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Review

Pandemic, War, Natural Calamities, and Sustainability: Industry 4.0 Technologies to Overcome Traditional and Contemporary Supply Chain Challenges

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Abstract: *Background*: The supply chain ecosystem is becoming fragile and difficult to manage due to the complexities in its interlinked functions such as planning, procurement, production, logistics, distribution, and sales. Recently, organizations have started embarking on "Industry 4.0 technologies", a name used to denote transformative modern-day technologies such as Artificial Intelligence, Machine Learning, automation and robotics, Internet of Things, Big Data Analytics, Blockchain, and so on to make faster decisions, optimize current practices, provide end-to-end transparency, increased collaboration, and superior warehouse management, which can collectively make it an "Intelligent supply chain". However, a comprehensive understanding of the subject is required to understand the benefits and challenges of adopting them. *Methods*: Hence, the article aims to systematically review the literature to identify various challenges associated with supply chain management and provide an overview of the role of Industry 4.0 technologies in addressing them. In addition to traditional complexities, the uncertainties arising from contemporary challenges such as the COVID-19 pandemic, war, natural calamities, and difficulties businesses face in developing and adopting sustainable business practices. *Results and Conclusions*: The study shows that although it is hard to predict the level of disruptions during any global events, it is possible to be prepared through Industry 4.0 technologies that can give agility, transparency, and resilience to the supply chain.

Keywords: Industry 4.0; supply chain 4.0; artificial intelligence; blockchain; big data analytics; additive manufacturing; supply chain challenges; upstream and downstream supply chain; COVID-19; sustainability

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1. Introduction

The system of people and entities that work in coordination to move goods or services from a source to the point of consumption is a supply chain, and the unpredictable event that disrupts its functioning is the supply chain disruption [1]. The supply chain is considered the heart of a business's operation, and the COVID-19-pandemic-induced supply chain disruption has proved that both global and domestic businesses of all scales and sectors are vulnerable to breakdown [2]. The involvement of multiple stakeholders, such as procurement, production, logistics, distribution, and sales, and unpredictable external factors, such as suppliers, customers, competitors, and market conditions, add multiple complex layers to it and choke the entire system. The diverse global distribution of the supplier and customer network further increases the complication. However, an agile supply chain that can increase the pace of product development, rapidly introduce new products, and quickly respond to changing customer behavior and external factors is essential to stay alive and increase the competitiveness of the business [3].

Numerous internal and external factors can disrupt a supply chain network. The ripple effect in the supply chain refers to the breakdown at one entity that can trigger failures at the other entities [4]. Both forward (supplier-side) and backward (customer-side)

disruption triggers the failure of a supply chain network, which can lead to a ripple effect [5]. Although proper risk identification and mitigation plans are a part of traditional supply chain management practices, the techniques can handle only the expected disruptions, while they are vulnerable to failures, especially in handling unanticipated events [6]. One such forward and backward disruption caused due to the COVID-19 pandemic became a major stressor for the global supply chain network, and studies have shown that integrating digital technologies into the supply chain can mitigate and control the ripple effect to a greater extent [7]. History has shown us that the pandemic is not a one-off event that can be shrugged off, as many such unpredictable events in the past, such as massive flooding in Thailand hampering the hard disk supply chain, hurricane Katrina disrupting gasoline supply in some parts of the US, flooding of Queensland in Australia, affecting the global coal supply chain, and the ongoing war between Russia and Ukraine disturbing energy and natural resources supply chain reminds us of the need to make future supply chains immune to such unforeseen disruptions.

Throughout the history of supply chain management, several technologies have emerged in an attempt to transform traditional practices and improve their effectiveness. The aim of such technologies is to build supply chain network resilience and transparency by techniques such as maintaining additional safety stock, doing business with multiple diverse suppliers, optimizing network structures, creating supplier development plans, and providing higher visibility to data and product flow across the supply chain [8]. In addition, in the last few years, industries have started embarking on the "Industry 4.0 technologies", an expression that is used to collectively denote the advanced digital, computing, and networking technologies such as Artificial Intelligence (AI), Machine Learning (ML), automation and robotics, Internet of Things (IoT), cloud computing, Big Data Analytics, and blockchain that have the potential in modernizing the traditional supply chain into a digitally managed and connected infrastructure [9]. Hence, a holistic approach to digitalizing and relooking at the current operational practices is required to manage the supply chain efficiently and mitigate the associated risks. The technologies work together by automating all the processes, placing sensors in every machine, creating a network, and collecting and analyzing the data generated to achieve the highest operational effectiveness and improve the quality of the manufactured parts. In other words, modern technologies work in sync to convert a traditional supply chain into a data-driven digital supply chain, a supply chain 4.0 ecosystem.

Hence, the purpose of this study is to introduce various Industry 4.0 technologies from the supply chain and logistics perspective and determine how the technologies can collectively work to solve the current and future challenges associated with the function. The study provides four important contributions. First, it introduces the various traditional challenges that a typical supply chain function faces in addition to the contemporary challenges in Section 3. Second, the various Industry 4.0 technologies and how they can help in solving the challenges are discussed in Section 4. Third, the role of Industry 4.0 technologies in supporting a sustainable supply chain is discussed in Section 5. Fourth, as every new technology has its own benefits and challenges, industries must be aware of the risks associated with adopting new technologies. Hence, the challenges, future directions, managerial implications, and limitations of the study are discussed in Section 6. A narrative or descriptive review approach was followed, and the findings were summarized in different sections of the article by studying, organizing, and reviewing the literature. While already there are few pieces of literature on the application of Industry 4.0 technologies to overcome supply chain challenges, apart from traditional challenges, the current study also focuses on the contemporary supply chain challenges the world currently faces due to unforeseen circumstances such as the COVID-19 pandemic, the Russia–Ukraine war, natural calamities due to climate change, and challenges businesses face in developing and adopting sustainable business practices.

2. Review Methods and Materials

To understand the traditional and contemporary supply chain challenges and to evaluate the impacts of a few important Industry 4.0, a comprehensive study of the previously performed research was conducted. The different combinations of keywords such as "supply chain" (including "supply chain 4.0", "logistics", and "inventory") and Industry 4.0 technologies such as Artificial Intelligence, blockchain, Internet of Things, and so on were used to find the relevant articles in the databases such as Google Scholar, Scopus, and Web of Science. A preliminary screening of the articles to identify their relevance to the study was conducted by reading the title and abstract. The main findings and conclusions are summarized in a narrative or descriptive format. The key takeaways, future directions, limitations, and conclusions are reported. It should be noted that the study does not include all the articles published on the topic but is focused only on covering the latest and important progress in the area to summarize and inform the readers on the status and future direction. The steps followed for the study are shown in graphical format in Figure 1.

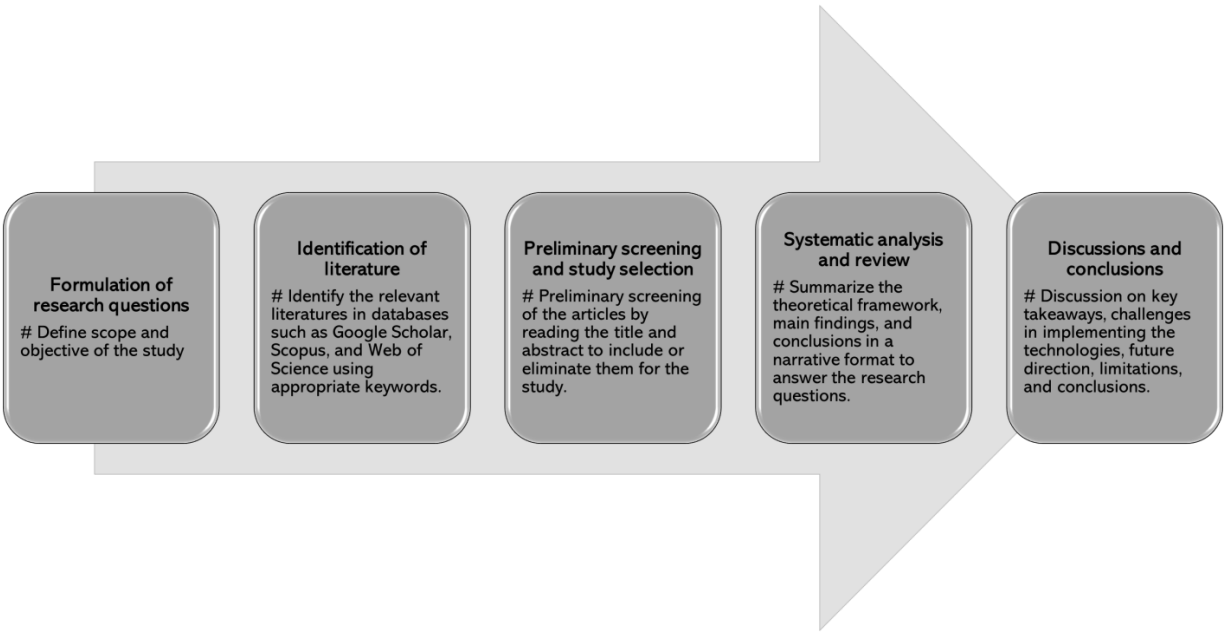

Figure 1. Methodology followed for the study.

3. Challenges in Supply Chain and Logistics

The entire sequence of activities, such as sourcing, processing, and delivery of products to the customers, is the supply chain, while the activities involved in acquiring, storing, and transporting the products between different functions are the logistics. Hence, logistics is an integral part of the supply chain [9]. In addition, an organizational supply chain can be divided into upstream and downstream activities, and supply chain management involves managing both to ensure an uninterrupted flow of goods and services [10]. The upstream portion of the supply chain refers to the organization's suppliers and the activities performed to maintain the relationship with them, and the downstream portion of the supply chain refers to the post-manufacturing activities, such as managing the distribution and delivery of products to the end customers. While both the upstream and downstream supply chain can be commonly referred to as external supply chain management, the organization's internal supply chain is responsible for converting the raw material or semi-finished products and processes received from the external suppliers into the finished product and inventory management. The typical upstream and downstream supply chain of a manufacturing organization is shown in Figure 2.

