chain	Findings
[54]	Examined the impact of building big data analytics for an organization to enhance supply chain agility	Supply chain agility	There is no evidence to support the mediational influence of organizational versatility on the channel of big data analytics capability.
[55]	A decision framework that integrates two-stage House of Quality and multicriteria decision-making was constructed	Supply chain resilience and mitigation of sustainable supply chain risks	Management decision-makers can determine where big data analysis enablers can be most cost-effectively improved to promote risk resilience of sustainable supply chains; this ensures the efficient implementation of effective big data strategies.
[56]	The study assessed the mediating effect of green innovation and the moderating effect of technological intensity	Green supply chain performance	It was confirmed that technological intensity moderated the relationship between green innovation and green supply chain performance.
[57]	Integrated infrastructure is needed to break down information silos to improve supply chain performance	Firms and managers	Integrating information silos in big data analytics as inputs for novel product concepts.
[58]	Reduced the inadequately recognized essence of big data in terms of its significance in SCM from a business process standpoint	Business processes and decision-making practices	Value creation, value discovery, and value capture all resemble distinct quality dimensions and offer a multi-faceted standpoint regarding how to realize the value of big data.

4.3. Artificial Intelligence (AI)

Supply chains have a remarkable influence on cost-cutting measures, the ability of a business to adapt to changing market conditions, and the quality of its customer interactions. Businesses desire speed, dependability, and traceability while still keeping costs low, meeting deadlines, and optimizing inventory [59,60]. The most frequent problems leading to major incidents (political upheaval, natural disasters, suppliers' financial instability, etc.) should be monitored and avoided by supply chain managers. In already unstable circumstances, these variables could complicate the SC [61]. An SC is a collection of businesses that participate in many processes and activities that result in the value that is then transferred to the final consumer in the form of goods and services through upstream and downstream links [62]. These links, processes, and activities necessitate observation, forecasting, prediction, and optimization to function effectively in the complex environment in which supply networks operate—and to build a more agile and resilient SC. AI-based applications have emerged recently across a variety of industries, including supply chains [63]. AI provides machines with the ability to act creatively and carry out tasks without human involvement. Organizations use AI and machine learning to acquire insights into warehousing, logistics, and SC management, among other areas. From a broad perspective, AI can be characterized as a system's capacity to replicate human intelligence, with the ideal ability to reason and execute actions that have the highest likelihood of attaining a particular goal [64].

The implementation of predictive methodologies enabled by AI enables the quick evaluation and more effective mitigation of risks or unruly events that may occur across the SC. It also makes it possible for consumers to identify supply chain patterns. AI can rapidly and accurately identify pertinent SC data using algorithms to create models that help managers to better understand how each process functions and suggest opportunities for improvement [65]. AI helps businesses to continuously learn about areas that need improvement, pinpoint variables that have an impact on performance, and to forecast performance in this latest approach of using AI to enhance the supply chain and seek optimization [61]. AI may prove to be an important technology in the digitalization of the supply chain. Figure 8 depicts the benefits of AI in various functions of SC management. With the application of AI, SC management will become more effective, efficient, and economical. AI can be used in the planning, analysis, and automation of delivery, back office procedures, and warehouse operations. Table 3 provides the recent studies on AI for sustainable SCM.

