
LITERATURE REVIEW

This chapter presents a literature review to uncover the background and gain baseline knowledge about the use cases and adoption of I4.0 technologies in global supply chains. This also performs a comprehensive analysis of research questions and gaps.

2.1 Supply Chain and I4.0

When compared to other business functions, the supply chain involves the most complicated processes, including the challenge of coordinating with numerous suppliers for raw materials and partially finished goods as well as the challenge of delivering next-stage finished goods to customers, all in the right quantities on schedule and accordance with production processes (Sert et al., 2020). Because of the importance of minimizing expenses and carbon footprint while maximizing satisfied customers, these coordination processes are extremely difficult to manage. To address this complexity and balance between profit and sustainability researchers and practitioners have analyzed the supply chain network. For instance, to determine the optimal location for facilities such as distribution centers or warehouses while focusing on carbon footprint and optimal routes, strategic location and routing concepts are used (Fathi et al., 2021). The demand patterns, cost of transportation, and the requirement of service levels are analyzed to strategically reduce the distances and lead times (Chae & Olson, 2022; Sert et al., 2020). Furthermore, to determine the inventory levels reorder points and replenishment procedures are investigated (Saif-Eddine et al., 2019). In addition, to create efficient processes production quantities, resource allocation, and operation sequencing are determined (de Sousa Jabbour et al., 2019). The goal is to reduce total expenses, increase service levels, or balance trade-offs between various performance criteria (Daskin & Tucker, 2018; Egri et al., 2023). furthermore, multi-objective optimization is used to find the optimal trade-off solutions that optimize many objectives at the same time while taking into account their interdependencies (Hasani et al., 2021; Zhao et al., 2024). To identify the optimal solutions based on the provided objectives and restrictions, each problem type necessitates particular mathematical models, algorithms, and approaches. Resilience and sustainability are critical for supply networks; however, while there has been substantial research on sustainability and resilience separately

in the literature, empirical evidence shows that the two concepts are interconnected (Fahimnia et al., 2019).

The previous contribution and research gaps of the key literature are presented in Table 1.

Table 1: Literature Review

Authors	Aim	Methodology	Results	Research Gaps
Bag et al., 2018	To identify the I4.0 adoption enablers of SC sustainability.	Systematic literature review	13 enablers are identified and the study shows that limited studies in the area and social aspect of sustainability are ignored in many studies.	Literature review-based study and does not provide ranking or adoption priority.
Luthra & Mangla, 2018	To identify challenges to I4.0 adoption for SC sustainability.	Analytical Hierarchy Process and Explanatory Factor Analysis	Organizational challenges, Technological challenges, and Strategic challenges are identified as major issues.	Focused on the Indian context does not represent a global perspective.
Liu & De Giovanni, 2019	To investigate the relationship between supplier and green process innovation investment based on I4.0 technologies.	Mathematical modeling	The use of I4.0 can enhance the economic and environmental aspects of sustainability.	A limited number of stakeholders are considered in the model.
Manavalan & Jayakrishna, 2019	To investigate the Internet of Things (IoT) to attain sustainability in	Systematic literature review	Shows the role of IoT in various aspects of SC including technology and	Literature review-based study and does not provide

	the supply chain.		sustainable development.	practical findings.
Min, 2019	To discuss the ways to enhance supply chain resilience using BCT	Literature review-based study	Features like Efficient transactions, asset tracking, etc can improve resilience.	Theory-based study
S. Kamble et al., 2019	To develop a blockchain adoption model for supply chains	Survey and structural equation modeling	Technology adoption model for blockchain	Based on certain assumptions
Fosso Wamba, 2019	Analysis of continuance intention in blockchain-enabled supply chain	expectation-confirmation model (ECM)	Application of extended version of ECM	The study considered only stakeholder trust
Mastos et al., 2020	To analyze I4.0 and SC sustainability through IoT-enabled scrap metal management solution.	IoT-enabled Case Study.	Shows the deployment of I4.0 in the scrap metal industry and its impact on SC sustainability	Does not consider the whole supply chain and case-specific study.
Lohmer et al., 2020	Analyze the influence of BCT on supply chain resilience.	An agent-based simulation study	Smart contracts and collaborations with time-efficient processes can improve the resilience of a supply chain.	Theory-based study
Fosso Wamba et al., 2020	blockchain's effects on supply chain efficiency	The survey-based technology adoption model	Performance can be improved with blockchain technology	More variables can be included

