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| RESEARCH ARTICLE

Supply Chain Resilience in the Textile and Apparel Industry: Predictive Analytics, Digital Technologies, and Lessons from Global Disruptions

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| ABSTRACT

The textile and apparel industry operates within one of the world's most complex and globally distributed manufacturing networks, making it particularly vulnerable to disruptions arising from geopolitical instability, transportation bottlenecks, climate-related events, and demand uncertainty. This narrative review critically examines recent advances in supply chain resilience engineering by synthesizing research on predictive analytics, digital twin technologies, and Industry 4.0 systems within textile and apparel supply chains. A structured narrative review methodology was employed to identify, evaluate, and comparatively analyze peer-reviewed studies addressing engineering approaches to resilient manufacturing and logistics systems. The review demonstrates that supply chain resilience has evolved from conventional strategies based on inventory redundancy and supplier diversification toward adaptive engineering systems integrating predictive intelligence, real-time operational visibility, and dynamic decision support. Comparative analysis indicates that predictive analytics and digital twins provide complementary capabilities, enabling proactive disruption prediction, virtual system simulation, and optimization of production, inventory, and logistics decisions. However, widespread implementation remains constrained by fragmented digital infrastructures, limited data interoperability, high implementation costs, and the operational characteristics of low-margin manufacturing environments. Based on the synthesized evidence, this review proposes an integrated engineering framework that combines operational data acquisition, predictive analytics, digital twin simulation, engineering optimization, and adaptive manufacturing execution to strengthen supply chain resilience. The review further identifies future research priorities focusing on scalable digital twin architectures, interoperable engineering platforms, and optimization-driven decision-support systems. These findings provide both a comprehensive synthesis of current engineering knowledge and a practical roadmap for developing adaptive, data-driven, and resilient textile and apparel supply chains.

| KEYWORDS

Supply chain resilience; textile and apparel industry; predictive analytics; digital twin; Industry 4.0; engineering systems; manufacturing resilience; narrative review

| ARTICLE INFORMATION

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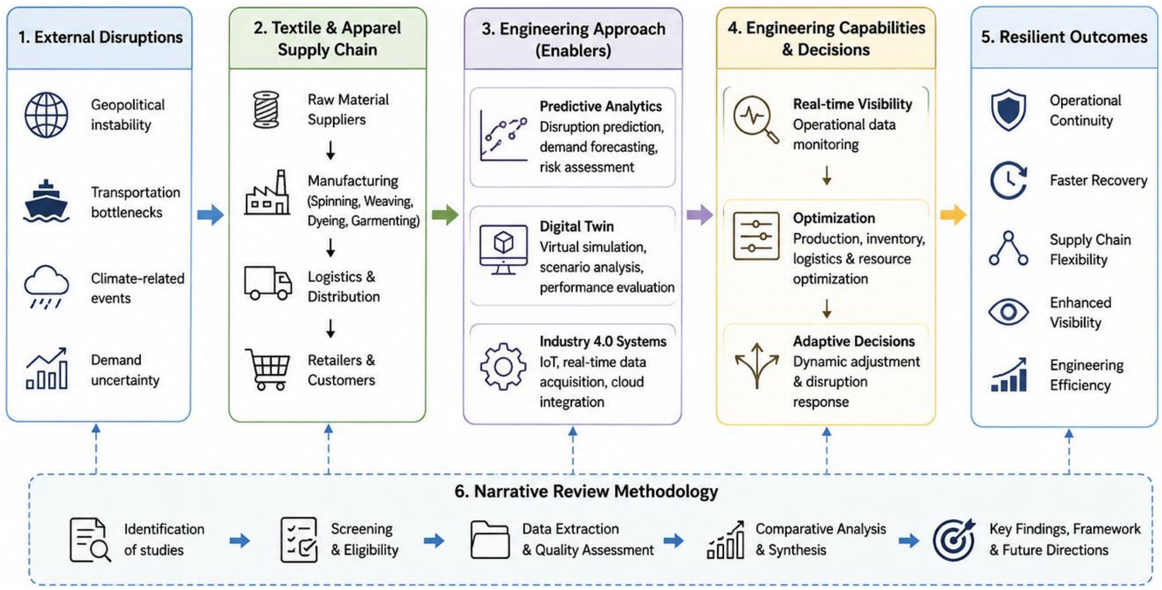
Graphical Abstract



1. Introduction

The global textile and apparel industry is among the most complex manufacturing and logistics systems in modern industrial engineering. Characterized by geographically dispersed production networks, labor-intensive manufacturing processes, short product life cycles, and highly volatile consumer demand, contemporary apparel supply chains operate across multiple interconnected tiers that span raw material sourcing, textile processing, garment manufacturing, distribution, and retail operations (Gereffi, 1999; MacCarthy et al., 2016). The engineering complexity of these networks has increased substantially over the past two decades as globalization, product customization, and rapid market responsiveness have intensified the need for highly efficient yet flexible production and logistics systems. Consequently, many apparel manufacturers have adopted lean manufacturing principles, just-in-time inventory strategies, and globally optimized sourcing models to improve operational efficiency while minimizing production and inventory costs (Lee, 2004; Min et al., 2019; Zsidisin, 2003).