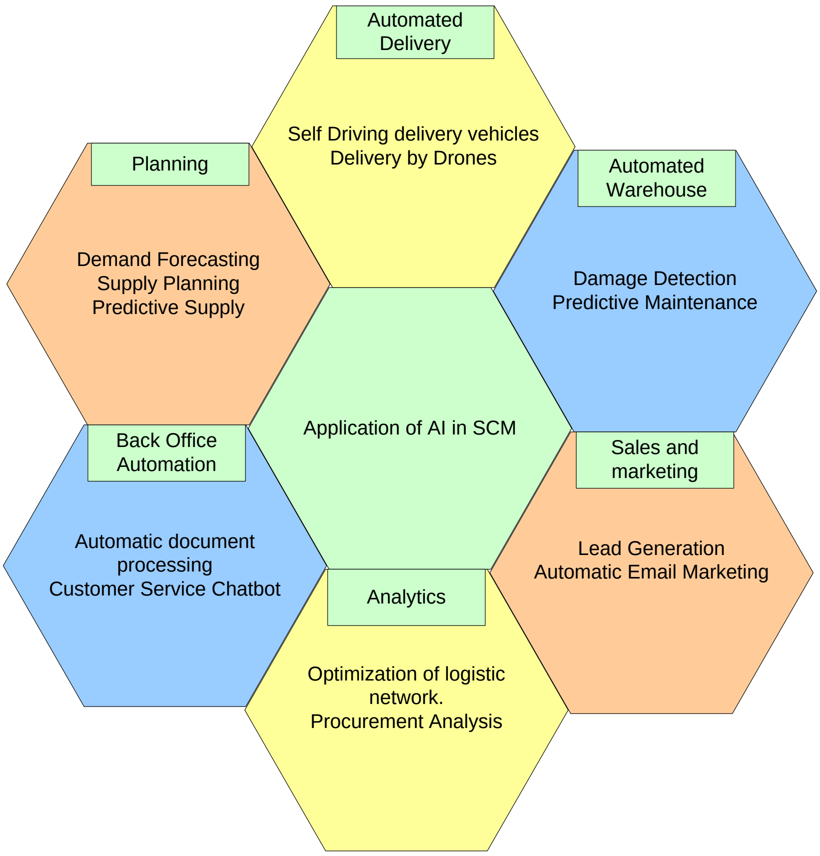

Figure 8. Application of AI in sustainable SCM.

Table 3. AI for sustainable SCM.

Ref	Objective	Supply Chain	Findings
[66]	Micro-service architecture is used with semantic information to annotate data sources from online systems while also conducting post-processing activities such as supply chain monitoring, estimated delays, and goods location analysis	Post-processing in the supply chain	The proposed architecture is beneficial for enhancing situational understanding of a supply chain's condition and connections.

Table 3. *Cont.*

Ref	Objective	Supply Chain	Findings
[67]	AI is used to improve operational performance	Overall supply chain management	Identifies multiple value-creation elements associated with the application of AI in the supply chain.
[68]	A quality assessment model that joins particular issues to the most important key performance indicators for each supply chain management subsystem	Overall supply chain management	The most trustworthy KPIs for each selected problem can be predicted using a graphical user interface (GUI) based on neural networks and the multilayer perceptron artificial intelligence algorithm.
[69]	Identified the issues encountered in creating a resilient and sustainable supply chain before and during COVID-19	Overall supply chain management	The problem areas identified in SSCM before COVID-19 are demand planning, supply chain traceability, purchasing process planning, and production management.
[70]	The application of Graph Neural Networks (GNN) in an automated technique to recognize potential links unidentified to the buyer is envisioned	Interdependencies between suppliers	Integrated Gradient to augment the consistency of the proposed methodology by prioritizing input data that impact GNN judgments.

4.4. Blockchain

In the modern era of technology, almost all company models have been experiencing significant upheavals as a result of ongoing advances in cutting-edge information and communication technology (ICTs) [71]. The blockchain is a well-known and extremely disruptive technology that is already changing well-established business models and opening up new possibilities throughout the whole SC. Blockchain often refers to a completely distributed system of cryptography for recording and storing a linear event log of networked actor interactions that is consistent and immutable [72]. A system called blockchain was developed to conduct transactions in the digital currency market [56–58]. Blockchain applications have already attained a high level of authority in the financial industry but have recently been expanded to domains such as operations and SC management. It is viewed as a paradigm that presents both a crucial issue and an opportunity. For example, blockchain has the potential to significantly increase security, efficiency, accountability, and trust, as well as reduce costs [73]. Additionally, blockchain is thought to be able to solve SCM traceability problems [74] and aid in fostering more intimate and reliable relationships [75,76], not only between companies and their suppliers but also within SCM as a whole. On the one hand, a decentralized, blockchain-enabled smart contract has the potential to significantly increase SCM's efficiency. On the other hand, blockchain can be used in conjunction with other cutting-edge technologies to exert a disruptive effect in all specialized domains [77].