Esmaeilian et al., 2020	To analyze blockchain technology and I4.0 for supply chain sustainability.	Systematic literature review	Shows how blockchain and IoT can enhance the visibility and traceability of SC and thus sustainability.	Literature review-based study and does not provide practical findings.
Chalmeta & Santos-deLeón, 2020	To analyze sustainable SC concerning Big data and I4.0.	Systematic literature review	Identified six research categories for future research	Literature review-based study and does not provide practical findings.
Mastos et al., 2021	To analyze I4.0 solutions for circular SC management.	I4.0 enabled Case Study	Shows how traceability, visibility, and automation can optimize the circular economy model.	The study is specific to a particular geographic location.
Birkel & Müller, 2021	To analyze the potential of I4.0 in SC sustainability.	Systematic literature review	Shows the interrelation between I4.0 and the triple bottom line of sustainability.	Literature review-based study and does not provide practical findings.
Naseem & Yang, 2021	To explore the potential of I4.0 in SC sustainability.	Systematic literature review	A framework is developed to explain the effects of I4.0	Literature review-based study
Bayramova et al., 2021	To identify the impact of blockchain solutions on supply chain resilience	Literature review	Blockchain technology has a positive impact	Theory-based study
Khan et al., 2021	To investigate the effects of blockchain on sustainable	Partial least squares structural equation	Blockchain technology along with green information systems has a	The impact of individual behavioral barriers needs to be investigated

	supply chain practices	modeling (PLS-SEM)	positive influence on sustainable practices	
Irannezhad et al., 2021	Readiness assessment of blockchain technology implementation	The fuzzy best-worst method	readiness assessment and management approach for blockchain implementation is presented	The proposed study depends on the expert's knowledge
S. S. Kamble et al., 2021	Investigation of the relationship between BCT and sustainable supply chain performance.	Survey-based statistical analysis	Discovering that the performance of the sustainable supply chain is positively impacted by blockchain technology.	Based on specific sectors can be more generalized.
Liu et al., 2021	To study the role of blockchain implementation challenges in supply chain sustainability	The Bayesian best-worst method	interconnection of barriers and the priority of each element is given	Results are not experimentally tested
Agi & Jha, 2022	To develop a framework for blockchain adoption in the supply chain	Diffusion of Innovation (DOI) theory and DEMATEL	The relative advantage of the technology and the external pressure are the most prominent enablers.	Respondents are from a specific region.
Yousefi & Mohamadpour Tosarkani, 2022	Investigation of performance improvement, because of blockchain implementation.	The fuzzy data envelopment analysis model	The performance of the mineral supply chain may be significantly impacted by blockchain technology.	Specific industry-based study

Strandhagen et al., 2022	To analyze shipbuilding SC and I4.0 enabled SC sustainability challenges.	I4.0 enabled Case Study	Provided a set of nine digital solutions to enhance the SC	The study is specific to a particular SC.
Zhou et al., 2022	To improve the reliability of the information disclosure in SC using blockchain technology	Mathematical modeling	Identified that blockchain technology adoption enhances the reliability and performance of SC.	A deterministic model does not consider uncertainty.
Pandey et al., 2023	To analyze the impact of I4.0 and blockchain on SC resilience and sustainability.	Grey DEMATEL	Internal integration and data management are some of the critical success factors.	A qualitative study based on the opinion of experts.
Wang et al., 2023	To improve the reliability of SC with disruption risk.	Mathematical modeling	The role of subsidies in preventing frequent disruptions and enhancing reliability is explored.	The study considers only subsidy policy to enhance the reliability of SC.
Hashim et al., 2023	To achieve the reliability of SC through risk mitigation.	Multi-criteria decision-making approach	Postponement in SC is highlighted as a crucial risk.	A qualitative study based on the opinion of experts.
Kucukkoc et al. (2024)	A batch scheduling problem	Differential evolution and genetic algorithm approach	Found that the algorithms performed well with the complexity of batch scheduling problems.	Tested for limited data

Komkowski et al., 2024	Explored the integration of I4.0 into lean practices and discussed the dynamic capabilities offered by it	Multi-criteria decision-making approach	Discussed the key aspects of integration of I4.0 into lean practices	A qualitative study based on the opinion of experts.
Oliveira et al., 2025	The impact of the technology environment on supply chain strategy and operational performance	Exploratory Study	Discussed the key aspects of the impact of the technology environment	A qualitative study based on the opinion of experts.
Krishnan et al., 2025	Industry 4.0-driven business model innovation for supply chain sustainability	Exploratory Study	Discussed business model innovation for supply chain sustainability	A qualitative study based on the opinion of experts.
Govardhan et al., 2025	Significance of Industry 4.0 in Achieving Sustainable Performance Across Supply Chains	Multi-criteria decision-making approach	Identified the key factors	A qualitative study based on the opinion of experts.
Chouhan et al., 2025	Resilience enhancers and barriers analysis for Industry 4.0	Multi-criteria decision-making approach	Identified key barriers	A qualitative study based on the opinion of experts.

2.2 Supply Chain Resilience and Sustainability (SCRS)

Resilience refers to the capacity for resistance and recovery from unanticipated disturbances making a supply chain act in a way that is both resourceful and prompt, bringing things back to normal, or better (Bayramova et al., 2021). On the other hand, sustainability refers to a system's capacity to satisfy present needs without endangering the ability of future generations to do the same. Sustainability entails the long-term, equitable maintenance of ecological, social,

and economic processes (Ivanov, 2018). The relation between resilience and sustainability is that resilience is a necessary condition for sustainability. A system that is not resilient cannot be sustainable, as it will not be able to withstand the various shocks and stressors that it will face over time. In contrast, a resilient system is more likely to be sustainable, as it can adapt to changing conditions and maintain its essential functions and structures (Azmi et al., 2022). Moreover, sustainability can enhance resilience by promoting the development of more robust and diversified systems that are better able to cope with uncertainties and disruptions.