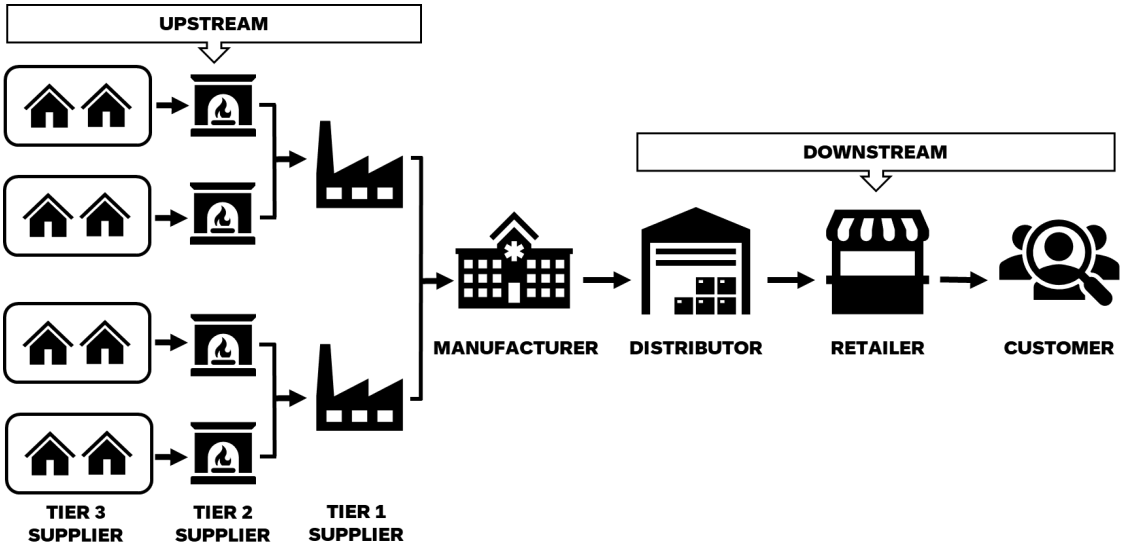

Figure 2. Upstream and downstream supply chain.

Typically, the risk in the supply chain is categorized into operational risks and disruption risks. Traditional high-frequency, low-impact day-to-day challenges such as fluctuations in lead time, delivery, demand fulfillment, and so on are a part of the operational risks, while the low-frequency, high-impact disturbances that occur due to major regional or global events such as the pandemic, natural calamities, change in regional politics, war, and so on are a part of the disruption risks [7]. The interconnectedness and interdependencies of a supply chain network in which any disruption in one function affects the other is the supply chain complexity (SCC) [11]. Inefficiencies in supplier management, inaccurate demand forecasting, product quality, data accessibility, inventory management, products not meeting customer expectations, and poor risk mitigation strategies are a few of the traditional challenges that organizations face. Additionally, unpredictable and unforeseen events can also lead to non-traditional disruptions, which are discussed in the following section.

3.1. Traditional Challenges

The supply chain is usually visualized as a function that is inefficient, data-intensive, physical records or paperwork management, time-consuming, and error-prone due to manual reconciliation processes. Apart from such administrative challenges, the various traditional challenges associated with the various functions of supply chain management are discussed in this section.

3.1.1. Planning and Forecasting

As "demand" is the starting point of all supply chains, its efficiency depends on the accuracy of planning and forecasting. The supply chain planning matrix consists of a comprehensive planning and forecasting strategy which includes demand planning, strategic network planning, production planning, and scheduling, purchase and material planning, distribution planning, logistics planning, and demand fulfillment [12]. Currently, organizations across sectors use Enterprise Resources Planning (ERP) systems in combination with the Advanced Planning and Scheduling (APS) system to improve their operational and production efficiencies. However, the traditional ERP system is fully centralized and is prone to interoperability issues. For instance, as the supply chain of large organizations deals with numerous manufacturers, retailers, and wholesalers who all have their own ERP systems, it creates a virtual boundary that prevents sharing of data between them. This can lead to a lack of trust, transparency, and traceability to the available data across the entire supply chain network.

Bullwhip effect, which is also denoted as the Forrester effect, whiplash effect, or whipsaw effect, is another traditional supply chain problem that refers to the distortion in the supply chain created due to irregular orders in the lower part of the supply chain that creates a large variance in the product demand which moves upwards from the retailer to the manufacturer [13]. The variation in the demand climbs up to each supply chain link, where the underestimation or overestimation of demand leads to a huge fluctuation and affects the smooth functioning of the entire supply chain network. The inaccuracies and lack of transparency in the communication between the internal and external stakeholders of a supply chain network are identified as the primary cause of this challenge. Excess inventory, product unavailability, high supply chain cost, revenue loss, and inaccuracies in production planning are a few of the consequences of the bullwhip effect [14].

3.1.2. Supplier Relationship Management

Maintaining a good relationship with suppliers is crucial for the uninterrupted functioning of an organization's supply chain [15]. Hence, the objective of supplier relationship management (SRM) is to maintain the continuity of the supply of high-quality products or services within the multi-tier levels of the supply chain [16]. It is a combination of various business practices and information flow components that are used to monitor, communicate, collaborate, and coordinate to drive values for the enterprise and its suppliers [17]. Although SRM is an important goal of all organizations, they often face conflicts and challenges in ensuring a good relationship between the parties. Ensuring quality, lack of communication, lack of transparency to supplier processes, risks due to lack of visibility to upstream and downstream supply chain, meeting compliance requirements, driving innovation, managing cost, and conflicts over contracts, shipments, and delivery are the common challenges in supplier relationship management.

3.1.3. Product Quality

Product conformance, product performance, and product reliability are the three key indicators that measure the quality of a product. The goal of all supply chain practices is to improve production performance and efficiency, which in turn adds value to the product [18]. The value addition must meet customers' requirements of quality, availability, and affordability. However, product quality problems are not always associated with production quality problems or poor quality-control practices followed by the manufacturer [19]. Typically, it also depends on the supplier's quality, but large organizations usually have their supply chains extended across the globe to keep their costs low and mitigate regional disruption risks, which can lead to a lack of visibility of the quality of raw materials used and the product quality maintained at the lower tier of the supply chain [20]. Especially a foreign firm that does business with a large global supplier network cannot have visibility to data such as quality of raw material used, possible contaminations, extended supplier network involved, product quality compliance, and damages during logistics [21]. To mitigate the challenges, a few scholars have suggested following supplier evaluation strategies such as supplier identification, supplier selection, supplier evaluation, supplier development, and supplier integration as a part of Supply Chain Quality Management [22,23]. Nevertheless, a robust system to share information across the supply chain network and gain total supplier visibility using new-age digital technologies is required to avoid the risk embedded in the multi-layer supply chain.

3.1.4. Inventory Management

The fluctuations and variabilities that arise out of inaccuracies in product demand can lead to poor inventory management that impacts both cost and service [24,25]. Inventory management is a double-edged sword that, if managed properly, can reduce cost and increase profitability, while excess inventory can burden the supply chain, and that would have a devastating impact on the organization's bottom line. Overstock is a situation that arises when surplus inventory enters the supply chain. It contributes to higher

inefficiencies in the supply chain, such as diminishing bottom line, restrictions in cash flow, outdated product specifications, and higher storage, labor, insurance, and logistics costs, whereas understock can result in missing business targets, diminishing revenue, damaged reputation, and lost customer confidence. However, smart, agile, interconnected, autonomous, and data-driven warehouse and inventory management can overcome the challenges to a greater extent. Hence, businesses, irrespective of their role as manufacturers, distributors, wholesalers, or retailers, must have a robust system to predict customer preferences and evaluate market conditions to obtain accurate demand forecasting and lower inventory cost.

3.1.5. Competitiveness and Customer Service

The rapidly changing global market scenario has made manufacturing companies highly responsive and act quickly to the changing customer requirement and provide value-added products and services to enhance competitiveness and customer satisfaction [26]. Offering high-quality products, increasing value addition, and rapid innovation are the few important strategies for organizations to survive in the highly competitive market. In addition, businesses that keep looking for opportunities beyond their regional boundaries, both to acquire new customers and deal with global supplier networks, add multiple layers of complexity to their current challenges [27]. However, reducing manufacturing costs, increasing sales and profitability, and bolstering supplier relationships are the three key success factors for a supply chain to obtain a competitive advantage and provide superior customer service. With so much of resources (energy, time, and money) spent to acquire new customers and retain the current customer base, organizations have started focusing more on establishing a superior relationship with their customers and comprehended that reliability, responsiveness, and relationship (the 3 Rs) are highly critical for superior customer service. However, creating, acquiring, sharing, and managing the knowledge pool to enhance an organization's competitiveness and understanding of consumer preferences and maintaining constant communication and relationship with the entire supply chain network to deliver superior customer service are a few of the challenges that persist [28]. Hence, advanced data-driven behavioral analysis and web-based customer interaction tools are a few techniques that can be explored to solve the contemporary problem.

3.1.6. Risk Identification and Mitigation

In today's competitive market environment, supply chain networks are becoming highly complex due to the presence of a lot of uncertainties [29]. Hence, identifying and mitigating the risks associated with the supply chain network is one of the critical but challenging tasks for organizations. Some of the common supply chain-related risks include higher complexity and competitiveness, lack of supplier diversification (higher reliance on one specific supplier or suppliers from one geographical location) or excessive diversification, lack of transparency across the supply chain network due to dependence on outdated technologies, poor inventory management, failure to prepare for unforeseen disruptions from the economy, environment, or politics, and lack of cost control measures. In general, the risks associated with a supply chain can be categorized into risks arising within the supply chain (internal) and risks outside of it (external) [30]. The supply chain without a proper risk management technique would often result in suboptimal results and inconsistent processes. The four basic steps in risk management are risk identification, risk assessment, risk management, and risk monitoring [31]. However, apart from setting up processes and governance models, model-driven and data-driven digital technologies can be adopted by organizations to improve the visibility and transparency of the supply chain network, which can minimize disruptions and their associated risks.