Blockchain technology helps to prevent conflicts that arise when several changes are made simultaneously from different computers in a distributed database [78]. Blockchain and distributed databases are similar in that both rely on several computers to run their operations and perform maintenance. Physical documents used in international trade, such as letters of credit (LC), are essential, and intermediaries who participate in such transactions ensure that the trade runs smoothly. Blockchain technology can completely change the way that the world's supply chains are organized by eliminating intermediaries and the need for physical document verification. Reducing risks is one of the main goals of SCM. Relational risks in collaboration are a significant danger when a business partner falsifies facts to take advantage of an opportunity [79]. When a company wishes to provide value to its clients, logistics services frequently play a crucial role [80]. Three aspects of SCM are likely to benefit from blockchain technology: supply chain financing, smart contracts, and greater visibility and traceability of a supply chain [81]. Blockchain technology has proven to be very useful in the finance domain. In the same way, it may be very useful in the technological advancement of supply chain management. Figure 9 shows that real-time information on the items in the SC can be shared among the stakeholders in the SC by utilizing blockchain. Table 4 provides the recent studies on blockchain for sustainable SCM.

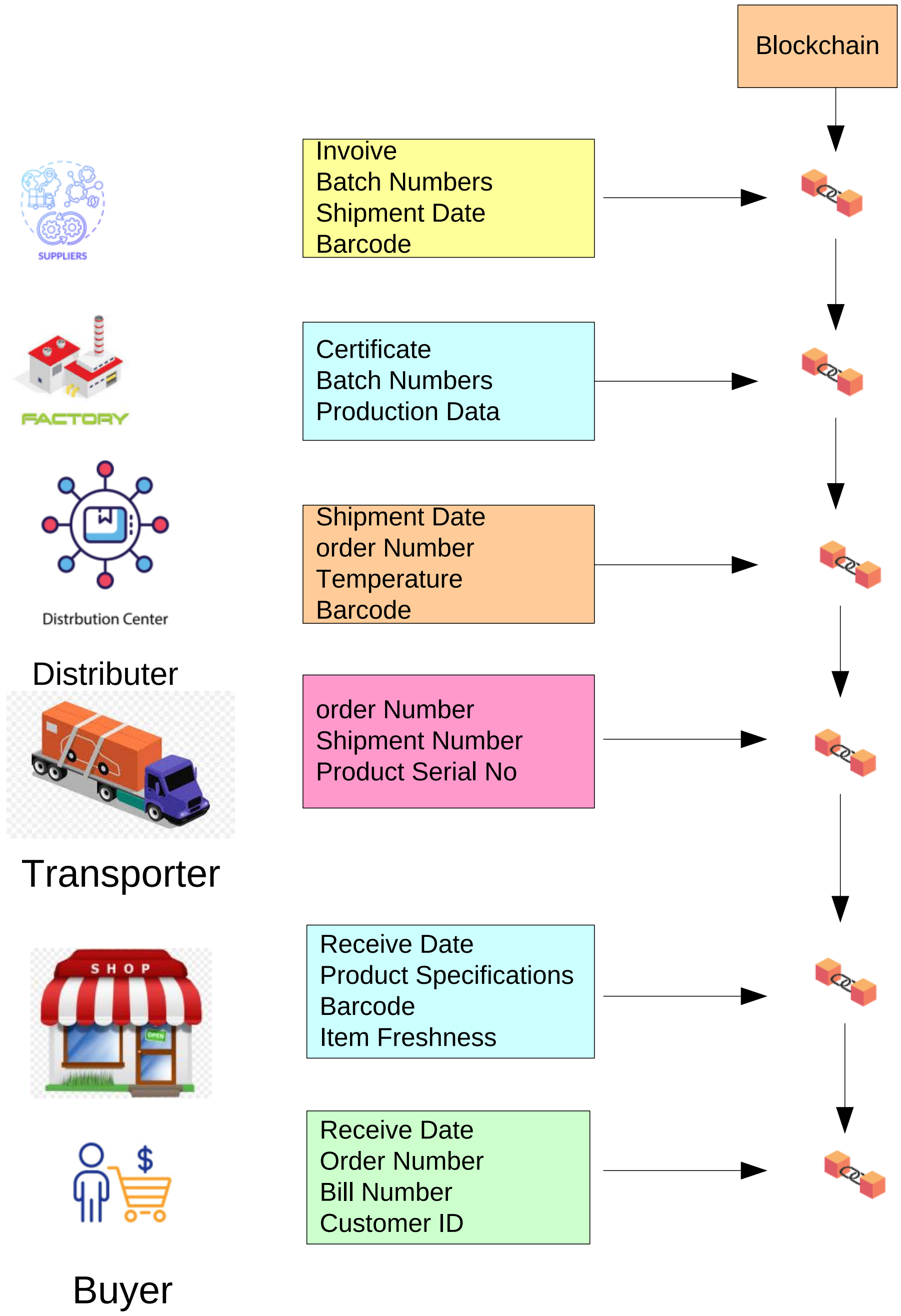

Figure 9. Application of blockchain in sustainable SCM.

Table 4. Blockchain for sustainable SCM.

Ref	Objective	Supply Chain	Findings
[82]	The utilization of blockchain technology in combination with IoT infrastructure has standardized and benefited modern supply chains while also improving value chain systems	Value chain networks	The combination of blockchain and IoT improves end-to-end traceability and allows for the rapid recall of dangerous goods.
[83]	Examine the impact of RFID, Industrial IoT (IIoT), and blockchain technologies on supply chain transparency (SCT)	Supply chain transparency	RFID technology has an inadvertent influence on SCT via blockchain technology and IIoT.
[84]	Implemented blockchain-based model for IoT SCM	Accurate data and strategic business processes	Reduces the computational, storage, and latency specifications while standardizing data exchange.
[85]	The impact of blockchain technology on sustainable supply chain practices to improve organizational performance	SC sustainability in small and medium enterprises (SME)	Organizational performance is influenced by environmental, operational, and economic effectiveness.
