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Industry 4.0 and Digital Supply Chains: A Review of Flexibility, Viability, and Antifragility

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Abstract

Global supply chains are quickly exposed to disorders driven by epidemics, geopolitical crises and climate phenomena, which make traditional risk management strategies inadequate. While industries such as IoT, blockchain, Big Data Analytics, Cloud Computing and Digital Supply Chain Twins (DSCTS) provide 4.0 technologies that transform capacity, existing research remains still fragmented. Current studies emphasize either improving operational performance, strengthening flexibility, or conceptual structure for digital twins - but some integrate these approaches. This article undergoes structured literature to consolidate evidence in these domains and identify research gaps. Five important deficiencies showing conclusions: (1) Lack of empirical verification and study across the industry-case studies-; (2) Insufficient attention to organizational and human factors including leadership, skill and cyber security; And (3) weak detection of multi-technology integration and coordination.(4) The lack of quantitative metrics for viability, (5) The behavioral and organizational dimensions of digital supply chain agility not explored. Construction on these insights, the proposed agenda located Industry 4.0 technologies and DSCT as an ambition of dynamic capabilities, not only promotes flexibility and strength, but Also antifragility. The review contributes to an ideological structure, which combines technologies, organizational inability and resolution management strategies, and offers both theoretical progress and practical guidance for designing sustainable supply chains.

Keywords
Industry 4.0, Digital Supply Chain, Resilience, Antifragility, Viability, Dynamic Capabilities

1. Introduction
Due to market instability, globalization, and growing complexity, supply chains are now strategically enabling resilience and competitiveness. The advent of Industry 4.0 (I4.0) has brought about a paradigm shift in the design, management, and operation of supply chains within this dynamic environment. Industry 4.0, regularly known as the "fourth industrial revolution," integrates advanced virtual technology such as the Internet of Things (IoT), Big Data Analytics, Artificial Intelligence (AI), Blockchain, Cloud Computing, and Cyber-Physical Systems to permit clever, related, and data-pushed operations (Kagermann et al. 2013; Frank et al. 2019). These technologies are actually extensively recognized because of the spine of digital supply chains, imparting unprecedented visibility, traceability, and decision-making talents. Supply chains are historically evaluated based on their efficiency, responsiveness, and financial performance, yet recent disruptions consisting of the COVID-19 pandemic, geopolitical conflicts, and climate-related activities have demonstrated that efficiency by itself is insufficient (Ivanov 2020). Organizations now require supply chains that are not simplest bendy and possible, however also able to showing antifragility—the capability to adapt and grow stronger underneath pressure (Ivanov and Dolgui 2020).

Flexibility ensures responsiveness to fluctuations in demand and delivers, viability emphasizes long-term survival and adaptability, at the same time as antifragility movements beyond resilience to highlight put-up-disruption development. The adoption of Industry 4.0 technologies with supply chain control has been identified as a promising path to acquire those abilities (Bag et al. 2021). For example, IoT-enabled transit tracking, Big Data and AI support forecasts in real-time visibility of goods that are in demand for prognosis ensure blockchain confidence, while digital twins simulate the supply chain scenarios to test customized strategies (Tjahjono et al. 2017; Queirroz).

These advances not only improve operational decision making but also allow companies to configure the network dynamically when they occur with disruptions, and strengthen both feasibility and antifragility. Despite the growing literature mass at the intersection of industry 4.0 and supply chains, there are many gaps. First, most studies have focused on the technical aspects of using I4.0 technologies without a comprehensive analysis, how they specifically enable flexibility, viability and antifragility. Secondly, while flexibility is widely discussed, the concept of antifragility in supply chains remains underexplored in literature (Ivanov 2021). Finally, most pre-studies are conceptual or case- based, and lack of systematic reviews that synthesize evidence from several contexts to provide a composite understanding.

Therefore, the purpose of this paper is to undergo a systematic literature of 25 research published between 2015 and 2025, to check how industry 4.0 and digital supply chain novels contribute to flexibility, viability and antifragility. In particular, the paper wants to address the following research questions:

1. How might supply chain integration of Industry 4.0 technologies enhance flexibility, viability, and antifragility?
2. What are the key benefits and challenges of implementing the 4.0-enabled digital supply chains?
3. What research gaps and future directions are revealed from the current knowledge body?