3.1.7. Data Accessibility and Management

An efficient and successful supply chain management requires access to data. Quality data refers to the availability of the right data at the right point in time, which enables

the supply chain managers to obtain visibility to the required data that can be analyzed and organized to take action and make data-driven decisions rather than deciding based on intuition. The core of supply chain data management lies in the ability to track the status and location of the product or services at every stage throughout the supply chain network [32]. In addition, due to the involvement of multi-tier supplier networks that spread across the globe, the data management system must be agile, secure, and robust. Currently, although most of the industrial supply chain has moved away from using physical ledgers, emails, and excel sheets to an Enterprise Resource Planning (ERP) system, the challenges in providing visibility to data at every stage of the network persist. In addition to interoperability issues, centralized database management systems are prone to manipulation and security threats [9]. However, poor data collection practices, lack of time and resources, security and privacy issues, lack of funding, reluctant to adopt new IT infrastructure, return on investment, lack of suitable technical resources, scalability and interoperability, and small-scale organizations not seeing value in the expensive new data management systems are identified as some of the major challenges that businesses face in data accessibility and management [33].

3.2. Contemporary Challenges

Apart from the traditional challenges, the modern supply chain is frequently disrupted by unforeseen challenges such as the COVID-19 pandemic, geopolitical tension, war, economic sanctions, shifting focus toward ESG (Environmental, Social, and Governance), and natural disasters (extreme weather events due to climate change) have induced a huge amount of uncertainty into the entire supply chain network. The overall consequences of such contemporary supply chain challenges are briefly discussed in this section, with a focus on COVID-19-induced challenges.

3.2.1. Scarcity of Raw Materials

In the past few decades, the world has changed into a single global economy in the way that it is organized and governed by participating nations [34]. Hence, any disruption in one nation can have a ripple effect on the rest of the nations. Unlike the world of the past, western countries have a larger reliance on their Asian counterparts for raw materials. Recently, countries closing their borders to prevent the spread of COVID-19 has led to a severe scarcity of raw materials that has affected almost all sectors, from pharmaceuticals to automobiles. The lack of raw materials and spare parts has led to the closure of many manufacturing industries across the globe [35]. Most of the manufacturing supply chains faced challenges in meeting the demand and increasing the production capacity due to the shortage of raw materials [36]. In addition, the panic-purchasing of essential items by consumers, which is a commonly seen behavior during crisis times, has further increased the demand for certain types of products and, in turn, their raw materials [37]. While the prices of raw materials such as metals and oil fell due to the lack of demand [38], the price of semiconductors increased due to the high demand for consumer electronics. Nagao et al. [39], in a recent study, have shown that trade agreements between countries, such as Trans-Pacific Partnership (TPP), can have a positive impact on maintaining the cost even during disruption events such as the COVID-19 pandemic. Similarly, while the pandemic reduced the demand for oil, the Russia–Ukraine conflict has increased it tremendously due to the economic sanctions and ban on buying Russian energy, which resulted in a huge demand-supply gap. However, rather than the scarcity of raw materials, the scarcity of the right information on the product demand during such an extraordinary situation can lead to inaccurate demand forecasting and a mismatch in the demand–supply cycle.

3.2.2. Increase in Transportation Cost

During the COVID pandemic, the regional and international movement of products and services was severely affected due to the strict control of cross-border transactions imposed to prevent the spread of the disease. The manufacturers that fully depend on

global suppliers to meet their raw material and spare part requirements were severely impacted [40]. Higher demand for certain types of products leads to a higher quantity of the product being shipped, which increases transportation costs. In addition, the logistics providers increase the freight cost to compensate for the increased lead time due to the road and border closures [41]. The reduced shipment quantity due to the shortage of raw materials further adds to the average transportation cost of the products. For a supply chain that is spread across multiple countries, the additional dependency on a specific regional supplier to compensate for the lost supply from the affected countries further increases the transportation cost in addition to the higher import duties [42]. Additionally, the highly dynamic nature of the restrictions placed on the movements of people and goods and the urgency in the global delivery of critical raw materials and essentials have significantly increased freight costs. The limited airfreight capacity, frequent cancellation of flights, added hygiene measures, and additional handling instructions result in higher transportation costs [43]. In addition to the pandemic, the increase in crude oil prices triggered by the Russia–Ukraine war has further resulted in higher transportation costs.

3.2.3. Demand Forecasting

Any major global disruption, such as a pandemic or war, can lead to huge uncertainty in the demand and supply cycle, which has a different impact on different industries. For instance, as people were forced to stay indoors, the aviation, automobile, and oil and gas industries suffered due to the lack of demand, while sectors such as pharmaceuticals, electronics, semiconductors, and chemical products faced a surge in demand. The sudden change in demand and consumption patterns due to a fall in income and job losses has severely affected current forecasting practices. New personal and social behaviors emerged as most of the day-to-day activities were performed indoors, which led to a demand for newer products [44]. However, most of the demand forecasting challenges were mainly influenced by challenges in both the supply chain side and the supply and demand side. Nevertheless, the economy of most of the countries took a huge blow due to the huge fluctuation in the production and consumption patterns as the daily wage workers in unorganized sectors lost their jobs while the employees of organized sectors worked from home [45]. A sudden and temporary demand for certain products, a surge or drop in demand for other products, a high fluctuation in demand, and a change in supply channels (from large shopping malls to independent brick and mortar stores, and offline to online channels), which leads to demand spike in one channel and drop in the other for the same product, are few challenges faced during the pandemic [46].

3.2.4. Logistical Challenges (Port Congestion)

Maritime transport is considered a critical means to keep global trade flowing and maintain the stability of the global supply chain, as more than 90% of cross-border transportation happens through the sea [47]. The restrictions placed on air travel and road transport due to the pandemic have caused congestion at seaports, resulting in delayed delivery and increased lead times. During the early stages of the pandemic, shipping companies stopped their services on certain routes, which led to a demand-supply gap. The companies rushing to meet the high demand led to a sudden increase in container traffic. Due to the limited capacity of the ports, ships queuing up to load and unload lead to port congestion. In addition to the short-term challenges, such as longer lead time and reduced customer service, logistical challenges can trigger long-term consequences, such as a reduction in sales and revenues, lost business opportunities, higher debt, closure of factories, and even the possibility of companies going bankrupt [48]. The frequent and prolonged congestion seen at various ports during this pandemic has proven that future maritime logistics must have adequate risk management techniques and quick recovery plans in place.

3.2.5. Changes in Consumer Behavior

The consumption pattern and consumer preferences have a very strong influence on the supply chain [49]. In addition, changes in cultural, social, personal, economic, and psychological factors also have a significant influence on consumer behavior [50]. However, globalization and the rapid advancements in technology in the past decade are changing consumer preferences at a never-seen pace, which puts organizations under severe pressure to produce products that have a very high quality and a robust manufacturing process to consistently meet the quality. Hence, apart from product quality, the organizations are facing additional challenges, such as pressure to update the product features regularly, keep pace with the trend, constantly innovate, and keep costs low. During the pandemic, the demand for hygiene, cleaning, and staples increased, while a decline in the non-essentials was observed, which disrupted the entire demand-supply predictions. Hence, building an agile supply chain that can fulfill the fluctuations in demand is the need of the hour. In addition to quality, the compliance and safety standards (such as permits, licenses, and certifications) that the products meet are another area of challenge that an enterprise supply chain often faces. However, most of these challenges can be addressed through digital supply chain integration [51], which can give much-needed visibility and control to an organization's supply chain network.

3.2.6. Labor Shortage

Supply chain disruptions due to heavy shortages in the workforce are a huge problem that organizations across the globe currently face. It is presumed that an aging workforce that prefers early retirement, border controls that limit immigrant labor, and demands for work flexibility and higher wages are seen as some of the reasons [52]. However, to understand the labor shortage during the pandemic, the overall labor market can be classified into three categories, the first group includes essential workers that were able to continue their work and are in high demand, the second group that was able to work from home, and the third group who lost their job during the pandemic [53]. The closing down and reduced operating hours of non-essential manufacturing industries, restaurants, schools, travel, tourism, entertainment, and leisure activities have led to unemployment in certain sectors (the third group) while bringing huge labor demand in the other sectors, especially for the medium and high skilled labor (the first and second group) [54]. This led to a significant increase in the shortage of certain types of skills, while workers with other types of skills were plentiful. In addition, the strict lockdown measures implemented by governments have forced low-skilled workers to leave the cities and reverse-migrate to their hometowns, which has affected many small-scale industries and unorganized sectors [55]. This resulted in an unusual situation in which labor shortages begin to coincide with a high unemployment rate which shows that people are in no hurry to return to their jobs, or they are very selective in picking only a certain type of job, such as the ones that can be performed remotely. Additionally, as the modern-day supply chain is mostly technology-driven, finding the right workforce with a unique mix of domain and technological skills is becoming difficult.

The study shows that apart from traditional challenges, today's supply chain is stormed by numerous contemporary challenges. The global supply chain is interwoven to the extent that a flooding disaster in 2011 in Thailand, a small Asian country, rattled the entire hard drive supply chain and led to hard disk shortages throughout the world. Hence, the medium and large-scale organizations that do business with the global supplier network are severely affected even by small regional disruptions, which can lead to a chain of events that further rattles the entire global economy. However, most of the challenges can be addressed through systematic approaches and by investing heavily in technology. After all, contemporary challenges cannot be addressed by traditional techniques, but they need a modern-day solution. Increasing the visibility and transparency of data at every stage of the supply chain network, increasing the flexibility of the production units to repurpose assets to quickly adapt to the changing supply–demand

cycle, and maintaining good communication to the entire supply chain agents (customers, manufacturers, and transportation), innovation in product, production, and process, and investing on building a resilient supply chain by adopting new-age digital, computing, and networking technologies (Industry 4.0 technologies) are a few techniques that can help organizations to be prepared for such unforeseen future disruptions. In this context, the benefits of Industry 4.0 technologies in the supply chain and logistics are discussed in the coming sections.