[86]	Blockchain's characteristics are especially important for enforcing sustainability standards in developing countries	Sustainable supply chains	Researchers should also investigate whether purchase intention and willingness to spend large amounts vary significantly across countries and customers of different generations.

4.5. Digital Twin

A digital twin is a fascinating area of technical research within the context of Industry 4.0 [87]. A type of cyber-physical device known as a "digital twin" creates a high-definition visual representation of a physical object using several IoT sensors. Machine learning algorithms are then used to combine and evaluate the huge amounts of data that the digital twin has collected to support organizational and strategic decision-making [88]. The supply chains that make up an organization's logistics networks become more complicated as they adapt to the rigorous demands of global markets. The visibility of the firm's supply chain is frequently significantly impacted by this, which may have an adverse influence on the core business of the organization.

Digital twin (DT) is one of the tools included in Industry 4.0. Industry 4.0 is a tool that raises the technical maturity level of any organizational structure by enabling the adoption of digitalization, integration, and automation in the production and SC network [89,90]. Businesses can only maintain their market position in a more cut-throat environment by taking advantage of the coordination between production management and logistics [91]. The advantages are attained by using logistically integrated production management, which also includes the design of the information system needed for formulating plans and execution [92]. A digital twin is an almost perfect replica of a process or product that has parameters and variables that are clearly described. The method used to create a digital twin is simulation modeling [89]. DT brings improved connectivity to SCM [93,94]. Assume that the DT idea links several life stages along the chain. The influence on sustainability is increased by the DT's assistance in disseminating production information to various recycling sector stakeholders [95,96]. A digital twin supply chain (DTSC) needs a unified data management strategy to develop a fresh, integrated supply chain perspective [97,98].

DTs also bring to SCM improved end-to-end visibility [99]. As stated by [100], DTSC can be a retrofittable and affordable option for supply chain asset tracking, which is one of the most important functions of SCM. Table 5 illustrates the recent studies on digital twin for sustainable SCM.

Table 5. Digital twin for sustainable SCM.