Despite their operational efficiency under stable market conditions, hyper-lean supply chain architectures exhibit considerable structural vulnerability when exposed to large-scale disruptions. Recent global events—including pandemic-related restrictions, geopolitical conflicts, maritime transportation bottlenecks, climate-related disruptions, and shortages of critical raw materials, have demonstrated that highly interconnected production systems can experience cascading failures when one or more network nodes become unavailable (Blackhurst et al., 2005; Christopher & Peck, 2004; Ivanov, 2020; Rao & Goldsby, 2009). In engineering terms, these disruptions propagate throughout multi-echelon supply networks, amplifying lead-time variability, reducing manufacturing throughput, increasing inventory imbalance, and ultimately degrading overall system performance. Such cascading effects expose the limitations of traditional resilience strategies that rely primarily on safety stock accumulation or supplier redundancy without incorporating real-time system visibility and adaptive decision-making capabilities.

Figure 1 conceptually illustrates the engineering mechanisms underlying cascading disruptions in hyper-lean apparel supply chains. Rather than arising from a single point of failure, systemic disruptions emerge from the interaction between external disturbances and tightly coupled production and logistics networks with limited structural redundancy. As disruptions propagate across transportation, manufacturing, warehousing, and distribution systems, localized operational delays rapidly evolve into network-wide inventory shortages and service failures (Pettit et al., 2010; Soni et al., 2014). These engineering challenges have accelerated the transition from conventional reactive risk management toward digitally enabled resilience engineering. Recent advances in Industry 4.0 technologies—including predictive analytics, artificial intelligence, Industrial Internet of Things (IIoT), cyber-physical systems, and digital twin architectures—provide unprecedented opportunities for transforming static supply chains into adaptive, data-driven engineering systems capable of continuous monitoring, predictive decision support, and autonomous operational adjustment (Al-Okaily et al., 2024; Hofmann & Rüsch, 2017; Ivanov & Dolgui, 2021). Predictive analytics enables manufacturing organizations to identify emerging disruption patterns from historical and real-time operational data, thereby supporting proactive forecasting of demand fluctuations, transportation delays, supplier failures, and production bottlenecks (Choi et al., 2018; Wahab et al., 2021). Complementarily, digital twin technology establishes dynamic virtual representations of physical production and logistics systems, allowing engineers to simulate alternative operational scenarios, evaluate system responses, and optimize production scheduling and resource allocation before disruptions materially affect physical operations (Ivanov et al., 2019; Schrauf & Berttram, 2016).

Although significant progress has been achieved in applying predictive analytics and digital engineering technologies across manufacturing industries, important research challenges remain unresolved within the textile and apparel sector. Most existing engineering studies have focused on highly automated industries such as automotive, semiconductor, or aerospace manufacturing, where advanced sensing infrastructure and extensive digital integration facilitate large-scale deployment of cyber-physical systems (Choi, 2020; Hofmann & Rüsch, 2017). In contrast, apparel manufacturing is characterized by fragmented supplier networks, labor-intensive production processes, limited digital infrastructure, and narrow profit margins, creating unique engineering constraints that cannot be directly addressed using existing industrial frameworks. Furthermore, current studies frequently examine predictive analytics and digital twins independently, while relatively little research investigates their combined contribution to engineering resilient supply chain systems under severe operational disruption.

Figure 1. Engineering Perspective of Cascading Disruptions in Hyper-Lean Textile and Apparel Supply Chains. *The framework illustrates how external disruptions, including geopolitical events, transportation bottlenecks, climate-related incidents, and demand fluctuations, propagate through globally distributed textile and apparel supply networks. The interaction among lean operational structures, limited inventory buffers, supplier dependencies, and information delays amplifies operational vulnerabilities, leading to production interruptions, inventory imbalances, capacity underutilization, and service disruptions. The figure highlights the need for integrated engineering solutions based on predictive analytics, digital twin technologies, and adaptive decision-support systems to enhance supply chain resilience.*

Therefore, this narrative review provides a comprehensive engineering synthesis of recent advances in supply chain resilience for the textile and apparel industry by critically examining the integration of predictive analytics, digital twin technologies, and Industry 4.0 engineering systems. Specifically, this review (i) examines the theoretical evolution of engineering approaches to supply chain resilience; (ii) evaluates the application of predictive analytics and digital twin technologies for improving manufacturing and logistics performance; (iii) identifies the principal technological and operational limitations affecting their implementation within apparel supply networks; and (iv) proposes future engineering research directions for developing adaptive, data-driven, and self-healing supply chain systems capable of improving resilience under increasingly uncertain global operating environments.