By answering these questions, this review contributes to both theory and behavior. It highlights strategies for using digital technologies to create a robust, adaptive, and antifragile supply chain.

2. Methodology

2.1 Research Design

This study examines how Industry 4.0 technologies can create digital supply chains that are adaptable, sustainable, and antifragile using a systematic literature review (SLR) technique. Because it offers a clear, repeatable, and organized method for locating, assessing, and synthesizing previous research, a systematic review was used (Tranfield et al. 2003). By adhering to clear inclusion and exclusion criteria, the systematic approach reduces bias in contrast to narrative reviews and provides solid findings (Figure 1).

The methodology employs a five-phase approach (summarized in figure 1) that was adapted from PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) :

1. Review planning, including establishing the study topics and scope.
2. Finding pertinent literature (choosing a database and search method).
3. Selection and screening (quality evaluation and inclusion/exclusion criteria).
4. Analysis and synthesis (thematic synthesis, classification, and coding).
5. Reporting and integration (outline findings, points to holes and discusses the effect).

Recent systematic reviews in supply chain and industry 4.0 are in accordance with this strategy (Fatorachian and Kazemi 2021; Ismail et al. 2025).

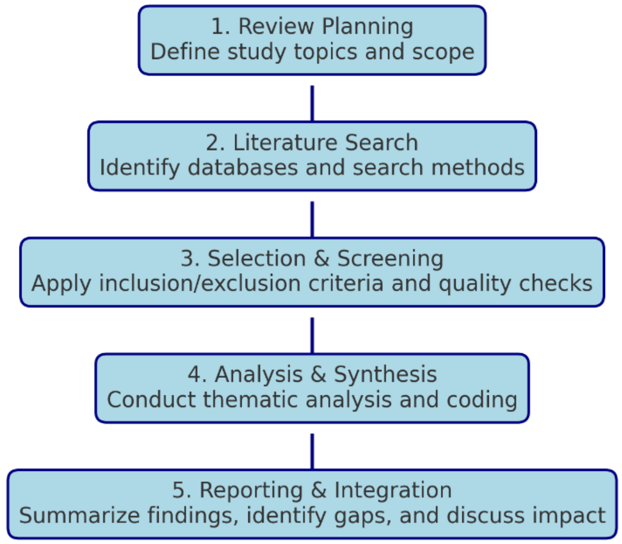

Figure 1. The five-phase PRISMA-based methodology

2.2 Search Strategy

A methodological search approach was created for the guarantee of copying ability and understanding.

Scopus, Web of Science, IEEE Xplore, Science Direct, Taylor & Francis and Springerlink are between the databases.

- Duration: January 2015 to May 2025. This corresponds to the time of the official launch in 2011 and later from the time of explosive growth when Industry 4.0 acquired sufficient traction in the supply chain study (Falorchian and Kazmi 2021).
- Keywords: combinations from three different categories:
  - Words associated with Industry 4.0: "Industry 4.0," "Digitalization", "Smart Manufacturing" and "Cyber-Physical System."
  - The term "supply chain management", "logistics", digital supply chains "and" smart supply chain "are examples of the supply chain Terminology.
  - Capability phrases include " resilience ", "flexibility", " sustainability ", "viability" and " antifragility ".

2.3 Screening and Selection Process

The selection process followed a PRISMA flow:

1. Preliminary identification: 200 articles found in database searches.
2. Title and abstract screening: 87 Articles were excluded as irrelevant (not focused on both industry 4.0 and supply chain).
3. Review of full thread: 56 papers were evaluated for eligibility.
4. Final inclusion: 25 articles fulfilled all criteria and were included in the review.

Inclusion criteria:

- Between 2015-2025, publications in peer-reviewed journals or conference proceedings.
- Addressing one or more from the following structures: flexibility, viability, flexibility, antifragility or stability.
- clearly focus on Industry 4.0 technologies that are relevant in references to supply chain.

Exclusion criteria:

- Non-English publication.
- Pure technical studies (eg robotics design without supply chain application).
- Studies that only focus on construction without supply chain perspective.

This structured selection secured adaptation to review goals, which corresponds to the best practice (Ismail et al. 2025).