4. Industry 4.0 Technologies in Supply Chain Management

The transformation of industrial practices into new techniques dominated by the technologies available at that time is the Industrial Revolution. The world has so far witnessed three industrial revolutions. The first industrial revolution began in the middle of the 18th century when steam-powered engines and mechanization were introduced, which made the people leave their villages and migrate to nearby cities to work in factories. The mechanization of agriculture, textile industries, railroads, machinery, internal combustion engines, and electric power were the technologies behind the second industrial revolution that started in the middle of the 19th century. The third industrial revolution began in the 1950s and was driven by the invention of transistors and microprocessors that also introduced computers and electronic devices into the factories. Currently, we are living to see the fourth industrial revolution, or Industry 4.0, slowly unfolding around us. This revolution can be called the computerization of manufacturing, in which advanced digital technologies are married to industrial machines and processes to achieve operational efficiency, productivity, and automation to the highest possible extent. The foundation of Industry 4.0 was built over four important modern technologies as Networking, data, and computational (Smart sensors, IoT, Blockchain, and cloud computing), Analytics and Intelligence (Artificial Intelligence, Machine Learning, and Big Data Analytics), Human-machine interaction (Automation, Robotics, COBOTS, and Drones), and Advanced manufacturing (Additive manufacturing) as shown in Figure 3. Given that the fourth industrial revolution would radically change the entire production process, it is also expected that supply chain and logistics functions would undergo a drastic transformation [56].

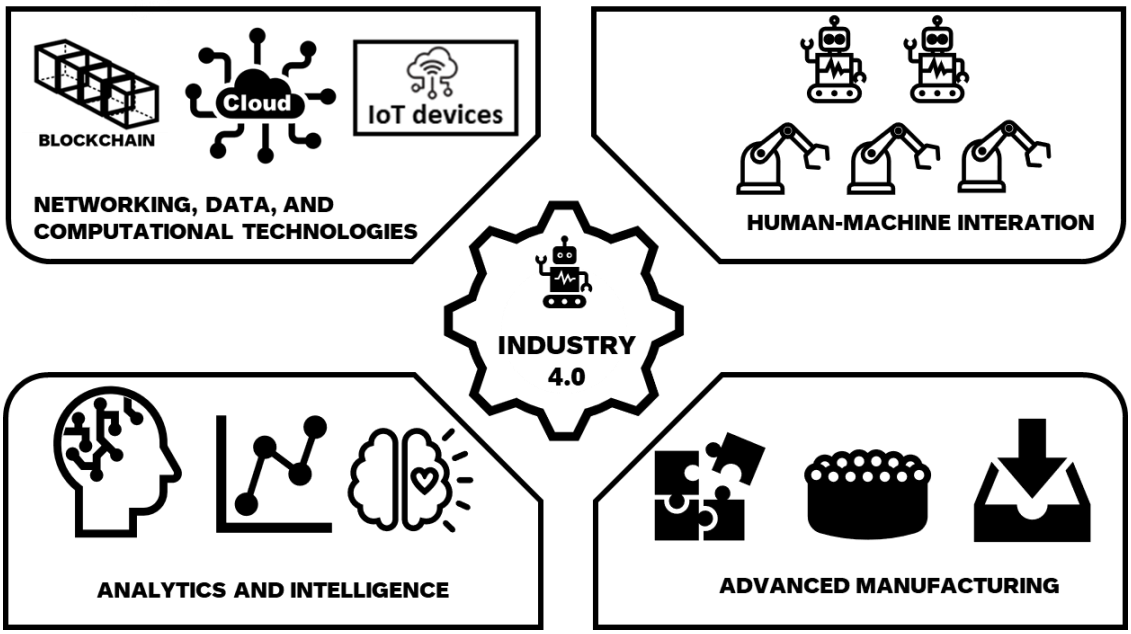

Figure 3. Foundation of Industry 4.0 technologies.

Gone are the days when supply chain and logistics management were considered a network of functions that worked to convert raw materials and deliver a finished product

to the end user or customer. The scope of the modern supply chain has grown beyond conventional boundaries and is pounded every day with new challenges which strive to improve business competitiveness and growth. The entire supply chain is tangled with numerous internal and external factors which put an enormous amount of pressure on the everyday functioning of a business. For instance, more than 70% of the survey participants from 17 countries that were a part of the Geodis supply chain survey 2017 have responded that their supply chain is either 'very' or 'extremely' complex, and achieving extended visibility is one of the major objectives to efficiently manage it, which nicely sums up the complexity involved in supply chain management [57] and the need for digital technologies. The extended supply chain visibility and transparency can be categorized into six major parts. They are visibility in procurement and inventory management, operations, logistics finance, quality control, sales, and customer service [58].

However, in the coming years, the various Industry 4.0 technologies are believed to act as the main driving force in supply chain management, such as supply planning, logistics, performance management, order management, stakeholder relationship, and strategic supply chain. They can provide multidirectional communication across the supply chain network and bring a transformation in service, cost, capital, and agility to a traditional supply chain. The various enabling technologies and their application are discussed in the following sections. Although there are numerous advanced digital, computing, and networking technologies developed in the last decade that can bring a transformation and help address contemporary supply chain challenges, only the most popular technologies are discussed.

4.1. Artificial Intelligence

Artificial Intelligence (AI) is an algorithm-based intelligence fed to machines to provide problem-solving abilities and decision-making skills and perform human-like assignments. In other words, the technique makes machines think and behave like humans. It is a combination of several digital and software technologies that acts as the driving force of Industry 4.0 [59]. Although the origin of the technology can be traced back to the 1940s [60], with numerous incremental advancements, it has gained widespread acceptance and implementation in the past decade in almost all sectors. Implementing the technique in supply chain management can provide an integrated end-to-end solution from purchasing to sales to increase efficiency and productivity. The ability of AI to analyze a huge volume of data in a shorter time, provide granular level visibility to data, reduction in cycle time, improve operational efficiency, continuous process improvement, and data-driven decision-making capabilities would help in the complete transformation of the function.

Although many different AI techniques were applied by scholars to address the supply chain-related challenges, studies have shown that Artificial Neural Networks (ANN), Fuzzy Logic (FL), Multi-Agent and Agent-Based Systems (MAS and ABS), and Genetic Algorithm (GA) are the most used techniques. In addition, data mining, case-based reasoning, swarm intelligence, support vector machines, decision trees, k-means clustering, and Bayesian networks are a few other techniques used by scholars [61]. Mobarakeh et al. [62] have applied a bootstrapping method to address unpredictable and irregular demand forecasting challenges of a business aircraft supply chain and concluded that the technique can result in significant cost savings. An IoT-based risk monitoring system and fuzzy logic approach was successfully applied by Tsang et al. [63] to control the quality of product and reduce safety-related issues in a cold supply chain. Similarly, Ignaciuk and Wieczorek [64] have applied a Genetic Algorithm for inventory control strategies and optimizing the goods flow process in logistic networks and proved that the technique is highly effective even in scenarios that have high analytical and computational complexities. An agent-based simulation framework was successfully applied by Ferreira and Borenstein [65] for supply chain production planning problems, which can also be used for inventory control. The major challenges faced by organizations across the globe during unpredicted events such as the COVID-19 include suppliers not meeting delivery obligations, fluctuations in customer

demands, and the spike in demand due to panic buying. However, AI can be used to identify and mitigate risks, enable sustainable supply chain processes and logistics, and provide supply chain resilience, risk management, data-driven supply chain, decision model, technology management, network design, and optimization algorithms to improve supply chain efficiency [66]. Table 1 shows the different studies from the literature that have applied different AI techniques for various supply chain and logistics-related challenges, as reported by Toorajipour et al. [61].

Table 1. Application of AI techniques in various functions.

Field of Research	Subfield and Related Literature
Marketing	Sales forecasting [67], Sales management [68], Sales promotions [69], Pricing models [70], Market segmentation [71], Customer segmentation [72], Marketing decision support [73], Direct marketing [74], and Industrial marketing [75]
Product design	Design specifications of new products [76] and Product life-cycle management [77]
Logistics	Container terminal management [78], General logistics [79], Inbound logistics processes [80], Logistics systems automation [81], Lot-sizing [82], and Logistics workflow [83]
Production	Assembly line balancing [84], Assembly automation [85], Production monitoring [86], Production forecasting [87], Production systems [88], Production planning and scheduling [89], Production data management [90], Integrated production management [91], General production management [92], Flexible manufacturing systems [93], Decision support systems [94], Manufacturing problem solving [95], Quality control and improvement [96], Quality monitoring [97], Product line optimization [98], Workflow management [99], Product-driven control [100], and Low-volume production [101]
Supply chain	Demand forecasting [102], Facility location [103], Supplier selection [104], Supply chain network design [105], Supply chain risk management [63], Inventory replenishment [106], Crisis management [107], Global value chains [108], Supply chain process management [109], General supply chain management [110], Supply chain integration [111], Supply chain planning [112], Maintenance systems [113], and Sustainable supply chain [114]

4.2. Internet of Things (IoT)

The modern supply chain function is bombarded with a myriad of challenges due to varieties of reasons, such as the presence in multiple geographical locations, which makes it vulnerable to regional issues, ever-changing customer demands, product customization, price competitiveness, increase in product complexities, adaptation to changing technological advancements, fluctuations in socio-economic and political factors, and natural calamities [115]. In recent years, technologies such as the Internet of Things (IoT) have been seen as a critical enabler for efficient and flexible supply chain management and support smart factory ecosystems or Industry 4.0 [116]. It is a system of interconnected machines, artificial intelligence utilities, or people [117]. While the aim of Industry 4.0 is to transform industrial production to the next level, the objective can be fully realized only when the supply chain and logistics become data-driven and fully digitized using technologies such as IoT. The typical data flow from various supply chain sources collected using IoT devices to a secure cloud server is shown in Figure 4.