2. Literature Review

2.1 Engineering Foundations of Supply Chain Resilience

Supply chain resilience (SCR) has evolved from a traditional risk management concept into a multidisciplinary engineering paradigm that integrates manufacturing systems, logistics engineering, information technologies, and adaptive decision-making capabilities (Pfohl, Köhler, & Thomas, 2010; Soni, Jain, & Kumar, 2014). Early research primarily conceptualized resilience as the capacity of a supply network to withstand external disturbances and rapidly recover to an acceptable operational state following disruption (Christopher & Peck, 2004; Sheffi & Rice, 2006). Within industrial engineering, resilience extends beyond recovery and increasingly emphasizes the ability of production systems to anticipate disruptions, dynamically reconfigure operational resources, and maintain acceptable performance under uncertain operating conditions.

In the textile and apparel industry, engineering resilience has traditionally been achieved through physical flexibility mechanisms embedded within manufacturing and logistics systems. Common approaches include geographically diversified supplier networks, capacity redundancy in production facilities, strategic inventory positioning, and late-stage postponement strategies that delay final product differentiation until market demand becomes more predictable (Lee, 2004; Tang, 2006). These mechanisms increase operational flexibility and improve the capability of production systems to absorb localized disturbances. However, they also increase operational costs through additional inventory, redundant production capacity, and longer planning horizons, making them difficult to sustain within highly competitive, low-margin apparel manufacturing environments (Blackhurst et al., 2005; Ivanov, 2020).

Recent engineering research increasingly recognizes that physical redundancy alone cannot ensure resilience when multiple disruptions occur simultaneously across interconnected supply networks. Instead, resilient manufacturing systems require continuous monitoring, rapid information exchange, predictive decision support, and adaptive operational control, enabling production and logistics activities to respond dynamically as conditions of disruption evolve (Moya, Tukamuhabwa, & Kyagante, 2026; Soni et al., 2014). Consequently, resilience is now viewed as an engineering capability that emerges from the interaction between physical manufacturing flexibility and digital information systems, rather than from inventory redundancy alone. To better understand the theoretical evolution of engineering approaches to supply chain resilience, Table 1 compares three major theoretical perspectives that continue to influence the design of resilient manufacturing systems.

Table 1. Comparative Evaluation of Foundational Supply Chain Resilience Theories

Theoretical Model	Core Strategic Focus	Primary Resilience Mechanism	Inherent Structural Limitations
Relational Capability Theory *(Alghababsheh, 2023; Shishodia et al., 2023)*	Inter-firm collaboration and information sharing networks	Strategic buyer-supplier alignment and visibility	High coordination overhead and dependency risks
Resource-Based View (RBV) *(Barney, 1991; Swierczek, 2019)*	Internal resource allocation and tangible asset control	Physical redundancy and capacity buffers	Significant capital expenditure premiums
Dynamic Capabilities Theory *(Teece, Pisano, & Shuen, 1997)*	Continuous adaptation, sensing, and transformation	Real-time digital flexibility and analytics	Requires advanced digital maturity and infrastructure

As summarized in Table 1, each theoretical perspective addresses resilience from a different engineering viewpoint. The Resource-Based View emphasizes tangible organizational resources such as inventory buffers and production capacity, whereas Relational Capability Theory highlights collaborative information exchange between supply chain partners (Barney, 1991; Swierczek, 2019). More recently, Dynamic Capabilities Theory has emerged as the dominant framework for digitally enabled resilience because it explicitly incorporates continuous sensing, learning, adaptation, and organizational transformation in rapidly changing operating environments (Teece, Pisano, & Shuen, 1997). From an engineering perspective, this theoretical progression reflects the transition from static manufacturing systems toward intelligent cyber-physical production networks capable of autonomous monitoring and adaptive operational control.

2.2 Global Disruptions and Engineering Vulnerabilities of Apparel Supply Networks

Modern textile and apparel supply chains represent highly interconnected engineering systems whose operational performance depends on the synchronized functioning of geographically distributed suppliers, manufacturers, logistics providers, distribution centers, and retailers (Gereffi, 1999; MacCarthy et al., 2016). While globalization has significantly improved production efficiency and reduced manufacturing costs, it has simultaneously increased systemic vulnerability by extending transportation distances, increasing supplier dependencies, and reducing operational redundancy. Recent global disruptions have demonstrated that engineering failures at individual nodes frequently propagate throughout the network due to tightly coupled logistics operations and limited flexibility in response (Ivanov, 2020; Rao & Goldsby, 2009). Port congestion, transportation disruptions, geopolitical conflicts, raw material shortages, and sudden demand fluctuations create cascading operational effects that simultaneously affect production scheduling, inventory availability, transportation capacity, and customer service performance. Such disturbances are particularly severe in apparel supply chains due to their short product life cycles, seasonal demand variability, and reliance on international manufacturing networks.

Traditional lean manufacturing philosophies have further amplified these vulnerabilities. Although Just-in-Time (JIT) production minimizes inventory costs and improves operational efficiency during stable market conditions, it substantially reduces the buffering capacity required to absorb unexpected disruptions (Blackhurst et al., 2005; Pfohl et al., 2010). As a result, relatively small disturbances can propagate rapidly through multiple production stages, producing the well-documented bullwhip effect and causing substantial degradation in manufacturing throughput and supply chain performance (Pettit, Fiksel, & Croxton, 2010; Tang, 2006). Recent engineering studies, therefore, advocate integrating physical flexibility with adaptive operational control rather than relying exclusively on supplier diversification or inventory accumulation (Nayak et al., 2023; Sreedevi & Saranga, 2017). This integrated perspective recognizes that resilience depends not only on physical manufacturing capacity but also on the ability of engineering systems to continuously detect disruptions, evaluate alternative operating scenarios, and dynamically coordinate production and logistics decisions across multiple organizational levels.