2.4 Quality Assessment

Each article was evaluated using a quality evaluation structure based on five criteria (Futorchian and Kazmi 2021; Ivanov and Dolgui 2021):

1. Industry 4.0 and relevance for integrating the supply chain.
2. Methodology rigor (systematic approach, empirical evidence or theoretical contribution).
3. Innovation of insight (addressing flexibility, viability, antifragility).
4. Clarity in conclusions and contributions.
5. Impact (citations, journal quality, practical significance).

2.5 Data extraction

A structured data extraction template was developed to capture the main details:

- Bibliographic details description (author, year, journal).
- Industry 4.0 technologies were discussed (eg IoT, Big Data, AI, Blockchain, Digital Twins).
- Study of supply chain dimensions (procurement, production, logistics, distribution).
- Addressed abilities (flexibility, viability, antifragility, flexibility, stability).
- The most important conclusions and boundaries.

2.6 Synthesis approach

The review combines concept-centric analysis with narrative synthesis (Webster and Watson 2002). The results were classified in the following top categories:

1. Technology driver: Blockchain, AI, IoT, Big Data Analytics and Digital Twin (Ivanov and Dolgui 2021; Fallorchian and Kazmi 2021).
2. According to Ismail et al. (2025), supply chain capabilities include flexibility, viability, and antifragility.
3. Applications in global disruptions, shipbuilding, pharmaceuticals, and agricultural supply chains are examples of contextual insights (Kazancoglu et al. 2021; Jodlbauer et al. 2023).

2.7 Limitations of Methodology

Despite being systematic, this review has certain drawbacks.

- Industry reports and grey literature may not be included if published peer-reviewed articles are the only source used.
- Despite scanning many databases, terminology differences may have prevented some pertinent research from being found.

3. Literature Review

The rapid dissemination of industry 4.0 technologies has conveyed the landscape in supply chain management. Historically, the supply chains preferred lean practice, efficiency and minimization, but forced the companies that were forced to investigate the Covid-19 epidemic, geopolitical crises and climate disruptions to investigate the operational priorities (Ivanov 2020). Quickly, discourse has moved towards the formation of the supply chain that is not only flexible in the short term, but which is also viable in sustaining operations over the long run and even **antifragile**, capable of learning and prosperous in the face of disruptions (Taleb 2012; Ivanov and Dolgui 2021). The growing literature body emphasizes how digitalization and industry 4.0 tools enable this change to provide real - time visibility, future decision-making and to offer collaborative platforms that support adaptation in the supply chain. This section synthesizes systematic insights from selected 25 articles, performed in five thematic groups: technical enablers, industry specific applications, flexibility and agility, viability and sustainability, resilience and antifragility.

3.1 Technological Enablers of Digital Supply Chains

The core of the digital supply chain has a portfolio of advanced technologies - IoT, Big Data Analytics (BDA), Artificial Intelligence (AI), Blockchain, Cloud Computing and Digital Twins - which together allows connection and adaptation. Ivanov and Dolgui (2021) were groundbreaking to the perception of the digital supply chain Twin, which in real-time equipment series processes and allows companies to model resolution, experiment with recovery strategies and dynamically allow configuration networks. Their work suggests how digital twins adaptable to flexible systems and potentially increase the supply chains from antifragile systems that benefit uncertainty.

Fatorachian and Kazemi (2021) empirically demonstrate that IoT sensors and BDA improve end-to-end visibility in procurement, production and logistics, leading to more fit reactions and less obstacles. Supplement, Ismail et al. (2025) emphasizes that although digital tools are widely used for **resilience-building**, their ability to support antifragility is underutilized because most companies adopt it defensively rather than strategically. Blockchain has also proven to be an important promoter of trust and openness in the global network. Quiroz et al. (2019) show that blockchain increases the traceability, but the adoption is slowed by interoperability challenges and high integration costs slow down.

Frank et al. (2019) observe that companies often use isolated technologies - for example, IoT sensor without AI analysis - which only gets incremental benefits. They claim that true changes require integration of ecosystem levels of many industries 4.0 technologies. This scene is supported by Zong et al. (2017), which conceptualizes cyber- physical systems such as the backbone of future construction supply chains, which are able to process data autonomously and enable real-time adaptation. All in all, these studies emphasize that Industries 4.0 tools is the infrastructure for smart, connected and data-driven supply chains, but integration into systems and partners is important to realize their full potential.