Supply chain disruptions can result from a variety of factors, including internal problems and external ones, affecting the SCRS. Internal problems may include machine failure due to improper inspection and maintenance, improper or inadequate integration between various departments, etc., whereas external problems may arise due to situations like natural disasters or accidents. These incidents typically happen quickly and without warning. In many supply chains, external supplier operations result in logistical activities like the provision of raw materials, component assembly, production, and product flaws. A corporation must build the logistics, procedures, and capabilities that enable quick and effective reactions as supply chain disruptions occur. This also boosts the organization's ability to carry out routine commercial operations (Kaviani et al., 2020). The research shows that collaboration with partners in the supply chain is essential during disruptions because it promotes visibility, awareness, and decision-making in the face of challenges. It is possible to conclude that supply chains can benefit from resilience and sustainable practices.

2.3 Impact of I4.0 on SC sustainability and reliability

Numerous industries have had to reevaluate their current organizational structures as a result of shifting market demands, erratic consumer expectations, sustainability concerns, reliability issues, and constrained economic rewards (Schwab et al., 2019). Economic, environmental, and social factors must be considered in the production process due to Government regulations and consumer demands (Malek & Desai, 2019). The misinformation carried out in the SC creates various challenges and also negatively impacts the reliability throughout the SC (Akhtar et al., 2023). In addition, production systems need to be upgraded as they consume a significant amount of energy and contribute to GHG emissions. Therefore, it is essential to enhance the energy efficiency performance of these systems to achieve sustainability (Kluczek, 2019). To address these issues SCs are integrating popular solutions like blockchain technology, cloud computing, big data analytics, and IoT to meet sustainability norms (Zhou et al., 2022;

Machado et al., 2020). All these recent developments are considered essential elements of I4.0 (Leng et al., 2020). These technologies have appeared to assist sustainability and reliability in various SCs such as healthcare and manufacturing (Manavalan & Jayakrishna, 2019; Sriyanto et al., 2021). The manufacturing industry contributes significantly to the economic growth of developing nations, but it has a long way to go before its production practices are sustainable and reliable (Kamble et al., 2018). Infrastructure accessibility is one of the major determinants of the uptake of new technology in industrialized nations. The United States, Germany, and the United Kingdom have adopted new technology and attained sustainability (De Sousa, 2018). However, it is still considered a barrier in developing nations (Galati & Bigliardi, 2019).

2.4 Flexibility in the supply chain

The landscape of supply chain flexibility literature has undergone a transformative evolution, shifting its gaze from a singular emphasis on manufacturer flexibility to a broader perspective encompassing combined and cross-organizational flexibility (Huo et al., 2018; Siagian et al., 2021). Recent research endeavors have delved into diverse dimensions of flexibility, including supplier flexibility, manufacturer flexibility, logistics flexibility, and flexibility in decision-making, providing a comprehensive understanding of supply networks (Kamalahmadi et al., 2022). This multifaceted approach not only captures the intricacies of inter-organizational dynamics but also recognizes flexibility as a customer-centric capability. Authors have proffered varying definitions, converging on the concept of dimensional flexibility, which encapsulates the manifold facets of adaptability within a supply chain (Contador et al., 2020; Fayezi et al., 2017). Notably, some studies have ventured beyond, examining the ripple effects of flexibility on other pivotal factors like resilience and sustainability (Siagian et al., 2021). This holistic viewpoint acknowledges the intrinsic interconnectedness of supply chain elements, shedding light on the symbiotic relationship between flexibility and the capacity to withstand disruptions and promote enduring ecological, and social well-being with a better economy (Agrawal, 2020). In essence, the contemporary discourse on supply chain flexibility traverses a trajectory from isolated manufacturer-centric agility to comprehensive ecosystem-wide adaptability, underscoring its pivotal role in fortifying supply chains against uncertainties while fostering sustainable practices for the future (Kazancoglu et al., 2022; Mangla et al., 2014).

Considering the incorporation of social and environmental factors into decision-making throughout the supply chain is a step toward sustainability and resilience. Flexibility is a trait that should be given priority for both kinds of growth to support a closer connection between sustainability-related problems and strategic business objectives. This can result in many benefits in addition to cost savings and improvements in areas like competitiveness, profitability, quality, emission, etc., (Marchi & Zanoni, 2017; Prabhu et al., 2015; Y. Zhou et al., 2021). Existing literature has extensively examined the complex interrelationship among flexibility, resilience, and sustainability within supply chains (Fayezi et al., 2017). This dynamic interplay generates a synergistic effect that amplifies the influences contributing to both resilience and sustainability (Kazancoglu et al., 2022). The capacity to rapidly address unforeseen disruptions and challenges significantly heightens supply chain resilience. Moreover, the adoption of flexible strategies encompassing diversified sourcing, adaptable manufacturing, agile logistics rerouting, and informed decision-making not only bolsters resilience but also augments sustainability efforts. The incorporation of I4.0 technologies further magnifies these impacts, leading to more pronounced enhancements across these dimensions (Pandey et al., 2023; Polas & Raju, 2021).