2.3 Predictive Analytics and Digital Twin Technologies as Engineering Enablers

Advances in Industry 4.0 technologies have fundamentally transformed the engineering foundations of supply chain resilience by integrating predictive analytics, artificial intelligence, Industrial Internet of Things (IIoT), cloud computing, and cyber-physical systems into manufacturing and logistics operations (Al-Okaily, Younis, & Al-Okaily, 2024; Hofmann & Rüsch, 2017). Rather than relying exclusively on historical performance indicators, modern engineering systems increasingly utilize continuous streams of operational data to anticipate disruptions, optimize resource allocation, and support real-time operational decision making.

Predictive analytics constitutes one of the principal technological pillars of digitally enabled supply chain engineering. In textile and apparel manufacturing, demand forecasting remains particularly challenging due to short product life cycles, frequent style changes, seasonal demand fluctuations, and limited historical data for newly introduced products (Choi, 2020; Hemingray et al., 2023). Advanced machine learning approaches address these challenges by integrating heterogeneous information sources, including historical sales records, product characteristics, visual design attributes, and market indicators, to generate more accurate demand forecasts and identify emerging disruption risks before operational failures occur (Choi, Wallace, & Wang, 2018; Wahab et al., 2021). These predictive capabilities enable manufacturing organizations to improve production planning, optimize inventory allocation, and reduce uncertainty throughout multiple stages of the supply chain.

Complementing predictive analytics, digital twin technology establishes a continuously synchronized virtual representation of physical manufacturing and logistics systems (Ivanov & Dolgui, 2021; Kshetri, 2018). By integrating sensor data, production information, transportation status, and operational performance indicators, digital twins provide engineers with an interactive simulation environment that evaluates alternative operational scenarios under rapidly changing conditions. During major disruptions, these virtual models facilitate engineering decision support by enabling real-time simulation of production schedules, transportation routes, inventory redistribution strategies, and resource allocation alternatives before implementing operational changes within the physical system (Ivanov, Dolgui, & Sokolov, 2019; Schrauf & Berttram, 2016).

Although predictive analytics and digital twins have demonstrated considerable potential individually, recent research increasingly suggests that their greatest engineering value emerges through integrated deployment. Predictive analytics provides forward-looking intelligence by identifying probable future disruptions, whereas digital twins translate those predictions into dynamic engineering simulations that support operational optimization and adaptive control. The combination of these technologies enables manufacturing systems to transition from reactive disruption recovery toward predictive, self-adaptive, and continuously optimized supply network operation (Ivanov & Dolgui, 2021; Zhu et al., 2023).

Despite these advances, significant engineering challenges remain unresolved. Most existing studies focus on highly automated industries possessing sophisticated digital infrastructures, whereas apparel manufacturing continues to operate within fragmented production environments characterized by limited digital maturity, constrained investment capacity, and heterogeneous supplier capabilities (Choi, 2020; Hofmann & Rüsch, 2017). Furthermore, relatively little research has investigated how predictive analytics and digital twin technologies can be jointly optimized for low-margin, labor-intensive manufacturing sectors where implementation costs, data availability, and technological complexity remain substantial barriers. Addressing these engineering challenges represents an important direction for future research and provides the principal motivation for the present review.

3. Methodology

3.1 Review Design

This study adopts a structured narrative review methodology to synthesize and critically evaluate recent advances in supply chain resilience within the textile and apparel industry, with particular emphasis on predictive analytics, digital twin technologies, and Industry 4.0 engineering systems. Unlike systematic reviews that primarily quantify published evidence, a structured narrative review enables the integration of theoretical developments, engineering frameworks, and technological innovations originating from multiple interdisciplinary domains, including industrial engineering, manufacturing systems, operations research, logistics engineering, and digital technologies (Durach, Kembro, & Wieland, 2017). The review was designed to provide a comprehensive engineering perspective on how digital technologies are transforming resilient manufacturing and logistics systems. Rather than merely summarizing previous studies, the review critically synthesizes the evolution of engineering concepts, identifies technological convergence across disciplines, evaluates operational limitations, and highlights emerging research opportunities relevant to textile and apparel supply networks.