Pandey et al. (2023) propose a review about supply chain risks inside the context of Industry 4.0 and advise an analysis framework that combines digital technologies with management practices. The study highlights how IoT, blockchain, and big statistics analytics can reduce conventional risks including demand uncertainty, inventory mismanagement, and supply delays by enhancing real-time monitoring and predictive capabilities. On the other hand, the authors also warning that Industry 4.0 produce new sorts of risks, which includes cyber-security threats, technology integration failures, and high implementation costs. The framework emphasizes a balanced approach in which digital adoption is complemented with robust governance and risk-mitigation techniques to ensure sustainable supply chain overall performance.

3.2 Industry 4.0-Specific Applications

Food Supply Chains

Food supply chains are very sensitive to aggravated, waste and security problems, making them prominent candidates for Industry 4.0 applications. Kazancoglu et al. (2021) expand this argument by highlighting the predictive analytics is a critical tool for ensuring sustainability and resilience. Dolgui and Ivanov (2020) emphasize the role of digital scenario modeling to reduce ripple effects during crises such as pandemics, where food supply chains are particularly weak. Protopappas et al. (2025) present a case wherein IoT-enabled monitoring the usage of LoRaWAN sensors was deployed across food supply chains to measure temperature and humidity during transportation. The case confirmed how actual-time data sharing with stakeholders reduced spoilage rates, stepped forward food protection, and superior general supply chain transparency. This highlights the capability of IoT-primarily based solutions to cope with perishability and build consumer trust in food logistics.

Jabbour et al. (2020) explore the intersection of food supply chains, circular economy, and Industry 4.0 technologies. Their observation proposes a research schedule focused on reducing food waste through the integration of IoT, big data analytics, blockchain, and advanced automation. The authors argue that this technology effectively reverse logistics, improves traceability, and enables closed-loop processes with circular economy concepts. The article emphasizes that Industry 4.0 provides not only operational improvements but additionally a pathway for achieving sustainability through minimizing waste and maximizing aid utilization

Shipbuilding and heavy industry

Industries such as shipbuilding are characterized by long lead time and complex supplier networks. Kim et al. (2020) present a case study that shows how cyber-physical integration improves the supplier's collaboration, project coordination and planning. These findings indicate that industry 4.0 not only applies to rapidly growing consumables, but also in large-scale, capital-intensive areas where traditional flexibility is limited.

Manufacturing and Logistics

In manufacturing, Frank et al. (2019) shows that companies achieve better results while using the Industry 4.0 technologies holistically instead of piecemeal. Jodlbauer et al. (2023) adds that fragmented adoption causes solo effects, while integrated ecosystems improve system-wide viability. In logistics, Wang et al. (2020) shows that AI powered routing algorithms significantly reduce the delivery and improve customers' satisfaction.

Mutale and Bupe (2024) proposed a case study at DHL Zambia, that showed how the deployment of Industry 4.0

technologies like IoT, Blockchain, Big Data Analytics, AR/VR impacts core supply chain metrics. Their mixed-methods research showed significant impacts by mean improvements in on-time delivery, order cycle time, inventory turnover, supply chain cost, lead time, and forecast accuracy after adoption of these technologies. The study illustrated how integrating multiple digital enablers enhances both operational efficiency and resilience in logistics operations, even in emerging economy contexts.

Huang et al. (2023) adopt a dynamic resource-based totally view to analyze how Industry 4.0 technology have an impact on supply chain capabilities and resilience. Using empirical evidence from multiple firms across manufacturing sectors. the study demonstrated that the adoption of technology along with IoT, big data analytics, and cloud computing systems complements supply chain connectivity, visibility, and agility. These strengthened capabilities subsequently contribute to progressed resilience by allowing firms to anticipate, absorb, and recover from disruptions more effectively. The findings emphasize that Industry 4.0 creates not only technical efficiencies but also strategic dynamic resources that reinforce long-term competitiveness.