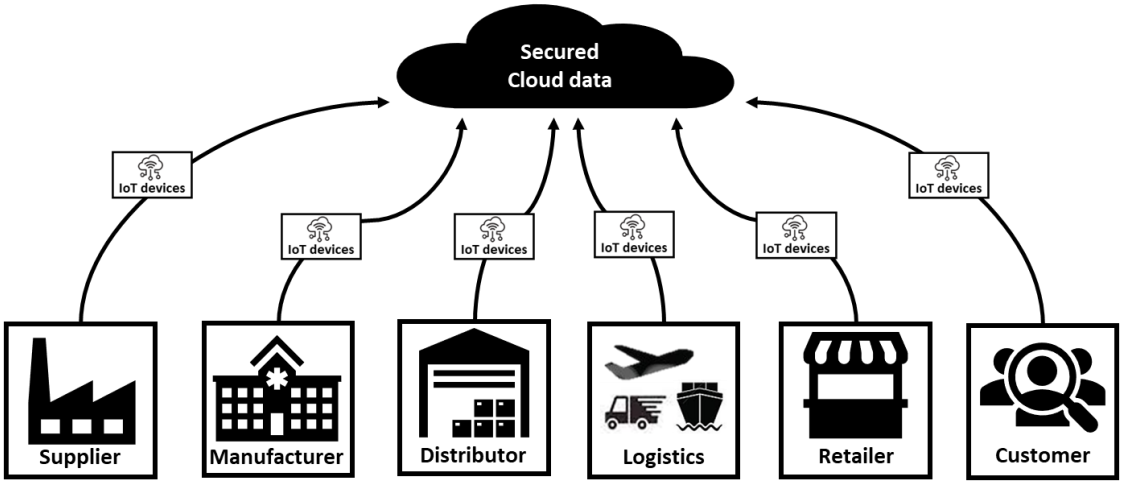

Figure 4. Data flow from various supply chain sources to the cloud using IoT devices.

The Radio-Frequency Identification tag (RFID) that was previously used to read, identify, and track products is seen as the precursor to IoT technology. It can provide an unprecedented level of visibility to the supply chain by connecting and creating a network of "things" (physical objects) that are a part of the supply chain. In other words, it integrates physical objects with the digital world through various advanced sensing, networking, and computing technologies. This enables the physical objects to communicate with each other using the "internet" (hence the name Internet of Things), and the real-time data collected from them can be used for the predictive and preventive analysis of various supply chain situations that requires immediate actions that in turn improves supply chain efficiency. It also allows remote management of supply chain operations, improved coordination between the partners, and provides accurate data for effective decision making. End-to-end visibility of data is critical in achieving a transparent supply chain that can withstand a massive disruption such as the COVID-19 pandemic or war. The recent increase in the penetration of IoT sensors is creating a massive network that can communicate with each other while generating an unprecedented volume of data that can be used for real-time monitoring and information gathering. Especially the food and perishable goods supply chain has already started realizing the true potential of IoT technology in their supply chain and logistics which provides insight into information such as real-time production planning and inventory management, temperature, pressure, and humidity inside shipping containers, tracking the exact location of goods at various stages with tamper-proof time stamping, and delivery tracking. By tracking a system's utilization details, the technology can also help in improving the overall operational efficiency of the system. Developing suitable algorithms and inventory management mathematical models can help in reducing wastage and shortage of such products [118,119].

The SCOR model (Supply Chain Operations Reference model) is a standard framework developed and endorsed by the Supply-Chain Council to improve supply chain processes in various organizations. To translate the business strategies into execution plans and policies, it has divided the supply chain management into various stages such as Plan, Source, Make, Deliver, Return, and Enable [120]. Accordingly, the various research studies based on using IoT in these supply chain processes, as summarized by Ben-Daya [115], are shown in Table 2.

Table 2. IoT in supply chain management.

Process	Role of IoT	Relevant Literature
Source	• Connect with suppliers to improve supply chain visibility. • Track activities in real time and obtain inspection details from suppliers to improve product quality. • Supply chain data collection for strategic planning.	Verdouw et al. [121], Ng et al. [122], Yu et al. [123].
Make	• Transparency on the status of parts and raw materials to minimize lead time and cost. • Combine product and after-sales service to reduce cost. • Real-time quality and maintenance data from the customer to improve product design. • Remote preventive maintenance to increase product life and customer satisfaction.	Wang et al. [124], Rymaszewska et al. [125], Putnik et al. [126], Ondemir et al. [127], Chukwuekwe et al. [128].
Deliver	• Inventory tracking to reduce logistics time. • Information sharing and joint ordering for collaborative warehousing, on-time delivery, and inventory accuracy. • Autonomous decision making to reduce time and cost. • Quality monitoring and quality-controlled logistics to eliminate waste and improve quality.	Reaidy et al. [129], Qiu et al. [130], Choy et al. [131], Kong et al. [132], Yao [133], Mathaba et al. [134].
Return	• Ease reverse logistics to reduce cost and lead time. • Enable traceability to improve visibility and reduce cost. • Monitoring product data while in use to improve customer satisfaction.	Gu and Liu [135], Parry et al. [136], Thürer et al. [137].

Such studies show that the availability of the right data at the right time would enable the supply chain participants to make an improved and timely decision that can enhance the operational efficiency of organizations [138,139].

4.3. Big Data Analytics (BDA)

The enormous amount of data generated from various devices is big data, and big data analytics is the process of analyzing the data to reveal information such as hidden patterns, correlations, market trends, and customer preferences, which can be used by organizations to make data-driven decisions. It is not just the amount of data that is generated and collected using various advanced technologies such as smart sensors and IoT, but it is also critical to use appropriate techniques to use data as a strategic tool to drive changes and make the right decisions. Usually, the data can be either structured, semi-structured, or unstructured in the form of numbers, texts, images, audio files, or social media feeds that are collected from various sources such as radio-frequency identification (RFID), global positioning system (GPS), point-of-sale (POS), smart sensors, IoT devices, instant messengers, or social media. Although data analytics is a combination of mathematics and statistical techniques, BDA is a technique used to analyze a huge volume of data to obtain meaningful insights and turn them into business intelligence [140].

Historically, supply chain managers and scholars have applied statistical and operational research approaches to manage and solve supply chain challenges [141]. However, the recent progress in digital and computing technologies such as BDA has opened a new avenue in approaching and solving the challenges using data-driven techniques. The BDA techniques used in the supply chain are also termed Supply Chain Analytics, and they are used for descriptive, predictive, preventive, and prescriptive analytics with little or no human intervention [142]. Unscheduled machine maintenance can lead to reduced Overall Equipment Effectiveness (OEE), which leads to reduced machine utilization and operation losses [143]. Richey et al. [144] have performed a systematic investigation on deploying Big Data across all the supply chain partners and studied its influence on the performance of the supply chain along with their obstacles. Literature studies have shown that data collection, improved interconnection and collaboration across various functions, agile inventory and warehouse management, manufacturing automation, predictive analytics, process control,

data-driven decision making at various functions, and superior financial and manufacturing management are a few other potential applications of BDA [145]. However, the four important requirements to enable BDA in an organizational supply chain are developing data generation capabilities at every source, integration of data across all supply chain functions and participants, developing appropriate analytics capabilities, and management accepting data as a decision-making tool and implementing data-driven culture [146].

4.4. Blockchain

A blockchain is a digitally managed, distributed, and decentralized ledger used to record transactions in an immutable format. It is a combination of various technologies such as computing, networking, cryptography, and mathematics [147]. The unique characteristics and features of the technology, such as immutability, decentralization, distributed ledger, and consensus mechanisms, make it attractive for all applications in which a transaction is performed. Studies have shown that the technology can be used to manage upstream, operational, downstream, and external supply chain complexities [9]. The application of blockchain technology in various supply chain and logistics functions, as discussed by Santhi et al. [9], is shown in Figure 5.

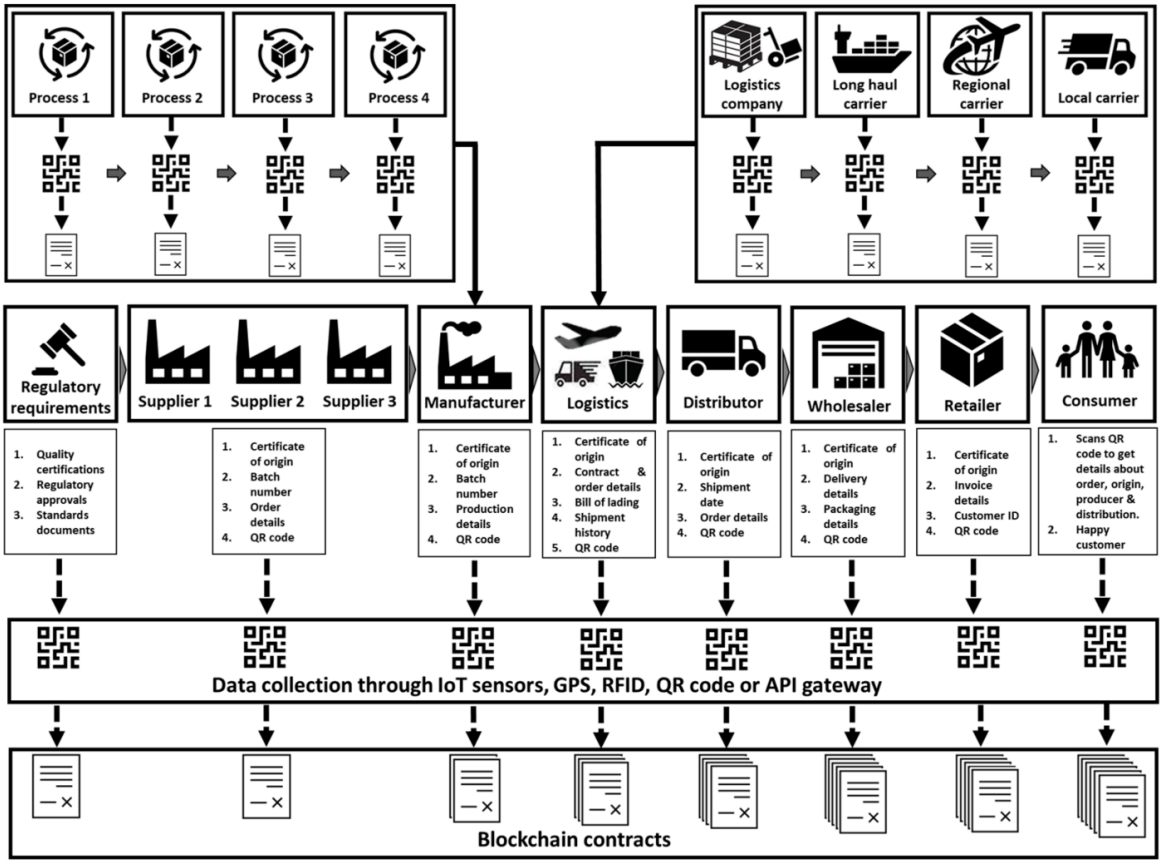

Figure 5. Application of blockchain in supply chain and logistics [9].