2.5 Benefits of I4.0 for flexibility and its impact on resilience & sustainability

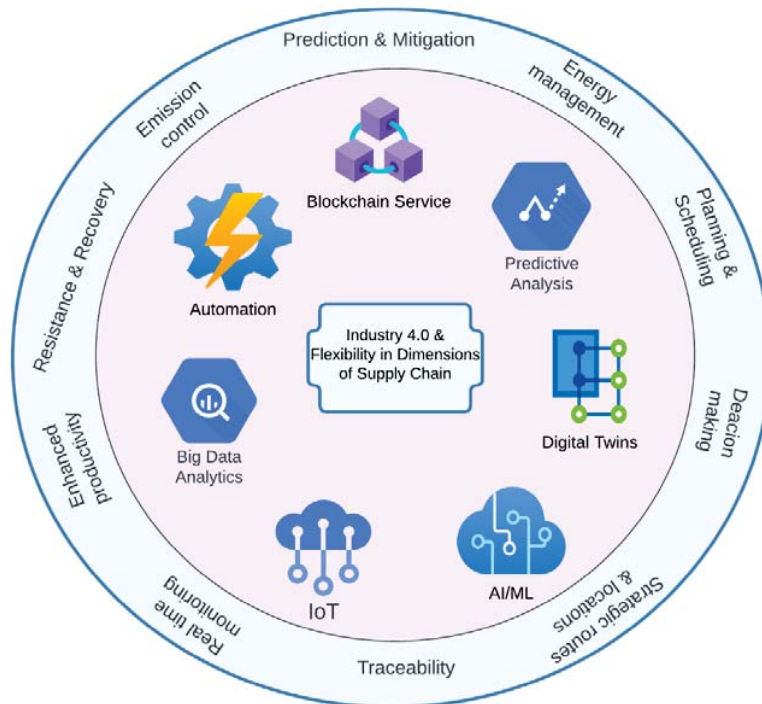


Figure 2: I4.0 to enhance the flexibility of supply chain dimensions

Figure 2 shows a comprehensive overview of the effects of I4.0 adoption on flexibility, resilience, and sustainability as explored in scholarly works. The diagram showcases the various attributes within the realm of I4.0 that contribute to the augmentation of flexibility, resilience, and sustainability, underscoring their interconnectedness and interdependence. Over the past few years, this technological development has merged several industries, including suppliers, manufacturers, and logistic companies, onto a single platform. I4.0 also enables efficient processes and smart contracts to handle uncertain scenarios efficiently and through transparency and traceability identify the issues before they become serious (Pandey et al., 2023).

Achieving sustainability in the supply chain relies on the active engagement of all stakeholders. Recognizing and addressing scope 2 and scope 3 emissions is essential for meeting net-zero emission targets. I4.0 plays a crucial role by integrating all supply chain participants onto a unified platform, fostering well-informed decision-making. This integration allows for the simultaneous analysis of various scenarios, enabling the selection of optimal courses of action during disruptions through predictive capabilities. Consequently, this not only reduces costs but also enhances the economic and social sustainability of the supply chain. Through the effective utilization of resources facilitated by Industry 4.0 technologies, the carbon footprint of the entire supply chain network can be significantly diminished. Consequently, Industry 4.0 not only improves the resilience and flexibility of the supply chain but also contributes significantly to its sustainability.

2.6 Integration of Blockchain Technology (BT)

According to the research that has been done so far, the implementation of BT may be one of the most important factors in the achievement of resilience and sustainability goals. Researchers conducted a bibliometric analysis, a systematic literature review, and a text mining approach, focusing mostly on publications over the last 20 years, to investigate the possible impact that BT could have on the performance of supply chains. They made the point that BT has the potential to play an important part in ensuring the reliability of supply chains, fostering trust, and safeguarding intellectual property (Fosso Wamba et al., 2020; Ghadge et al., 2020; Rejeb et al., 2021; Xu et al., 2020). Implementation of BT-enabled technologies in supply chains is also broadly discussed by researchers and traceability, transparency, stakeholder involvement, and collaboration along with supply chain integration and digitalization termed

as the major factors (Bär et al., 2018; Chang & Chen, 2020; Sobb et al., 2020). Researchers have also explored the different attributes and adoption factors of BT-enabled technology such as transparency, information immutability, smart contracts, technology readiness, traceability, flexibility, real-time information sharing, and security of the data capabilities. They have pointed out that BT-enabled technologies are emerging as important game changers for SCRS (Callinan, 2022; Kamble et al., 2019; Kim & Shin, 2019; Meidute-Kavaliauskiene et al., 2021).