Reaidy et al. (2024) observe how Industry 4.0 technology affect supply chain overall performance by way of focusing at the mediating role of integration and visibility. Drawing from survey and case-based data across manufacturing firms, the study shows that the direct adoption of technologies such as IoT, blockchain, and advanced analytics is not sufficient to guarantee performance gains. Instead, improvements are realized when these technologies enhance visibility of operations and enable integration across partners and functions. The results endorse that Industry 4.0 creates value primarily by facilitating real-time information sharing and seamless connectivity in turn drive agility, responsiveness, and typical supply chain performance.

Agricultural chemical supply chain
Gozali et al. (2024) advanced a case study at a pesticide company that simulated blockchain integration in its supply chain operations. The simulation showed how blockchain could strengthen supplier coordination, ensure real-time

traceability, and reduce risks related to delays or inconsistent quality. Results highlighted improved operational efficiency and higher resilience in handling disruptions across the agricultural chemical supply chain.

3.3 Flexibility and Agility
One of the most consistent findings in the literature is that Industry 4.0 technologies increase the flexibility and agility of the supply chain. Fatorachian and Kazemi (2021) strengthened it by showing that IoT-based visibility accelerates purchases and distribution responsibilities. Ivanov (2020) documented on how AI-driven production scheduling allow manufacturing systems to reconfigure rapidly, ensuring delivery reliability even under uncertainty. Frank et al. (2019) cautioned that isolated technologies result in efficiency often distributes without real flexibility.

3.4 Viability and Sustainability
Beyond flexibility, scholars emphasize the need for supply chains to achieve **viability** - the ability to maintain operations during chronic disruption. Ivanov (2021) showed viability as a combination of agility, resilience, and sustainability. Their models suggest that viability requires systemic coordination, not just solid efficiency. Kazancoglu et al. (2021) illustrated how Industry 4.0 reduces food waste and carbon emissions, corresponds to circular economics principles. Kusi-Sarpong et al. (2021) Demonstrated that Industry 4.0-enabled multi-criteria supplier selection strengthens both environmental performance and operational viability.

Jodlbauer et al. (2023) emphasized that systemic viability also requires cross -level collaboration, which are supported by platforms that share data and increase transparency. Similarly, Wang et al. (2020), argued that sustainability and viability are co-dependent, as digitalization reduces resource consumption by increasing competitive benefits. Overall, these studies highlight the fact that Industry 4.0 fosters viability by embedding sustainability and long-term adaptability into the fabric of supply chains.

3.5 Resilience and Antifragility
Resilience has long dominated supply chain research, but **antifragility**—where systems improve through stress—has recently emerged as a transformative goal. Ivanov and Dolgui (2021) contend that digital twins uniquely support antifragility by enabling firms to simulate stress scenarios and identify improvement pathways. Ismail et al. (2025) confirm that AI, IoT, and blockchain enhance resilience but note a gap in translating resilience into

antifragility.

Queiroz et al. (2019) highlight blockchain's role in building collaborative trust that endures after disruptions, a prerequisite for antifragility. Jodlbauer et al. (2023) emphasize that resilience must evolve into antifragility if supply chains are to survive in a VUCA (volatile, uncertain, complex, and ambiguous) world. Together, these studies recommend that Industry 4.0 offers the technical capabilities for antifragility, but organizational culture and governance are equally essential.

The 25 studies are visually grouped into five clusters in Figure 2, which shows a thematic map of the evaluated literature: Methodological Foundations, Resilience and Antifragility, Flexibility and Agility, and Viability and Sustainability. The subject categories are represented by blue nodes, and specific publications related to the themes they discuss are represented by green nodes. Viability, sustainability, and resilience and antifragility constitute the densest clusters on the map, indicating the high level of scholarly interest in how Industry 4.0 technologies facilitate adaptation and long-term survival in unstable contexts. On the other hand, predictive analytics and IoT applications are closely linked to flexibility and agility, underscoring their operational significance. This thematic map provides a comprehensive perspective of the relationships between themes and research.

Table 1 summarizes key studies in Industry 4.0 technologies in digital supply chains, showing their role in improving flexibility, resilience, and sustainability. Core tools like IoT, AI, Blockchain, and Digital Twins enhance visibility and adaptability. However, the gaps remain in empirical validation, human factors, and multi-technology integration (Figure 2).