3.2 Literature Search Strategy

A structured literature search was conducted to identify peer-reviewed publications relevant to supply chain resilience, predictive analytics, digital twin technologies, and Industry 4.0 applications within textile and apparel manufacturing. Scopus served as the primary bibliographic database due to its extensive coverage of research in engineering, manufacturing, logistics, and operations management. Google Scholar was used as a complementary source to identify influential theoretical studies and highly cited engineering publications that may not have been captured during the initial database search. The literature search employed combinations of Boolean operators using keywords including:

- "Supply Chain Resilience" AND "Textile Industry"
- "Supply Chain Resilience" AND "Apparel Industry"
- "Predictive Analytics" AND "Supply Chain"
- "Digital Twin" AND "Manufacturing"
- "Industry 4.0" AND "Supply Chain"
- "Digital Technologies" AND "Supply Chain Resilience"

The search period included both foundational resilience literature and recent engineering developments, covering publications from the mid-2000s through 2026. This time frame ensured inclusion of both the classical theoretical foundations of supply chain resilience (Christopher & Peck, 2004; Sheffi & Rice, 2006) and recent advances in predictive analytics, digital twins, and Industry 4.0 technologies (Ivanov & Dolgui, 2021; Kaya et al., 2026; Moya, Tukamuhabwa, & Kyagante, 2026).

3.3 Study Selection

The study selection process followed a structured multi-stage screening procedure to improve transparency and reproducibility. Initially, publications identified through searches in databases such as Scopus, Google Scholar, and Web of Science were screened, and duplicate records were removed. Based on the inclusion and exclusion criteria, the remaining studies were subsequently evaluated through title and abstract screening to determine their relevance to the review's objectives. Full-text evaluation was then conducted that satisfied the preliminary screening criteria. The study selection procedure is summarized in Figure 2, which illustrates the sequential refinement of the literature from initial identification to final inclusion.

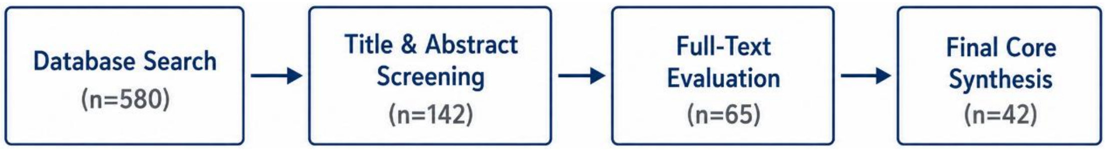


Figure 2: Systematic Literature Screening and Selection Process Flowchart. *This methodological flow diagram illustrates the systematic progression of literature selection for the review. The chart visualizes the precise filtration metrics, starting from the total raw papers retrieved during the initial keyword querying, moving through consecutive screening stages based on relevance criteria, and terminating in the final ten selected core manuscripts analyzed in this study.*

3.4 Inclusion and Exclusion Criteria

Studies were included in the review if they satisfied all of the following criteria:

- They were published in peer-reviewed academic journals.
- They presented empirical investigations, theoretical engineering frameworks, mathematical models, or structured conceptual developments related to supply chain resilience
- They specifically addressed textile, apparel, garment, manufacturing, or closely related industrial supply chains
- They investigated engineering approaches related to physical flexibility, predictive analytics, Industry 4.0 technologies, digital twins, and digital supply chain systems

Studies were excluded if they:

- consisted primarily of descriptive industry reports without scientific methodology;
- focused exclusively on agricultural production without relevance to manufacturing systems;
- lacked peer-review;
- provided insufficient methodological or conceptual detail to support engineering analysis.

3.5 Data Extraction and Critical Synthesis

Following article selection, each publication was examined using a structured data extraction framework. Information recorded from each study included:

- research objective;
- engineering methodology;
- technological approach;
- supply chain application;
- principal findings;

- operational advantages;
- engineering limitations.

The extracted information formed the basis for comparative synthesis across studies. Rather than reporting individual findings in isolation, studies were analyzed comparatively to identify recurring engineering themes, technological convergence, methodological differences, and unresolved research challenges. To provide an overview of the geographical distribution of the reviewed literature, the countries of the authors' affiliations were extracted from each included publication. For studies involving multiple-country collaborations, each country was counted once per study after standardizing country names and removing non-geographic descriptors. The resulting country-level publication frequencies were visualized using a choropleth world map (Figure 3) and a publication trend (Figure 4), providing a descriptive bibliometric overview of the global distribution of research contributions.