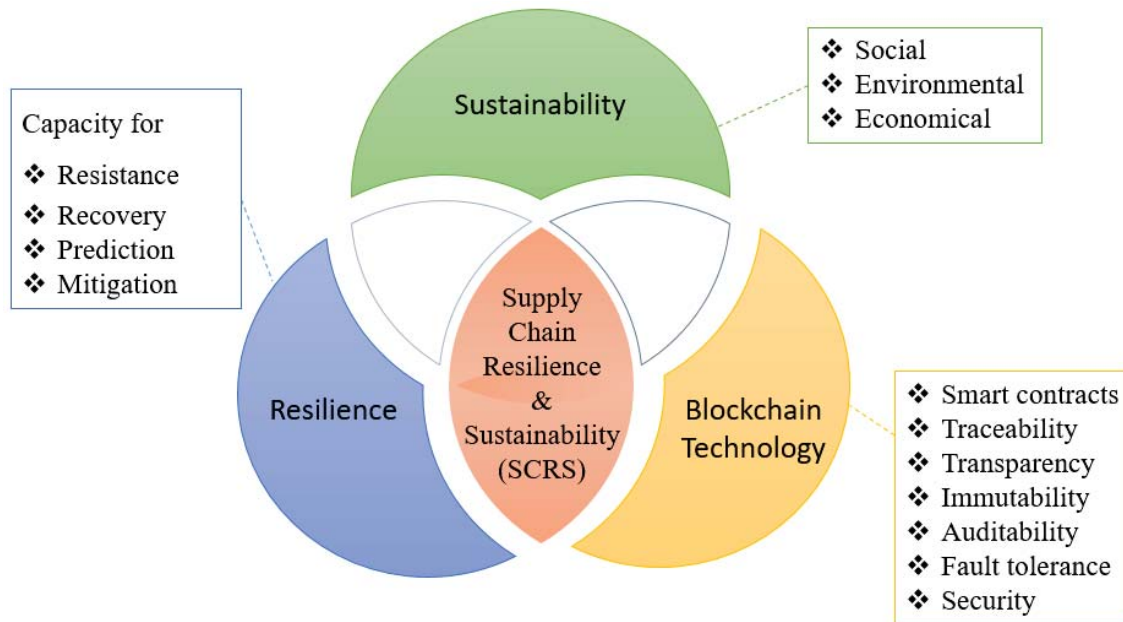


Figure 3: Resilience, sustainability, and blockchain technology

The integration of BT is increasing to support the resilience and sustainability characteristics in the supply chain, according to several surveys on BT adoption; more than 60% of businesses have already deployed or are in the process of implementing blockchain technology (Min, 2019). Researchers have analyzed the effect of BT on SCRS considering different aspects and methodology. For instance, the effect of BT on supply chain resilience is analyzed by Lohmer et al. (2020), through a simulation-based study, and the importance of smart contracts to improve resilience and sustainability is explained by Yousefi & Mohamadpour Tosarkani (2022). The importance of transparency and disintermediation properties of BT and its strong effect on supply chain performance is discussed by Li et al. (2021). The use case of BT for healthcare, food, and logistics in the supply chain is discussed by Kouhizadeh et al. (2021), and he suggested that transparency, traceability, and improved efficiency can help organizations increase their profits significantly. Figure 3 shows the relationship between supply chain resilience, sustainability, and BT.

2.7 Integration of Digital Twins (DT)

There has been ongoing research into the creation of a pathway to implement DTs. The literature on SC DTs is still in its infancy stage, additional research is required before they can be used. The research in DT currently is mostly focused on modeling methods and prototype frameworks depending on the usage scenario (You et al., 2022). Previous research has demonstrated that the utilization of SC DTs offers many benefits; however, the road to adoption is full of roadblocks. Burgos & Ivanov, 2021, performed a DT-based impact analysis on the food retail supply chain. The author devised a discrete-event simulation model with the assistance of a digital SC twin to investigate the workings of the SC and the dynamics of its performance. Liu et al. (2021) conducted a review of the DT with regard to the concepts, technology, and industrial applications that are related to it. Lee & Lee (2021) constructed a DT architecture for use in the modeling of real-time logistics simulation. This system can accurately estimate the arrival time of modules as well as potential dangers related to logistics. They also demonstrated that DT can be used to detect accurate module arrival times as well as logistics risks. Park et al. (2020) proposed a structural framework for the control of a cyber-physical logistics network based on DTs and suggested production plans based on DT simulation results. Wang et al. (2020) developed a DT simulation along with blockchain technology to manage industrial hemp supply chain risks. Kapustina et al. (2020) discussed the application of DT in logistics because of non-destructive quality control methods. Badakhshan & Ball (2022) introduced DT to the supply chain in order to control inventory and cash flow. In addition to DT, the author made use of machine learning (ML) and simulation in order to determine which policies regarding inventory and cash replenishment have the potential to minimize the negative effects of disruptions on SC performance. Marmolejo-Saucedo (2020) proposed the design and development of a DT based on simulators, data analytics, and a solver for a pharmaceutical company.

The researchers have contributed their capabilities to the field and developed an industry-specific conceptual framework. However, very little research is available discussing the roadblocks or barriers to the successful implementation of the technology from a global and general perspective. Perno et al. (2022) categorized the DT literature and suggested conceptual models that describe the facilitators and challenges to DT adoption. As well as their interrelationships, the study adds to the body of information already available on DTs. Neto et al. (2020) sought to go beyond the theoretical construction of DTs in manufacturing to see how the concept relates to the real industrial landscape. This link was validated by understanding what factors are driving companies toward technology today. What factors enable a successful

implementation of DTs, and what factors are causing friction and slowing implementation efforts? The authors have explored the difficulties of implementing a DT for cyber-security studies. Gunes et al. (2014) touched on the importance of the epic challenges of cyber-physical systems in various application domains. Their discussion included interoperability, security, reliability, sustainability, and predictability. Yevgenievich Barykin (2021) discussed the content of DT principles and the formation of a comprehensive management approach to their practical implementation in industrial supply chains. This took place with the harmonious participation of diverse specialists relevant to the issues of modern production. Ivanov & Dolgui (2019) analyzed the supply chain based on ripple effect and resilience and presented a supply chain DT framework. Bhandal et al. (2022) performed a bibliometric review of the applications of DT technology in operation and supply chain management. The authors identified four value clusters, such as research that explains how the implementation of a DT can improve supply chain operations at the level of business processes.