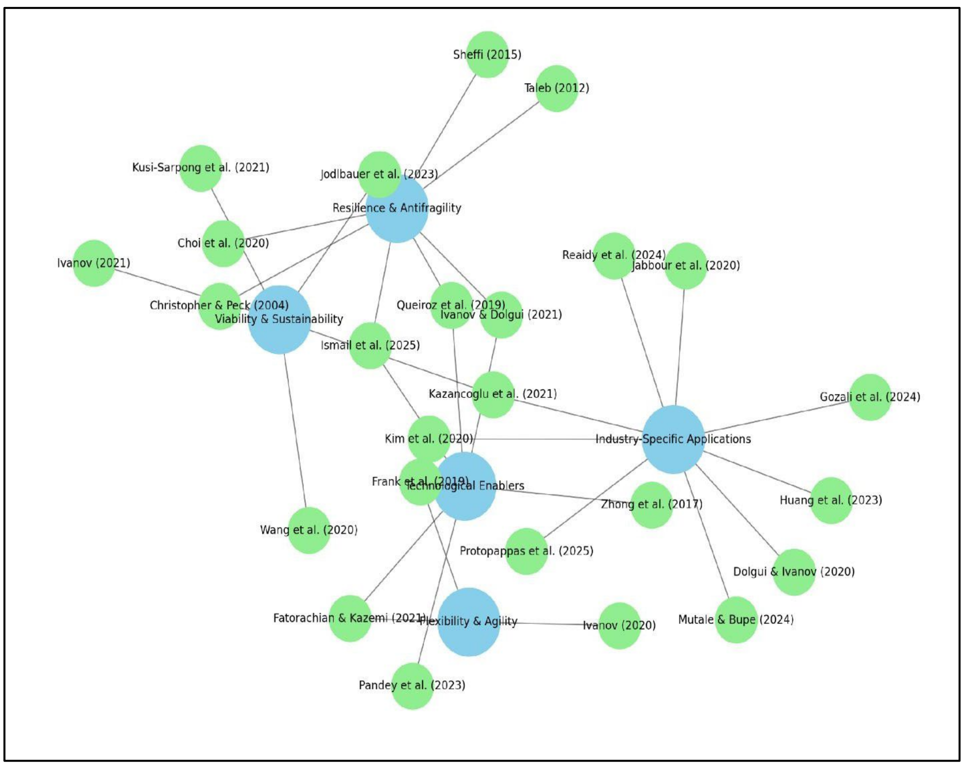

Figure 2. Thematic map

Table 1. Literature Review on Industry 4.0 and Digital Supply Chains

Theme / Focus Area	Key Authors / Studies	Main Contributions & Findings	Technologies Discussed	Identified Gaps / Limitations
Technological Enablers of Digital Supply Chains	Ivanov & Dolgui (2021), Fatorachian & Kazemi (2021); Ismail et al. (2025); Quiroz et al. (2019); Frank et al. (2019); Zong et al. (2017); Pandey et al. (2023)	Digital Twins allow real time simulation and decision modeling; IoT and Big Data improve end-to-end visibility; Blockchain enhances transparency and trust; Integration of multiple Industry 4.0 tools amplifies resilience and adaptability.	IoT, Big Data Analytics, AI, Blockchain, Cloud Computing, Digital Twins	Fragmented adoption of technologies; limited strategic integration across systems; minimal research on antifragility; cybersecurity and cost challenges.
Industry Sector Applications	Kazancoglu et al (2021); Dolgui & Ivanov (2020); Protopappas et al. (2025); Jabbour et al. (2020); Kim et al. (2020), Jodlbauer et al. (2023); Wang et al. (2020); Mutale & Bupe (2024); Huang et al. (2023); Reaidy et al. (2024); Gozali et al. (2024)	Food supply chains: IoT and predictive analytics improve freshness, sustainability, and reduce waste. Shipbuilding: Cyber-Physical Systems (CPS) improve collaboration and scheduling. Manufacturing & Logistics: Integrated I4.0 adoption enhances agility, customer satisfaction, and performance metrics. Agriculture: Blockchain strengthens traceability and coordination.	IoT, Blockchain, Big Data, AI, Cloud, CPS,	Limited studies in developing countries; fragmented use of digital tools; weak cross-sector integration.
Flexibility & Agility	Fatorachian & Kazemi (2021); Ivanov (2020); Frank et al. (2019)	IoT-driven visibility speeds up procurement and logistics; AI based scheduling and planning enables rapid reconfiguration under uncertainty; Integrated adoption creates greater agility than isolated technologies	IoT, AI, Big Data Analytics	Focused mainly on short-term responsiveness; lack of quantitative models and metrics for flexibility assessment.
Viability & Sustainability	Ivanov (2021); Kazancoglu et al. (2021); Kusi-Sarpong et al. (2021); Jodlbauer et al. (2023); Wang et al. (2020)	Viability defined as combination of agility, resilience, and sustainability; Industry 4.0 supports circular economy principles, reducing waste and emissions; Supplier selection via digital tools enhances both environmental and	IoT, Blockchain, AI, Cloud Platforms	Limited linkage between digital adoption and long-term viability; few empirical validations; sustainability outcomes underexplored.