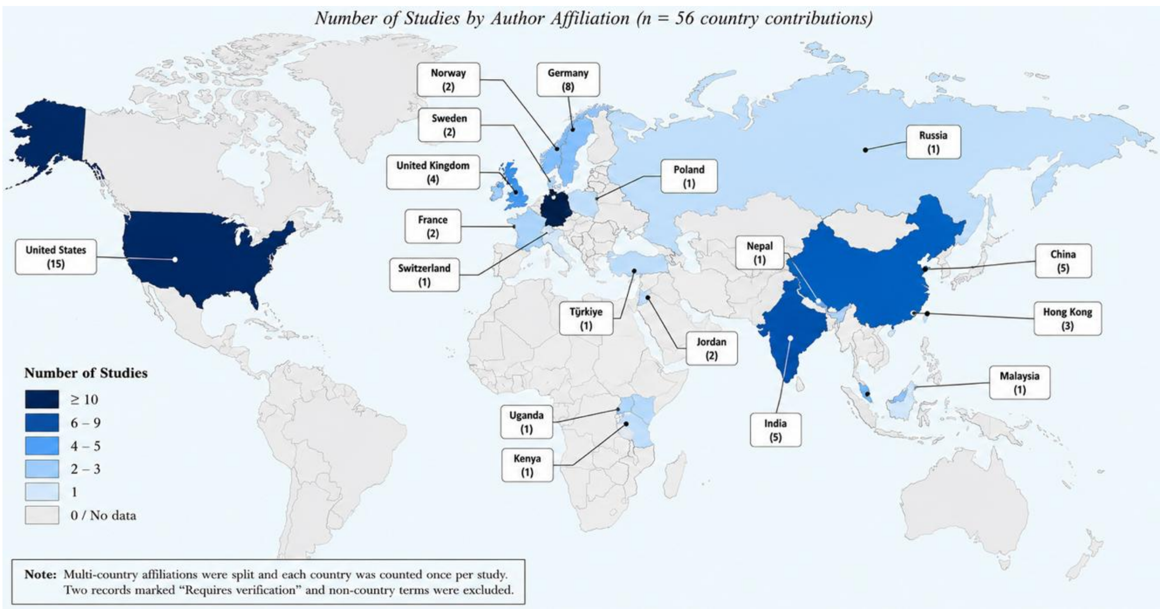


Figure 3: Global distribution of author affiliations among the 42 reviewed studies.

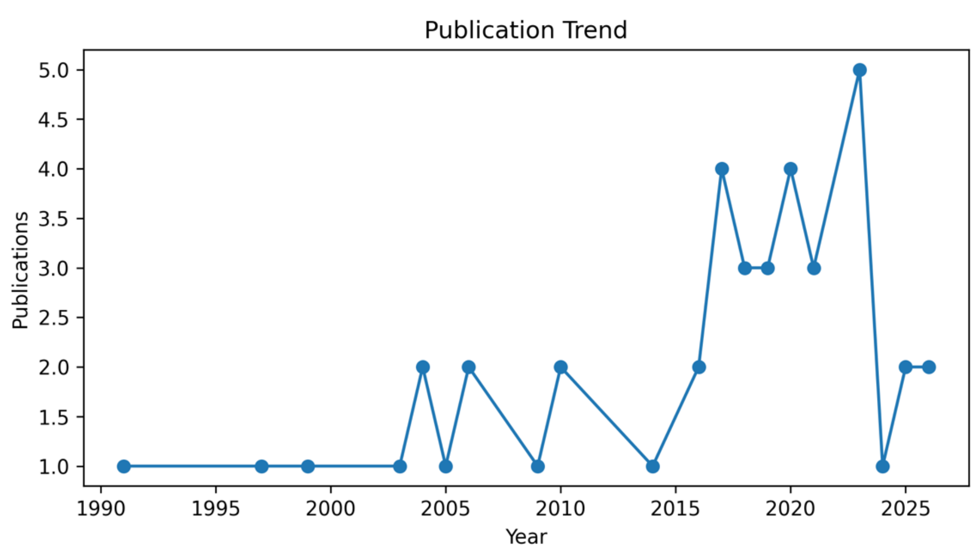


Figure 4: Publication Trend of the 42 Reviewed Studies

3.6 Methodological Limitations

Although a structured review methodology was employed, several limitations should be acknowledged. First, the review primarily considered peer-reviewed English-language publications indexed within major academic databases, which may have excluded relevant studies published in other languages or non-indexed sources. Second, because this study is a narrative review rather than a quantitative meta-analysis, no statistical synthesis of effect sizes was performed. Finally, engineering technologies such as digital twins, predictive analytics, and Industry 4.0 continue to evolve rapidly, so newly emerging developments may not be fully represented in the current evidence base. Despite these limitations, the structured search strategy, clearly defined inclusion criteria, and comparative analytical approach provide a transparent and reproducible foundation for synthesizing the current state of engineering knowledge regarding resilient textile and apparel supply chains.

4. Results and Discussion

4.1 Engineering Evolution of Supply Chain Resilience

The comparative analysis of the reviewed studies reveals a clear evolution in the engineering philosophy of supply chain resilience within the textile and apparel industry. Recent developments indicate a progressive transition from static protection mechanisms to adaptive engineering systems that can anticipate, respond to, and recover from disruptions with increasing autonomy. This evolution reflects a fundamental shift in resilience engineering, where operational continuity is no longer achieved solely through physical redundancy but through the integration of digital intelligence and real-time system coordination (Figure 5).

Early resilience strategies primarily relied on physical engineering solutions such as inventory buffers, supplier diversification, production redundancy, and late-stage postponement to maintain operational continuity during localized disruptions (Christopher & Peck, 2004; Sheffi & Rice, 2006). These approaches improved system robustness by providing additional capacity to absorb unexpected disturbances; however, they also introduced considerable economic penalties through increased inventory holding costs, underutilized manufacturing capacity, and reduced operational efficiency. The reviewed literature consistently indicates that such approaches remain effective for managing isolated disruptions but become increasingly inadequate when multiple disturbances occur simultaneously across geographically dispersed production networks (Blackhurst et al., 2005; Ivanov, 2020).