Ref	Objective	Supply Chain	Findings
[98]	Supply chain planning utilizing digital twin theoretical foundations	Aggregate planning, demand forecast, and inventory planning	DT enhances foreseen precision through dynamic and comprehensive data collection. DT improves planning verifications substantially with high-quality modeling.
[99]	The supply chain digital twin framework is built on system theories and the supply chain operations reference model	Supply chain operations	The digital twin improved the operations of the supply chain
[100]	A sustainable smart manufacturing strategy focused on information management systems for energy-intensive industries is proposed using digital twin and big data technologies	Product lifecycle	The use of digital twins increased energy savings and reduced environmental costs.
[101]	Reinforced machine learning has been incorporated into production and logistics systems to establish a framework for normative decision making	Overall supply chain	A framework for reinforced learning and data-driven digital twin generation has been suggested.
[102]	A novel approach is suggested for the smart supply chain	Modeling and optimization of the supply chain	There are new issues with predictive analytics for the smart supply chain that need to be resolved in order to decrease risks and boost agility.

5. Results

Based on the above analysis, this section discusses the significant findings on integrating Industry 4.0-enabling technologies in the area of supply chain management.

- In the context of IoT, IoT has the potential to reduce the environmental pollution caused by logistics to some degree. It also effectively cuts costs in all aspects of logistics, and the development of green logistics will undoubtedly take the lead in logistics.
- Previous research examined the results of developing big data analytics for organizations in order to improve supply chain agility. There is no evidence to support the mediational role of organizational versatility in the pathway to big data analytics capability. It was confirmed that the relationship between green innovation and green SC effectiveness was regulated by technological intensity.
- A graphical user interface (GUI) based on neural networks and the multilayer perceptron artificial intelligence algorithm predicts the most reliable KPIs for each selected problem. Prior to COVID-19, the problem areas identified in sustainable SCM were demand planning, supply chain traceability, purchasing process planning, and production management.

- In SCM, blockchain technology is primarily used for transparency in order to build trust with diverse individuals involved, achieve product traceability, lower product recalls, improve product safety, and minimize product counterfeiting. With blockchain technology, organizational performance will be influenced by environmental, operational, and economic effectiveness. RFID technology has an inadvertent influence on SCT via blockchain technology and IIoT.

6. Discussion

In this section, we present the comparison and contrast of previous studies with the current study. Along with this, the practical implications and future directions are discussed.

(a) Comparison and contrast of studies

The current study is focused on analyzing the role of Industry 4.0-enabling technologies with digitalization for achieving sustainable SCM. To validate the novelty of the current study, a comparison with previous studies is detailed and presented in Table 6. From Table 1, it is concluded that a few recent studies have been carried out on the concept of sustainable SCM, in which they have presented a systematic literature review. In these studies, the concepts of different Industry 4.0-enabling technologies that are significant in paving a path toward achieving sustainability in the supply chain with digitalization are lacking. However, this study presents the significance of different Industry 4.0-enabling technologies for the achievement of sustainable SCM in detail. Along with this, the study presents future directions that can assist researchers in enhancing the performance of SCM.

Table 6. Comparison of the current study with previous studies.

Ref	Objective	Concepts
[103]	To investigate the relationship between Industry 4.0 and supply chain resilience	SC resilience and Industry 4.0
[21]	Summarize the Industry 4.0 literature concerning the triple bottom line and SCM	Industry 4.0, triple bottom line SCM, and
[104]	A conceptual framework of the latest digital supply chains is introduced	Digital supply chain
[105]	Identified the Industry 4.0 components of sustainable supply chain and suggested research topics for future studies	Industry 4.0 and sustainable supply chain
[106]	Examined the function of IoT in a sustainable supply chain and	IoT and sustainable supply chain
Proposed study	Analyzed the different enabling technologies of Industry 4.0 for achieving sustainable SCM with digitalization	Industry 4.0-enabling technologies, digitalization, and sustainable SCM

(b) Practical Implications

This study provides managers with an overview of Industry 4.0 and its enabling technologies' implications for sustainable SCM from a practical perspective. By 2030, every nation, business, and the individual must work toward sustainability to ensure a safe and sustainable environment for future generations. This study empowers managers to identify which Industry 4.0-enabling technologies are appropriate for meeting the goal of sustainable SCM. It has already been concluded by different researchers in their studies of different fields that Industry 4.0-enabling technologies can achieve sustainability. This study assists managers in obtaining insights about the current advanced and emerging Industry 4.0-enabling technologies, such as IoT, AI, big data, cloud computing, and blockchain, which have the power to transform SCM into sustainable SCM with their unique and innovative characteristics.