At present, most organizations do not have a reliable system to track down the life cycle of a product from the raw material stage till the finished products reach the customers. This is primarily due to the reason that various key functions of the supply chain, such as demand forecasting, scheduling, purchasing, production, quality assurance, inventory management, information management, logistics, and customer service, use conventional standalone technologies that do not communicate or collaborate [148]. In addition, such centralized technologies are prone to hacking and do not provide visibility to data across the entire supply chain participants, which can lead to reduced performance of the supply

chain. For example, a large-scale manufacturer having no visibility to data of their supplier network that is spread across the globe can lead to poor planning, delayed production, poor warehousing and inventory management, and inferior performance [149].

However, integrating blockchain technology across all the participants of a supply chain network, such as suppliers, manufacturers, logistics providers, distributors, wholesalers, and retailers, enables the data collection from all the sources that can be stored in one place in a transparent, tamper-proof, and digitally distributed format which can be accessed without any intermediaries. Providing only the required access to the participants can ensure that they can view or add only the information that they are supposed to view or add. The technology also provides the facility to have digital proof of possession of assets which can help avoid counterfeiting and dual contracting [150]. Various systems such as sensors, GPS (Global Positioning System), RFID (Radio Frequency Identification) tags, NFC (Near-Field Communication), bar codes, QR (Quick Response) codes, APIs, and IoT-enabled devices can be used for data collection [151]. Almutairi et al. [152] have shown that Blockchain technology can provide benefits such as trust, transparency and accountability, cooperation, information sharing, financial exchanges, and supply chain integration. Such transparent and immutable data can lead to superior supply chain performance and higher overall customer satisfaction. It also gives prominence to information such as raw material sourcing sites (ensuring minerals are sourced from conflict-free mines), quality (avoiding duplicate parts), and avoiding unethical practices which are currently invisible to customers [153]. In addition, decentralized blockchain technology can be used by organizations to monitor various processes such as workflows, remotely identify and validate connected devices to avoid data tampering, and share legal, proprietary, and compliance data between the participants. Through a case study, Dehshiri et al. [154] have shown that efficiency, coordination, cooperation, information sharing, and cost reduction can be achieved in the automotive supply chain by implementing Blockchain. Other studies have also shown that a private blockchain can provide benefits such as high security, a high degree of trust, low implementation and operational costs, and data privacy. A blockchain-based digital identity enables fool-proof sanctions, thus preventing rogue nations from importing dual-use products or technologies [9].

In summary, improving traceability of products or services, immutability, providing provenance to ensure product source and quality, providing transparency and security to data, simplifying reverse logistics to support a circular economy, ensuring compliance and ethical practices, error-free inventory management, shipping details, and avoiding duplicate payments are few of the benefits of blockchain technology in supply chain management. Asset tracking and self-executable smart contracts that get executed automatically when predefined conditions are met are a few other potential possibilities of the technology that can help multi-organizational enterprises such as supply chain, logistics, and financial units to a greater extent.

4.5. Automation and Robotics

Although the terms "automation" and "robotics" are often used interchangeably, automation refers to the software program, machine, or technology that is used to carry out a certain task automatically with minimal manual intervention, whereas robotics involves programmable machines that can replace humans from labor-intensive, monotonous, and hazardous environment. In other words, robots are machines that can perform a wide variety of tasks, but automation refers to a special-purpose program, machine, or system that only performs a specific task. Software automation, Robotic Process Automation (RPA), and industrial automation are the three different types of automation, while robots can be categorized into semi-autonomous and autonomous robots. Although it was predicted long ago that robotics would become an integral part of the supply chain until now, they were working only in the production environment to automate certain processes [155]. The various technological and organizational challenges have delayed their implementation in the other functions of a supply chain. However, with the advent of Industry 4.0 tech-

nologies such as Artificial Intelligence, smart sensors, machine vision, IoT, and additive manufacturing, the current era would belong in the digital and computing technologies in which robotics is poised to take a giant leap into the industrial system. Especially autonomous robots are expected a play a critical role in supply chain and logistics management. In addition, the development of next-gen collaborative robots, also called COBOTS, are capable of collaborating with humans that can sense their surroundings, adapt, and learn rapidly. As the cobots are small, cost-effective, and highly flexible, they can easily adapt to the changing requirements on a shop floor and fit into various departments.

Automation and robotics would become an integral part of the self-steering supply chain of future industries that are highly efficient, flexible, and cost-effective [156]. The key differentiator between the traditional industrial robots and the new-gen cobots is the application of the latest technologies such as machine vision, smart sensors, superior navigation and communication channels, and advanced algorithm-based neural networks, which improves a cobots' ability to auto-learn, flexibility to adapt to changing requirements, and agility [157]. With the introduction of cobots, the current targeted application for complex and routine tasks would see a transformation into end-to-end deployment throughout the supply chain. Automated and uninterrupted manufacturing, intra-logistics using robots, material handling, unmanned assembly line and fabrication, robotic warehousing and packaging, autonomous trucks [158], automated last-mile delivery, reverse-logistics using drones, and delivery robots [159] are a few of the supply chain areas were automation, and robotics are expected to see significant growth in the current decade.

4.6. Additive Manufacturing (AM)

The Additive Manufacturing (AM) technology was developed in the early 1980s to replace the traditional manufacturing processes such as machining, casting, injection molding, forging, and so on. The process is used to convert a 3-dimensional CAD model (Computer-Aided Design) directly into a finished part by adding layers of material one over the other to obtain the required shape and size [160]. Hence, it is also called 3D printing or rapid manufacturing. The flexibility in using a wide variety of raw materials such as polymers, metals, ceramics, and so on makes the process a suitable alternative to traditional manufacturing processes. Especially process is attractive for making prototypes, reducing complexity in assemblies with lesser parts, and products that have limited lot sizes. As industries around the globe and across sectors have started realizing the benefits of Industry 4.0 technologies or smart factory technologies, a very high level of automation and product customization are expected as the key benefits, and AM is believed to play a major role [161]. Kunovjanek et al. [162] have grouped the benefits of AM technology in the supply chain context into different categories in line with the SCOR model, as shown in Table 3. Their study shows that reduction in production, transportation, and packaging costs, reduced ecological footprint, lead time reduction in product development, increase in supply chain throughput, and lower maintenance costs are a few important benefits of AM in the supply chain. They have also shown that aerospace and industrial, and consumer goods manufacturing companies have shown significant interest in AM technologies. However, other studies have shown that the automotive, healthcare, bio-medical, and energy sectors are the other key beneficiaries [163].

Table 3. AM in supply chain management.

Field of Research	Subfield and Related Literature
Plan	Process integration and simplification to reduce overall lead time in planning.
Source	Lesser inventory and transportation lead time due to reduced assembly parts.
Make	Reduction in raw material usage, lesser assemblies, and highly customizable parts to meet customer demand.
Deliver	Reduction in the dependency on multiple suppliers can reduce delivery lead time.
Return	Reduction in scrap and recycling of unused AM material.

Especially, AM technology became a crucial part of the supply chain due to the unforeseen disruptions caused in manufacturing companies due to the COVID-19 pandemic. It was used across various sectors to counteract the interruptions significantly by increasing the production of certain critical medical implants, offsetting the challenges caused by the non-availability of unskilled labor, and reducing the time to make complex and highly customized parts [164]. In many critical aerospace and defense applications, the technology has reduced the lead time to a few days from the current lead time of nearly a year due to blockages in forging and casting supply chains [165]. This gives product-based organizations the flexibility to adjust rapidly to fluctuations in demand, freedom of design, shorter development time, reduced component weight, and less inventory cost. As the AM can eliminate or significantly reduce secondary finishing operations such as machining, the overall energy requirement to manufacture parts is reduced, which also helps organizations to achieve their sustainable manufacturing targets.

5. Sustainable Supply Chain Management

Sustainability is an ideology that talks about ways to exist and grow without affecting resources for future generations. It is broadly classified into environmental sustainability, social sustainability, and economic sustainability, in addition to promoting good governance [166]. Implementing sustainability into supply chain management gives rise to Sustainable Supply Chain Management (SSCM) [167], whose objective is to implement sustainable practices into various functions of a supply chain so that the organizations can reduce their total carbon footprint and optimize their operations to achieve cost savings and profitability. Although sustainability must not be seen as a challenge (but a necessity), the lack of metrics to measure an organization's sustainability quotient and to implement and track sustainability at every supply chain function was difficult until a few years ago. However, with the advent of Industry 4.0 technologies, businesses have got an opportunity to relook into their current practices and processes to ensure adherence to sustainability. Hence, sustainability is synonymous with Industry 4.0 technologies, and one cannot exist without the other.