A second stage of resilience development emphasized collaborative coordination and information sharing across supply chain partners. The introduction of integrated planning systems and closer supplier relationships enabled organizations to improve visibility across multiple operational tiers, reducing uncertainty and facilitating faster responses to emerging disruptions (Pettit et al., 2010; Soni et al., 2014). Nevertheless, these coordination-based strategies remained largely reactive because decisions continued to depend on historical information rather than predictive operational intelligence. Consequently, although communication efficiency improved, engineering systems still struggled to anticipate rapidly evolving disruption scenarios before operational performance deteriorated.

The most significant transformation identified across the reviewed studies is the emergence of digitally enabled resilience supported by predictive analytics and cyber-physical engineering technologies. Unlike traditional resilience strategies that respond after disruptions have occurred, predictive analytics enables manufacturing organizations to estimate future operational conditions by continuously analysing production, logistics, and demand data (Choi et al., 2018; Wahab et al., 2021). Simultaneously, digital twin technologies create continuously synchronized virtual representations of physical manufacturing systems, allowing engineers to evaluate alternative production schedules, transportation routes, and inventory allocation strategies before implementing operational decisions within the physical network (Ivanov & Dolgui, 2021; Ivanov et al., 2019). The reviewed literature demonstrates that this combination transforms resilience from a reactive operational capability into a predictive engineering function that supports proactive system adaptation.

Another important observation emerging from the comparative analysis is the increasing convergence between physical manufacturing flexibility and digital decision support. Earlier resilience models frequently treated physical and digital capabilities as independent strategies. In contrast, recent engineering studies consistently demonstrate that the highest levels of resilience are achieved when physical flexibility mechanisms are coordinated through real-time analytical systems. For example, supplier diversification is considerably more effective when supported by predictive demand forecasting, while postponement strategies achieve greater operational efficiency when integrated with digital twin simulations that evaluate multiple production scenarios under uncertainty (Choi, 2020; Ivanov & Dolgui, 2021). These findings indicate that resilience should no longer be interpreted as a collection of independent risk-mitigation practices but rather as an integrated engineering capability arising from the interaction among physical infrastructure, operational data, and intelligent decision-support systems.

The analysis also highlights substantial differences in technology adoption across manufacturing environments. Large multinational apparel manufacturers increasingly possess the technological infrastructure required to implement predictive analytics, cloud-based information systems, and digital engineering platforms. Conversely, many small and medium-sized manufacturers continue to rely on conventional planning approaches due to limited digital infrastructure, fragmented supplier networks, and constrained investment capacity (Luthra & Mangla, 2018; Nayak et al., 2023). Consequently, the engineering challenge is no longer solely the development of advanced digital technologies but also their practical adaptation to resource-constrained manufacturing environments that characterize much of the global apparel industry.

Overall, the reviewed evidence demonstrates that supply chain resilience has evolved from a static inventory-oriented concept into a dynamic engineering capability supported by predictive analytics, digital integration, and adaptive operational control. Rather than replacing traditional resilience strategies, digital technologies increasingly complement physical flexibility by providing continuous situational awareness, predictive decision support, and enhanced coordination across complex manufacturing networks. This evolution establishes the engineering foundation for the comparative assessment of physical and digital resilience strategies presented in the following section.

Traditional Resilience

(Inventory Buffers

Supplier Redundancy

Safety Stock)

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Collaborative Resilience

(Information Sharing

Integrated Planning

Supplier Coordination)

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Digital Resilience

(Predictive Analytics

IoT

Real-Time Visibility)

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Adaptive Engineering Resilience

(Digital Twin

AI Decision Support

Dynamic Optimization

Self-Healing Supply Networks)

Figure 5. Evolution of engineering paradigms for supply chain resilience in the textile and apparel industry. *The reviewed literature indicates a progressive transition from inventory-based resilience strategies toward adaptive engineering systems supported by predictive analytics, cyber-physical technologies, and digital twins. Modern resilience is increasingly achieved through the integration of physical manufacturing flexibility and intelligent digital decision-support systems rather than through redundancy alone.*

4.2 Knowledge Flow from Resilience Strategies to Engineering Outcomes

To further synthesize the reviewed literature, a Sankey diagram was developed to illustrate the conceptual flow linking resilience strategies, enabling digital technologies, and engineering outcomes identified across the selected studies. Unlike the chord diagram, the Sankey diagram presents the directional relationships that characterize how conventional resilience practices are operationalized through digital technologies to achieve resilient supply chain performance. As shown in Figure 6, traditional resilience strategies, including forecasting, risk control, recovery, optimization, flexibility, integration, logistics coordination, supplier coordination, traceability, and decision support, are closely associated with a range of digital technologies such as predictive analytics, digital twins, Industry 4.0, blockchain-enabled traceability, the Internet of Things (IoT), big data analytics, cloud computing, and artificial intelligence. These technologies serve as enabling mechanisms that transform conventional operational practices into data-driven engineering capabilities supporting resilient manufacturing systems (Choi et al., 2018; Hofmann & Rüsch, 2017; Ivanov & Dolgui, 2021).