The amalgamation of two or three different Industry 4.0-enabling technologies has an impact on sustainable SCM and, from this study, managers may be able to identify which combination of technologies can assist them to achieve different targets in sustainable SCM. In the present scenario, the amalgamation of AI, blockchain, and digital twin would empower the creation of an intelligent system to process complex activity in global supply chains. Furthermore, the combination of these technologies allows organizations to create a road map for good performance in ESG and enables them to meet social targets by combining new data types with conventional operation data to monitor contemporary social metrics. The amalgamation of AI and IoT has shown an impact in the present scenario. IoT-assisted edge-based devices with AI can be incorporated into the SCM to generate predictions and analytics based on real-time data. This indeed empowers us to take immediate decisions in SCM stages such as raw materials, suppliers, inbound logistics, company operation, and the product use cycle.

(c) Recommendations

- Many organizations that are working towards environmental sustainability are currently issuing green bonds. In the context of the supply chain, the organization is issuing green bonds; however, they are many challenges in verifying that the particular organization is following environmental sustainability in its SCM. Thus, there is scope for implementing Industry 4.0 technologies to measure the environmental sustainability achieved by a particular organization.
- Digital twin implementation in the manufacturing industries allows the creation of a virtual SCM model [107–109]. The process of every stage of SCM will be experienced in real-time from the virtual representation. If manufacturing develops a digital twin model of SCM, then it will be beneficial for education institutes to teach students to understand the activities involved in it [110–112]. Moreover, a digital twin model of the manufacturing industry can be created to check the possibility of risks and impact on the environment and support society.
- The real-time implementation of IoT hardware in SC is still in the early stages. Industries need to speed up the implementation of IoT hardware, as it can assist in integrating blockchain for the visualization of real-time data in a peer-to-peer network with high transparency, security, and immutability. Moreover, the integration of 5G communication in the IoT hardware minimizes the latency in transmitting critical real-time data to the destination. Moreover, 5G communication enables us to effectively implement AI-assisted edge devices based on edge computing for better predictive analytics and real-time analytics, which can boost the performance of SCM related to the current context [113].
- Moreover, 6G envisions AI-powered methods to enhance the connectivity quality of service (QoS) and optimize resource usage. For agricultural supply chain management, an architecture utilizing a combination of unmanned aerial vehicles (UAVs), artificial intelligence (AI), and blockchain is suggested, to guarantee the tracking of inventories, traceability and transparency, and contracts [114]. Similarly, the combination of these technologies can be implemented in the supply chain management of manufacturing, strengthening its infrastructure and achieving sustainability.
- Fundamentally, the implementation of edge intelligence in IoT applications consumes high energy during the computational process. In aprevious study, a deep reinforcement learning (DRL) model that could reduce the CNN model dynamically depending on the energy determined by the accuracy prerequisites and energy management policy for IoT applications is proposed [115]. The proposed energy policy makes predictions about how much energy will be harvested and limits how much energy the edge device can use for deep learning inference.

(d) Future directions

The current study presents the significance of Industry 4.0-enabling technologies from the perspective of sustainable SCM. The current study can be further extended to discuss the remaining Industry 4.0-enabling technologies that are not discussed in this study. Currently, the performance of sustainability in any organization is measured with ESG metrics [116,117]. Thus, future studies need to discuss the ESG metrics about SCM and present how different Industry 4.0-enabling technologies support the acquisition of the data that are required in analyzing the ESG of an organization.

7. Conclusions

Sustainable SCM is a significant area that is progressing towards sustainability, emphasized by the United Nations as a requirement for the future. Industry 4.0-enabling technologies have played a crucial role in meeting sustainability goals in various fields. In this study, we have presented the significance and application of Industry 4.0-enabling technologies such as IoT, AI, cloud computing, blockchain, big data, and digital twin for achieving sustainable SCM. The study identified that these technologies are integrated for real-time tracking, inventory optimization, digital trading, demand analysis, and the optimization of operational management. This study suggests the amalgamation of technologies such as blockchain, AI, and digital twin for social sustainability in SCM. In addition to this, the study also discussed its limitations and also presented future directions for further research in sustainable SCM.

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