How DT integration is possible also depends on the accessibility of the implementation. If the application is only available as a black box, then at least a defined interface should be available for integration. However, aspects such as required visualization and rights management should be implemented in the merge implementation (Michael et al., 2022; Liu et al., 2023). Wärmefjord et al., 2020, intended to identify the problems, primarily in terms of processes and data flows, that must be in place to fully take advantage of the opportunities afforded by DTs for zero-defect manufacturing from the perspective of the present and future study areas and industrial needs. In light of the difficulties CM faces and the numerous opportunities presented by DT, H. Liu et al. (2022) examine the best approaches to combining CM and DT while weighing the pros and downsides of various combinations. The overall goal of this study is to investigate the reasons, benefits, and changes that condition monitoring is undergoing as a result of DT technology. Kasper et al. (2022) intend to close the gap between current computer science studies on DTs and their practical application in the energy industry. The suggested DT platform ought to open the door to standardized DT adoptions along with service isolation and, consequently, effective DT services. By doing so, DTs will be simple to implement in a variety of energy system-related applications and be able to host a variety of complicated models and services for a variety of industrial applications.

2.8 Integration of Big data and machine learning

Big data refers to extensive and complex datasets that can reach sizes measured in terabytes or even petabytes. The process of analyzing such large-scale, diverse digital data is known as big data analytics. Big data is often defined by five key characteristics, commonly called the 5Vs: volume, velocity, variety, veracity, and value. However, managing and working with big data pose several challenges, including data capture, analysis, storage, searching, sharing, visualization, transfer, and addressing privacy concerns. Traditional SQL queries and relational database management systems struggle to handle these massive datasets effectively. As a result, various scalable tools and technologies have emerged to address these limitations. Among them, Hadoop is a leading open-source distributed data processing platform, while NoSQL databases offer non-relational solutions for data storage needs. The extant literature primarily focuses on various aspects of flexibility and cross-organizational flexibility (Contador et al., 2020; Huo et al., 2018; Siagian et al., 2021). The existing body of research on the intricate interplay between flexibility, resilience, and sustainability within supply chains is currently constrained in scope. Limited research has explored the broader implications of flexibility, specifically its impact on important factors such as resilience and sustainability (Marchi & Zanoni, 2017; Siagian et al., 2021; Y. Zhou et al., 2021). In addition, there is a limited body of research on the integration of I4.0 technologies to enhance the aforementioned effects (Polas & Raju, 2021). Thus, the novelty of this study lies in examining the I4.0 adoption enablers concerning supply chain flexibility, resilience, and sustainability.

2.9 Industry 4.0 adoption enablers in global supply chains

The top management commitment has a significant positive effect on both I4.0 integration and purchasing strategy. Furthermore, I4.0 can enhance SC finance by integrating the platforms among various stakeholders and purchasing strategies. It can create a significant positive effect on competitive advantage (Tarigan et al., 2020). The business-centric use of the SC finance information system enables businesses to effectively partner across the supply chain and improve cash flow to maintain the system's transparency thus improving the reliability among stakeholders. This system can utilize a blockchain-based SC finance platform, IoT devices for data collection, and smart contracts for automating processes. The platform enables secure and transparent sharing of data among all parties involved in the SC finance process, including suppliers, buyers, financiers, and regulators. The IoT devices collect data on SC activities such

as product quality, shipping, and delivery times, which are later stored on the blockchain for easy access and verification (Guo et al., 2022). However, the adoption of I4.0 technologies has many roadblocks. The challenges that organizations and managers face in implementing I4.0 require a comprehensive understanding of the organizational and managerial factors that affect the adoption and implementation to attain competitive advantage (Agostini & Filippini, 2019).

Considering the limitations of the existing literature, it is necessary to pinpoint the major factors that influence the I4.0 adoption in SCs in terms of the social, economic, and environmental facets of sustainability. Government policies and collaboration among SC stakeholders are some key potential drivers of I4.0 adoption in SC (Luthra et al., 2020; Connor, 2020). In addition, the potential for corporate social responsibility and human resource management can promote sustainable practices and improve the well-being of workers and the environment by adopting I4.0. The policymakers and stakeholders should support the development of sharing economy initiatives that prioritize community participation, environmental sustainability, and social responsibility.