Triple Bottom Line (TBL) is a term used to evaluate the performance of an organization. According to it, an organization's focus must not only be on one bottom line (profit) but also on the other two bottom lines, such as environmental and social concerns (also referred to as protecting the planet and people, respectively) [168]. The range of activities, including sourcing of raw materials, design, production, movement of semi-finished, finished goods, services, marketing, and distribution, that goes into the creation of a finished product or service is the value chain. The process can become inefficient or create a lot of waste when the coordination between the functions fails. For instance, poor forecasting can lead to a bullwhip effect that can affect the entire supply chain, warehousing, and logistics planning. Global events such as the COVID-19 pandemic, war, or natural calamities can make traditional forecasting techniques inefficient, which leads to supply chain disruption.

Implementing all the three-sustainability pillars into an organization's supply chain and creating a digital network across the entire value chain is a challenge. However, introducing Industry 4.0 technologies into supply chain management will have a positive impact [169]. Especially a significant reduction in operational cost, process efficiency, and higher utilization of resources are a few of the immediate benefits of implementing AI and ML [170,171]. A transparent and real-time sharing of data using technologies such as Blockchain, cloud computing, and BDA would lead to higher forecasting and planning accuracy, which can prevent scrap and improve efficiency, and warehouse and logistics management. Currently, governments and businesses are attempting to eliminate fossil fuels to protect the environment by promoting electric vehicles. However, the cobalt mining sector in the Democratic Republic of the Congo, which presently holds more than half of the world's cobalt supply, which is used as a key ingredient in manufacturing rechargeable batteries, is barely regulated. Child labor, unsafe conditions, hazardous artisanal mining, and human rights violations are prevalent in the country [172]. Therefore, after all, pro-

moting electric vehicles alone will not help achieve sustainability unless the source of the raw material is known. In such cases, technologies such as Blockchain can provide tamper-proof data on the provenance of the raw material, which can help organizations adhere to ethical sourcing [9]. Recycling and reducing scraps produced during manufacturing is one of the important steps to achieving sustainability targets. Hence, an automated scrap recycling station in a smart factory environment connected using IoT can measure the bins' fill level while processing the optimal scarp transportation route in parallel without any manual intervention [173]. IoT sensors embedded in all the physical systems of the shopfloor can help in the real-time tracking of products, monitor machine health, and enable predictive and preventive maintenance, which can eliminate machine downtime. In addition, additive manufacturing technology can play a significant role in future factories for near-net-shaped manufacturing of products and reduce the large amount of scrap generated in conventional manufacturing techniques [161]. Similarly, automation and robotics can boost productivity, improve efficiency, provide flexibility, and enhance product quality. Ramirez-Peña et al. [174] have identified that Industry 4.0 technologies can lead to a lean, agile, resilient, and green shipbuilding supply chain. Similarly, Yadav et al. [175] have developed a sustainable supply chain management framework using Industry 4.0 technologies in the automotive sector. Ghisellini et al. [176] have indicated that the adoption of 6R practices (recycle, reuse, reduce, refuse, rethink, and repair) can have a direct impact on the organization's sustainability goals. The various challenges in implementing sustainability into an organization's supply chain are shown in Figure 6.

Figure 6. Challenges in adopting sustainability.

Although it is evident that imparting sustainable practices is necessary, the four major challenges that organizations are facing are policy, business, customer, and societal. Governments must frame suitable policies and laws so that companies can eliminate waste and encourage the use of more recycled materials, which in turn reduces their carbon footprint. A noteworthy financial incentive to encourage the usage of renewable energy sources can encourage businesses to move away from pollution-causing fossil fuels. Similarly, although

the triple bottom line is a starting point to measure an organization's sustainability focus, in reality, companies work to make attractive profits for their shareholders. Hence, unless regional and global policies are enforced to encourage businesses to follow sustainable practices, the concept of TBL and sustainability cannot be practically followed. In addition, it is imperative to understand the notion that the customer is the king and that it is he who creates the business. Hence, the customer and the society in which he is a part must collectively and cautiously prioritize between a cost-effective product vs. a product that adheres to and has undergone sustainable manufacturing processes. Unless all four, policy, business, customer, and society, come together, the goal of achieving sustainability cannot be met.

6. Discussion

The key takeaways from the study, the various challenges that organizations face in implementing Industry 4.0 technologies, future direction, managerial implications, and the limitations of the study are discussed in this section.

6.1. Key Takeaways

Given the complexity of supply chain management, Industry 4.0 technologies can be a game-changer that can provide immense benefits. Conventional supply chain management, with its numerous complexities, requires advanced data-driven technologies that can provide granular level insight into data which supports the functional managers in making data-driven decision making. For instance, demand and supply planning using advanced data analytics and ML-based techniques, real-time inventory management and asset tracking using IoT, improved transparency and visibility to the entire value chain using blockchain, end-to-end process optimization using AI technology, and creating an agile supply chain to meet changing customer behavior by integrating automation, robotics, and additive manufacturing are required to provide a competitive advantage to the organizations.

Traditional supply chain planning in an organization is divided into demand forecasting, supply planning, production planning, logistics planning, and sales and operations planning. The data flow across these functions is not transparent and is driven based on internal data. They are also not immune to unforeseen external events such as the COVID-19 pandemic, wars, natural calamities, and so on. However, data-driven planning using AI and ML algorithms and data analytics can make use of external data dynamically to avoid disruption shocks. Similarly, the technologies can be used in mitigating labor shortages and safety concerns by enabling remote working, process optimization, and machine utilization to improve productivity and part quality, reduce cycle time, and improve operational efficiency. Automation and Robotics and Robotic Process Automation can significantly reduce the dependency on low-skilled manual labor. Automation and contactless delivery of goods were made possible using IoT-enabled logistics and drones. Technologies such as digital fleet management, route optimization, and carrier analytics can help in improving operational resilience to mitigate the influence of such unforeseen external events. Wu et al. [177] have named Industry 4.0-enabled supply chain as Supply Chain 4.0 (SC 4.0), which has six distinct characteristics, as shown in Table 4.

However, studies have also shown that despite its numerous benefits, organizations are not fully prepared to take the next big leap by implementing these technologies into their systems for various reasons. Hence, the following sections discuss the challenges in adopting these technologies and the future direction.

Table 4. Characteristics of Supply chain 4.0.

Characteristics	Details
Instrumented	Systems integrated with sensors, RFID tags, and other data collection techniques to make data-driven decisions.
Interconnected	Fully connected supply chain participants with a seamless flow of data between them.
Intelligent	Intelligent system that can make collect and process a huge volume of data that can independently make decisions.
Automated	A high level of automation reduces manual labor, which can lower overall lead time and improve quality.
Integrated	A high level of collaboration across the supply chain participants with transparent and fool-proof visibility to data for decision making.
Innovative	Capability to collect and analyze data to support innovative process techniques and arrive at an efficient solution.

6.2. Challenges in Adopting Industry 4.0 Technologies

Although there are extensive academic studies on the implementation of Industry 4.0 technologies in supply chain and logistics management, only very little empirical evidence and real-life use cases exist. Especially, various social, technical, and technological challenges were identified as the key barriers. Through a series of interviews with managers of the Australian retail industry, de Vass et al. [178] have identified investment cost, lack of management support, resistance from employees, and organizations not willing to share business data as some of the key barriers. Through similar interviews with Japanese small- and medium-scale manufacturing industries, Prause [179] has identified that lack of relative advantage, high complexity, lack of compatibility with existing infrastructure, market uncertainty, lack of support from management, lack of details to implementation, and too early to adopt the technologies are seen as the top reasons. Through a similar study in Indian manufacturing supply chains, Raut et al. [33] have identified that lack of management and financial support, lack of required competencies, lack of guidelines, lack of required resources, and challenges in data integration and scalability are identified as the critical barriers. By reviewing 88 papers published between the years 2010 and 2018 Martins et al. [180] have categorized the challenges into technological, socio-cultural, technical, financial, environmental, and legal challenges, as shown in Figure 7.

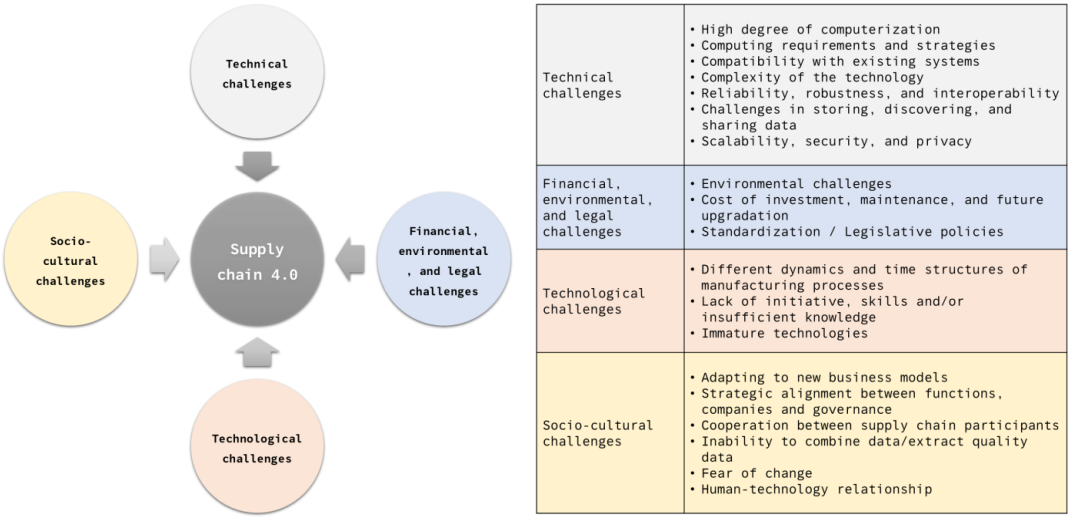

Figure 7. Classification of challenges in implementing supply chain 4.0 [180].

A similar study by Rad et al. [181] reviewing 221 articles published between the years 2005 and 2021 has identified a lack of technological infrastructure, concerns about data privacy and security, lack of expertise, financial challenges, support from management, and restructuring the supply chain and requirement on continuous customization as the major reasons. Similarly, Xin et al. [182] have identified that no management vision and strategy, lack of collaboration and coordination, absence of technological infrastructure, non-availability of required data, and lack of knowledge as the top five challenges. The scarcity of identifying professionals with expertise in Industry 4.0 technologies is another limitation [183]. From such studies conducted across diverse geographical regions and industrial sectors, it can be concluded that although there are numerous challenges in adopting Industry 4.0 technologies, a few common challenges are seen across various literature. Similar is the case in adopting and implementing sustainable practices. Hence, unless all four stakeholders (policy, business, customer, and society) come together and are backed by Industry 4.0 technologies, following sustainability would be practically difficult.