		operational performance.		
Resilience & Antifragility	Ivanov & Dolgui (2021); Ismail et al. (2025); Queiroz et al. (2019); Jodlbauer et al. (2023)	Digital Twins support stress-testing and post-crisis improvement; Blockchain builds post-disruption trust; Transition from resilience to antifragility critical Organizational learning and governance essential for antifragility.	Digital Twins, Blockchain, IoT, AI	Antifragility concept remains theoretical; behavioral and cultural dimensions neglected; absence of measurement indicators.
Overall Literature Insights	Consolidated from 25 reviewed studies (2015–2025)	Industry 4.0 technologies act as dynamic enablers for flexibility, viability, and antifragility. Digital transformation shifts supply chains from efficiency-driven to adaptive, data-driven, and sustainable systems.	Integrated Industry 4.0 Ecosystem (IoT, AI, BDA, Blockchain, Cloud, DT)	Lack of empirical verification; neglect of human and organizational factors; weak multi-technology integration; absence of quantitative metrics; limited study of behavioral/organizational dimensions.

4. Discussion

Integration of Industry 4.0 technologies in managing the supply chain represents an intensive change in how organizations conceptualize resilience, viability, and antifragility. While literature highlights sufficient progress, it also reveals fragmentation, uneven adoption and remarkable gap. This discussion synthesizes the findings of the five subjects known in the review and extends them to an important study of research gaps and future research directions.

4.1 Convergence of Technological Enablers and Supply Chain Capabilities

Reviewed studies continuously confirm that technologies such as IoT, Big Data Analytics, AI, Blockchain, Cloud Computing and Digital Twins act as enablers of (Ivanov and Dolgui 2021; Rhilorchian and Kazmi 2021; Quiroz et al. 2019). predictive analytics enable forecasting, blockchain ensures trust and traceability, and digital twins simulate disruptions to test recovery scenarios. Nevertheless, evidence also outlines fragmented adoption. Frank et al. (2019) and Jodlbauer et al. (2023) Caution is that separate technologies can improve efficiency, but are unable to provide systemic flexibility and viability. Complete integration is necessary, but it remains limited in practice. The research gap here lies in exploring **interoperability frameworks** and **cross-technology integration models** that allow multiple Industry 4.0 tools to work together seamlessly.

Future research must prefer multi-technology ecosystem for example, combination of IoT with blockchain for traceability, future disruption of AI for predictive disruption modeling and digital twins for scenario planning. Such integrated approaches are still rare in empirical studies, but represent the border of smart supply Chain.

4.2 Flexibility and Agility: Immediate Gains, Limited Integration

Flexibility is the most consistently reported outcome which are reported result of digitalization. Predictive analytics: IoT tracking and AI scheduling enable firms to adjust rapidly to fluctuations in demand and supply (Barnis et al. 2019; Ivanov 2020).

This highlights two research gaps:

1. The **behavioral and organizational dimensions** of digital supply chain agility remain underexplored. Most studies focus on technology but neglect human and managerial adaptation.

2. There is insufficient exploration of scalability - how flexibility is demonstrated in pilot projects or individual functions can be scaled throughout the supply network.

Future research should integrate socio-technical approaches, check how leadership, training and change management complement digital technologies to foster sustainable agility.