2.10 Industry 4.0 adoption barriers in global supply chains

To promote I4.0 adoption for global supply chain networks, it is crucial to create cost-effective, modular, and adaptable solutions. This will reduce the technical complexity inherited in I4.0 technologies and facilitate seamless integration in organizations of varying sizes. Previous scholarly investigations have shed light on significant barriers, encompassing technological, organizational, behavioral, and economic complexities. The existing body of literature suggests that addressing these obstacles can be achieved by fostering collaboration among participants in the supply chain, conducting continuous research and development to improve technology, and strengthening the technical skills of individuals engaged in the supply chain (Singh et al., 2023). The study by Mathivathanan et al. (2021) to identify and classify the barriers shows that the lack of business awareness and familiarity with I4.0 are the most influential barriers to adoption, while other barriers act as secondary and linked variables. The model developed by Alazab et al. (2021) suggests that facilitating conditions, trust, social influence, and effort expectancy are critical barriers that directly affect I4.0 adoption. By considering these barriers, organizations can determine whether and how to integrate I4.0 technology into their sustainable supply chain strategy. The cost of implementing I4.0 can be a significant barrier for some organizations (Agi and Jha, 2022).

To identify barriers to I4.0 in the supply chain researchers have used several approaches such as surveys, a combination of multi-criteria decision-making models, and a technology acceptance model (Zkik et al., 2022). Kouhizadeh et al. (2021) investigated the I4.0 adoption barriers using the DEMATEL approach and identified a lack of support and commitment from the management side as the main barrier. The model fails to include uncertainty in the decision-making. Queiroz and Fosso Wamba (2019) studied the I4.0 adoption behavior in a supply chain using partial least squares structural equation modeling however used a limited number of constructs. Saberi et al. (2019) used a survey method to identify barriers to I4.0 in the supply chain however, relationships among barriers are not explored.

Despite the potential benefits of I4.0 in sustaining connectivity and reliability among supply chain partners, the research is limited on the topic. Most of the research in this field provides a general outline of the barriers and is not categorized into groups for better understanding. To analyze and understand the barriers critical to the adoption of blockchain technology into the supply chain it is necessary to explore these barriers in the context of various groups and consider the vagueness of the decision making along with the correlation power of one barrier over another.

2.11 Optimization approaches using I4.0

The optimization approaches for supply chain networks are supported by mathematical models. However, to represent the complexities of real-world scenarios nonlinear terms are included which cause several challenges (Zahiri et al., 2017). For instance, the nonlinear models may exhibit multiple local optima requiring careful consideration of the solution algorithm as it may affect the convergence behavior. The computational complexity and nonconvexity also make it difficult to solve within reasonable time frame. Spiegler et al. (2016) suggested simplification methods to reduce the complexity of nonlinear models. The authors concluded that these linearized and simplified models improve comprehension of the system's dynamics and transient responses, particularly with regard to inventory and shipping. These simplified models sometimes lack the zest of real-world scenarios thus, specialized optimization techniques such as metaheuristics are preferred. Various metaheuristics are used to explore the optimal solution for complex supply chain networks. Sahebjamnia et al. (2018) proposed a hybrid algorithm to address complex networks. Such as a hybrid of simulated annealing and genetic algorithm or tabu search metaheuristic algorithms. As per the findings, the hybrid algorithms have turned out to be more successful in complex networks. Fathollahi-

Fard et al. (2021) proposed two hybrid meta-heuristic algorithms to solve a complex tire waste model for developing countries. The author combined a genetic algorithm a whale optimization method, a red deer algorithm, and simulated annealing to propose a solution approach. Mlekusch and Hartl (2024) also used a hybrid genetic algorithm to address the scheduling problem and showed that the algorithm delivered high-quality solutions, especially for large instances. Kucukkoc et al. (2024) used differential evolution and genetic algorithm approach for a batch scheduling problem and found that the algorithms performed well with the complexity of batch scheduling problems. To explore the demand, supply capacity, and main cost characteristics including transportation and shortfall costs, Zokaee et al. (2017) used a reliable optimization model. The aim of the developed model is to determine the strategic location for a four-tier supply chain.

Few available research has explored the logistics cost optimization in relation to the role of digital technologies of I4.0 which reduces cost by maintaining the coordination among supply chain stakeholders in an efficient manner (Ghobakhloo & Fathi, 2021). Efthymiou & Ponis (2021) performed a systematic literature review on the impact of I4.0 technologies on traditional logistics networks and identified three major challenges related to the training and development of the workforce, development of necessary infrastructure, and slow growth to adapt I 4.0 technologies. The successful implementation of I4.0 technologies necessitates that employee have the knowledge and skills necessary to operate and leverage them in their work. Systematic training and development of the workforce is required to attain this objective. Efforts should also be concentrated on developing digital literacy, data analysis skills, problem-solving abilities, and adaptability in order to utilize technological advancements effectively. Integration of I4.0 technologies into logistics networks demands physical (such as hardware, software, and connectivity) and organizational infrastructure (such as data management systems and cybersecurity measures) (Gebhardt et al., 2022; Mohajeri et al., 2022). Perotti et al. (2024) reviewed and conceptualized the role of I4.0 technologies for sustainable warehousing. The author discussed how I4.0 technologies can enhance warehouse processes from receiving the product to shipping and cross-docking. Bányai et al. (2019) used I4.0 technologies in the waste collection process and optimized the mathematical model related to waste assignment, scheduling, and routing. The existing research highlights the integration of I4.0 technologies within supply chains. Even so, there is a need to explore the impact of digital technologies on business models, processes, and working conditions within supply chain

networks, particularly in relation to carbon footprint tracking and reduction. (Chae & Olson, 2022).