6.3. Future Direction

Due to the unforeseen and unpredictable challenges thrown at the modern-day supply chain, such as the COVID-19 pandemic, the Russia–Ukraine war, natural calamities due to climate change, and challenges in developing and adopting sustainable practices, the businesses must adopt strategies that give them a very high level of resilience so that disruptions can be absorbed, and businesses can quickly bounce back. Currently, although organizations are following various strategies such as globalization and risk management, the few discussed global disruptions clearly show that the supply chain is still vulnerable and not fully immune from failures. Especially the supply and demand shocks faced during the COVID-19 pandemic is a clear proof of the integration of newer and advanced Industry 4.0 technologies into the supply chain [184].

The core theme of Industry 4.0 technologies is to connect the physical and digital realms to capture, share, and analyze data to achieve the highest possible process optimization and improve organizational efficiency. According to a study conducted by Deloitte [185], technologies such as the Internet of Things, Artificial intelligence, Cloud computing, Big Data Analytics, Advanced Robotics, Blockchain, and Additive Manufacturing were identified as the top transformational technologies by business leaders. However, these technologies were not developed to work in isolation but to collaborate with each other. Hence, the amalgamation of all the technologies can only make organizations realize their business goals. For instance, the technology stored and deployed in the cloud and the data collected from various processes through IoT too are stored in the cloud for real-time and easy access to data. Artificial Intelligence and Big data analytics techniques are deployed to study data patterns, obtain insights into the data, and make data-driven business decisions. Without such analytics techniques, the data collected from various sources would remain as a huge pile of data junk that does not serve the purpose. Similarly, automation, robotics, and additive manufacturing improve the versatility and resilience of the supply chain. As the supply chain is the core of any manufacturing organization, effective integration and collaboration across various functions and supply chain participants only can improve its efficiency, and Industry 4.0 technologies are expected to play the role of collaborator.

However, for any organization to adopt new technologies, the one important question that must be answered is, "Can the technologies add value to their supply chain and improve profitability?" The answer is "yes", and the few potential areas where it can add value are summarized below.

- A fully connected supply chain that allows real-time monitoring and improved communication and collaboration between various supply chain participants.
- Improved flexibility and better visibility of data across the supply chain partners, which can increase productivity, manufacturing efficiency, and profitability in addition to the ability to respond quickly to changing demands.

- A highly optimized and automated process that can reduce the time to market and improve an organization's efficiency.
- A very high level of data transparency and visibility empowers supply chain managers to make effective data-driven decisions.
- A highly flexible and agile supply chain that can quickly adapt to fluctuations in demand, enable product personalization and customization, and support rapid product development.
- Enable in-process process monitoring and control that can improve product quality and reduce scrappages, which can make the supply chain sustainable.
- Enhanced customer experience and customer satisfaction.

Despite having numerous advantages, organizations are still skeptical and are in a wait-and-watch mode before adopting these technologies due to a lack of clarity on a few critical topics. Hence, further research directions must be focused on the following:

- As the technologies mature over the years, they can address privacy, security, and cost implications. Hence, industries must openly collaborate with academics to build more successful use cases and address practical problems to exhibit real-life benefits.
- The creation of an industrial and regulatory framework for some of the novel technologies such as blockchain, reduction in implementation and maintenance costs, and easy availability of technical expertise can make the top management rethink their current strategies and embrace the technologies which will mark the beginning of the transformation of the traditional supply chain into supply chain 4.0.
- Developing new business models and strategies with the help of these technologies.
- Developing suitable technology infrastructure for quick implementation and complete digital transformation of legacy manufacturing units.
- In addition, the impacts of these technologies on sector-specific supply chains should be further explored.
- Detailed technical studies on various costs involved, breakeven, advantages, and disadvantages of implementing the technologies must be conducted.
- Apart from cost benefits, the focus of future studies must also be to understand the implications of these technologies on supply chain resilience and sustainability.

Some of the possible strategies to improve supply chain resilience that are discussed in the literature are diversification or multi-sourcing, vertical integration of supply chain, manufacturing decentralization, improving supply chain visibility across entire participants, localizing, leveraging online marketing, sales, and distribution, digitizing supply network, and suitable government policies and framework [184].

6.4. Managerial Implications

The focus of supply chain managers is to build resilience around the entire process, withstand unexpected disruptions, and quickly respond to any changes [186]. Superior supply chain resilience can be achieved only when the coordination, connectivity, and visibility between the supply chain participants improve, which would help them to rapidly adapt to the changes and make quick and data-driven decisions [187]. In this regard, the study shows that Industry 4.0 technologies can provide very high-level data visibility to the entire supply chain participants and improve the collaboration between them. The recent contemporary disruptions have once again proved that current supply chain practices are prone to challenges such as uncertainty, risk, vulnerability, and complexity. Therefore, managers must be aware of the benefits of implementing Industry 4.0 technologies and get themselves exposed to execute their strategies more efficiently by leveraging these technologies. The current study will help the supply chain managers to understand and familiarize themselves with the various important Industry 4.0 technologies, the current state of the art, and the pros and cons of implementing these technologies. In addition, the study emphasizes that management should focus on upskilling and developing the required competencies of the supply chain professionals for any future disruptions and educate them in handling the latest technologies. However, as summarized in the previous

sections, the willingness of organizations to implement these technologies is still low, which results in a lack of sufficient real-life use cases to make an informed decision. Hence, the article would help the supply chain managers and the management to understand the different infrastructures, capital, personnel training, and competencies required before experimenting with these technologies and to cope with future disruptions. As another practical implication, the study also outlines that the technologies can not only increase the competitiveness and operational efficiency of the businesses but can also offset the influence of sudden global small and large-scale disruptions such as the pandemics, wars, and natural calamities.

6.5. Contributions and limitations of the Study

The article introduces and summarizes the trends, current state of research, and gaps in the application of Industry 4.0 technologies on supply chain management. Apart from traditional challenges, the study also focuses on contemporary supply chain challenges. Firstly, the study clearly shows that Industry 4.0 technologies can have a positive impact in overcoming both traditional and contemporary supply chain challenges. Data-driven decision making in demand and supply planning, real-time inventory management, improved transparency and visibility to the entire value chain, and agile supply chain are some of the benefits that the technologies provide. Although it is difficult to predict or completely avoid massive global disruptions such as natural calamities, pandemics, or wars, the study emphasizes that implementing these technologies can make the supply chain resilient and agile. Secondly, apart from achieving cost savings and profitability, they can also help businesses to achieve their sustainability goals. Hence, the study highlights that agility, resilience, and sustainability are the three major benefits of Supply Chain 4.0. In addition, academic and industrial researchers can use the insights provided in the entire Discussion section to frame objectives for their future studies. However, like any other research, this study also has some limitations. Only a few keywords combinations such as supply chain, logistics, inventory, and Industry 4.0 technologies such as Artificial Intelligence, blockchain, Internet of Things, and so on are used to find the relevant articles published in the databases such as Google Scholar, Scopus, and Web of Science in the English language. Therefore, there are chances that some of the literature that is not indexed in such databases and published in other languages might have been missed out. In addition, as the article is written in a descriptive or narrative format, the study does not include all the articles published on the topic. Furthermore, the term "Industry 4.0" is used to refer to several advanced digital, communication, and networking technologies that are believed to revolutionize the way industries currently operate. However, only the top six technologies based on the authors' perceptions, such as Artificial Intelligence, Internet of Things, Big Data Analytics, Blockchain, Automation and Robotics, and Additive Manufacturing, are discussed. In addition, only a brief overview of these technologies was discussed by an objective grouping of a few selective pieces of literature based on their relevance and leaving the in-depth analysis to the readers.

7. Conclusions

In the last few decades, the supply chain has seen numerous challenges, which also resulted in the incorporation of many novel technologies and strategies which completely transformed the function. Even successful supply chain strategies such as sourcing and shifting the manufacturing base to a low-cost country, minimal inventory management, and just-in-time production have failed during extraordinary events such as the pandemic, war, and natural calamities. However, implementation of advanced Industry 4.0 technologies such as Artificial Intelligence, Internet of Things (IoT), Big data and analytics, blockchain, automation and robotics, and additive manufacturing provides the opportunity for industries to achieve the highest level of operational efficiency, agility, innovation, and customer service, which transforms it into a digital supply chain. In simple words, by automating every process, placing sensors in every asset, and creating a closed network, the technologies

collaborate to achieve the highest possible performance. The vertical and horizontal integration of these technologies into the product life cycle can bring a transformation across the supply chain network. The study shows that although it is difficult to predict or detect the level of disruptions during any global event, it is possible to be prepared and build a resilient supply chain. The focus of digitizing the supply chain is to provide advanced forecasting techniques, granular data access to customer preferences, predictive analysis in upstream and downstream activities, reduced lead time, real-time production with high flexibility to adapt to changing customer behavior, flexible logistics and delivery processes, real-time and end-to-end transparency, and visibility to the entire supplier network, a high level of automation throughout the supply chain to improve quality and process efficiency, and data-driven decision-making possibilities at every stage. The study shows that Industry 4.0 technologies can give agility, transparency, and resilience to the supply chain, which would make it customer-centric, demand-driven, and automated. In addition, the review shows that although the benefits of implementing Industry 4.0 technologies into supply chains are well recognized, the application, related research, and real-life use cases are still scarce, but it is clear that businesses that fail to embrace the technologies would eventually cease to exist. If the pandemic has exposed bottlenecks in our supply chain practices, integrating advanced Industry 4.0 technologies is the solution. Therefore, the question that organizations face is not "if" to adopt the technologies" but "when".

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