4.4 Viability and Sustainability: From Resilience to Long-Term Survival

Viability emerges as a wonderful capability, described because the capacity of supply chains to survive beneath chronic turbulence through integrating agility, resilience, and sustainability (Ivanov 2021). Several studies reveal how Industry 4.0 reduces waste and emissions, aligning with circular economic system dreams (Kazancoglu et al. 2021). Supplier selection frameworks further increase viability with the aid of embedding sustainability criteria into procurement (Kusi-Sarpong et al. 2021).

Yet, viability studies remain conceptually fragmented. While Ivanov (2021) affords a theoretical model, empirical validation is constrained. There is also inadequate exploration of **system-wide viability** across multi-tier networks. Jodlbauer et al. (2023) emphasize cross-tier collaboration, however few empirical researches operationalize this insight.

Two research gaps emerge:

1. The lack of quantitative metrics for viability. Unlike resilience (measured by using recovery time) or flexibility (measured by lead-time responsiveness), viability lacks standardized signs.
2. Limited attention to policy and governance frameworks that enable viability at local or countrywide ranges

Future research should focus on developing viability metrics, engaging in empirical validations, and studying the role of public policy in fostering viable supply chain ecosystems.

4.5 Resilience and Antifragility: The Next Frontier

Resilience has been a main theme for decades (Christopher and Peck 2004; Sheffi 2015), but antifragility represents a new limit. Ivanov and Dolgui (2021) argue that digital twins allow companies to replace interruptions in learning opportunities, while Taleb (2012) provides theoretical basis for antifragility. Empirical evidence under Covid-19 suggests that companies with strong digital infrastructure were not only resilient but also **reconfigured supply chains for long-term advantage** (Ivanov 2020; Dolgui and Ivanov 2020).

Despite the promise, antifragility remains underdeveloped in the supply chain. Most studies, including Ismail et al. (2025), still emphasizes resilience. Antifragility requires more than technology - it requires an **organizational willingness to experiment, learn, and embrace volatility** (Choi et al. 2020).

Research gaps include:

1. The lack of studies of empirical case shows clear antifragility.
2. Organizational culture and minimum detection of management mechanisms that support antifragile behavior.

Future works should design **frameworks and conceptualize model for antifragile supply chains**, integrate **behavioral and cultural dimensions**, and test these models across diverse industries and geographies.

4.7 Future Research Directions

Based on those gaps, this evaluation identifies numerous destiny research priorities:

- Technology Integration: Develop frameworks for interoperable multi-generation ecosystems (IoT, AI blockchain, virtual twins).
- Comparative Studies: Conduct cross-industry analyses to test transferability of digital practices.
- New Metrics: Create robust indicators for viability and antifragility, demonstrated through empirical studies
- Socio-Technical Approaches: Integrate organizational culture, leadership, and team of workers readiness into digital supply chain studies.
- Policy Research: Examine how national digital transformation initiatives (e.g., Saudi Vision 2030) shape supply chain resilience, viability, and antifragility.

5. Conclusion

The integration of Industry 4.0 technologies into supply chain signifies a major transformation rather than a simple technical development. By synthesizing evidence from more than 25 studies, this review validated how enablers inclusive of IoT, Big Data Analytics, AI, Blockchain, Cloud Computing, and Digital enhance not only flexibility and resilience, but also long-term viability and antifragility, however also long-term viability and antifragility. The analysis underscores that this technology should be considered as a part of an interconnected environment instead of isolated tools.

The study contributes to the principle with the aid of consolidating fragmented findings into an incorporated framework, broadening the discussion from resilience to viability and antifragility, and figuring out important studies gaps. Among those are the absence of standardized metrics, insufficient cross-industry comparisons, and a lack of attention to socio-technical elements such as leadership and culture. Practically, the evaluation emphasizes that piecemeal digital adoption is insufficient firms must construct holistic digital ecosystems, invest in personnel readiness, and deal with sustainability as a strategic driver of competitiveness rather than to a compliance requirement.

From a policy point of view, conclusions emphasize the importance of the supportive regulatory environment, with initiatives such as Saudi Vision 2030; how it increases national strategies However, research on the management structure is still rare, which indicates the need for further studies on incentives, standards, and cross-border collaboration. Finally, the review concludes that the future of the supply chains depends on the systemic integration of industry 4.0, organizational adaptability and proactive policies, which adds a roadmap building smart, sustainable, and antifragile supply chains capable of thriving in uncertain times.

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