The potential of I4.0 in the manufacturing industry has also been explored by researchers. Komkowski et al. (2024) explored the integration of I4.0 into lean practices and discussed the dynamic capabilities offered by it. Bagalagel & El Maraghy (2020) explored a product mix problem for a manufacturing system equipped with I4.0. The author found that I4.0 has immense potential in tracking, monitoring, and value addition in products. It helps streamline the production process which can be monitored in real-time, enhancing productivity. For example, IoT devices are extremely successful in tracking and monitoring the movement of products and raw materials within the production facility. It provides better visibility and inventory control (Gallego-García et al., 2022). Furthermore, it helps in accurate forecasting by collecting and analyzing the data in real-time (Gebhardt et al., 2022). The collected data can be utilized to identify improvement opportunities along with the process inefficiencies and bottlenecks within manufacturing facilities. I4.0 can also improve the production flows, and resource utilization for manufacturers. It also helps in minimizing wastage and downtime (Bányai et al., 2019; Govindan et al., 2018; Wong et al., 2021). Additionally, I4.0 technologies facilitate more automated and efficient product processing. Utilizing advanced robotics, automation, and AI-powered systems, manufacturers can optimize their operations, reduce costs associated with manual labor, and increase their productivity. I4.0 technologies contribute to the overall cost reduction of the manufacturing process by optimizing the flow of materials, minimizing handling and processing times, and guaranteeing precise quality control (Wankhede & Vinodh, 2021). Overall, the available literature has shown that the integration of I4.0 and sustainable solutions can lead to improved operational efficiency, cost savings, and reduced environmental impacts in the supply chain.

2.12 Research gap summary

The available research on I4.0 adoption in SC discusses the barriers and enablers of adoption. However, the exploration of I4.0 adoption in the context of SC sustainability and building a reliable SC is sparse in the literature. More studies are needed to explore these relations so that a comprehensive adoption framework can be suggested to the SCs. By addressing integration issues, enabling benchmarking in the context of I4.0 adoption can expedite the process of adoption. A systematic approach to identifying and evaluating these enablers can offer a framework for progressive adoption. Comprehending the complex interrelationships among

these enablers can additionally facilitate an efficient adoption voyage. SCs are complex networks with many different stakeholders, and it can be difficult to bring them all together on one platform. It necessitates large infrastructure investments that are compatible, but more crucially, it necessitates the commitment of management to these expenditures. Persuading stakeholders to invest in I4.0 becomes a difficult task if the advantages of its adoption are not well understood. Furthermore, a successful adoption process may encounter challenges due to a lack of familiarity with new practices, which emphasizes the significance of providing customized training at different organizational levels.

For firms, it is critical to realize that these challenges related to end-to-end visibility and communication, if left unresolved would reduce the resilience and sustainability of the supply chain. However, there are several barriers that inhibit the implementation of I4.0 in the supply chain framework. Some of the general challenges that prevent the diffusion of blockchain technology across the supply chain industry can be categorized under economic, legal, behavioral, and technological barriers (Bag et al., 2021; Ul Islam et al., 2022). Most I4.0 applications are conceptual representations with limited empirical evidence for implementation. Furthermore, little research has been done on the challenges of I4.0 adoption considering barriers under the roof of economic, legal, behavioral, and technical for global supply chains. Hence, this research study provides a systematic examination of the integration of I4.0 technology within supply chain networks and explores the potential challenges that may arise during its implementation.

To address this research gap this study aims to explore the following Research Questions (RQs):

RQ 1: What are the enablers and barriers of I4.0 adoption in global supply chains?

RQ 2: What are the interrelations among the enablers and barriers of I4.0 adoption in global supply chains?

RQ 3: What is the adoption priority of enablers of I4.0 adoption in global supply chains?

RQ 4: What is the impact of I4.0 adoption on global supply chain capabilities such as flexibility, reliability, resilience, and sustainability?

RQ 5: What is the impact of I4.0 technologies on supply chain sustainability and cost optimization?

This study makes a significant and novel contribution to the field by addressing a significant research gap in the adoption of I4.0 technologies to track and control emissions across scopes 1, 2, and 3 in supply chain networks. Despite the growing importance of sustainable practices, there has been limited exploration into the integration of I4.0 technologies for emissions tracking and management within supply chains (Hertwich & Wood, 2018; Cañas et al., 2021). In response to this gap, this study pioneers an investigation into the adoption of I4.0 technologies and their dual impact on both cost optimization and emissions reduction. This study goes beyond mere theory, delving into the practical implications of adopting I4.0 technologies within supply chains. This study develops a robust model for supply chain networks by comprehensively assessing the associated costs of technology integration alongside the environmental consequences in terms of carbon emissions. This model enables organizations to effectively track and manage their resource usage, energy consumption, and emissions output in real-time. This study seeks to delve into the impact and strategic adoption of I4.0 for supply chain optimization and the reduction of scope 1, 2, and 3 carbon footprints. In addition, this study investigates the interrelation between emission, I4.0 technologies adoption, and stakeholder capacity to bring new possibilities to the literature to move forward.