The diagram further demonstrates that these digital technologies collectively contribute to several engineering outcomes, including decision support, simulation, optimization, operational visibility, traceability, and structural resilience. Predictive analytics primarily supports forecasting and engineering decision-making through disruption prediction and demand forecasting (Choi et al., 2018; Wahab et al., 2021). Digital twin technology contributes to simulation-based optimization and adaptive production planning, while Industry 4.0 technologies improve system integration and operational visibility through real-time information exchange (Ivanov et al., 2019; Al-Okaily et al., 2024). Likewise, blockchain-enabled traceability strengthens transparency and supplier coordination by improving information reliability across distributed supply networks (Kshetri, 2018; Zhu et al., 2023).

Overall, the Sankey diagram illustrates that resilient textile and apparel supply chains are achieved through a sequential integration of resilience strategies, digital technologies, and engineering capabilities. Rather than operating independently, these components form an interconnected pathway that enables adaptive decision-making, improves operational visibility, and enhances manufacturing systems' capacity to anticipate, respond to, and recover from disruptions.

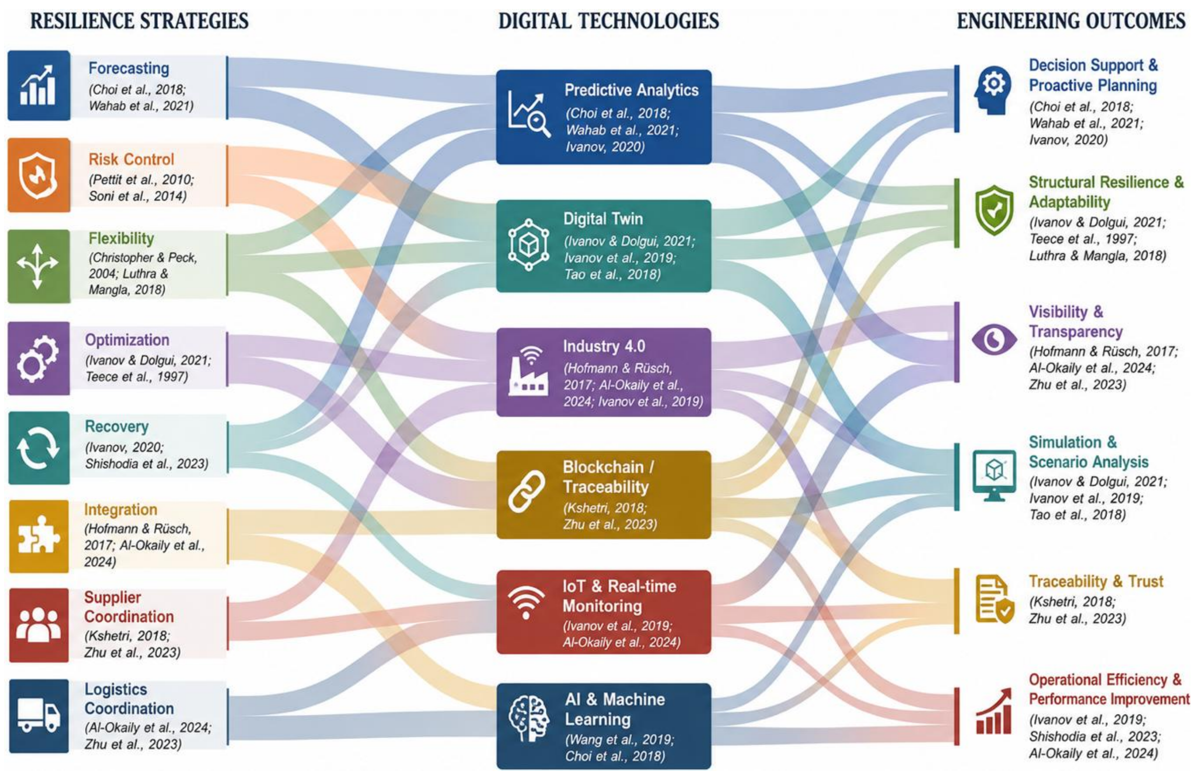

Figure 6. Sankey diagram illustrating the conceptual flow from resilience strategies to digital technologies and engineering outcomes in textile and apparel supply chains. *The diagram summarizes the relationships identified across the reviewed literature, showing how conventional resilience strategies are enabled by emerging digital technologies, including predictive analytics, digital twins, Industry 4.0, blockchain-enabled traceability, IoT, big data analytics, cloud computing, and artificial intelligence, to support engineering outcomes such as decision support, simulation, optimization, visibility, traceability, and structural resilience.*

4.3 Comparative Assessment of Physical and Digital Resilience Strategies

The comparative evaluation of the reviewed literature demonstrates that no single engineering strategy is sufficient to achieve resilient supply chain operation under increasingly complex disruption scenarios. Instead, resilience emerges through the complementary integration of physical manufacturing flexibility and digitally enabled operational intelligence. While conventional resilience mechanisms continue to play an important role in mitigating localized disruptions, recent engineering developments increasingly emphasize predictive decision support, continuous system visibility, and adaptive operational control as essential capabilities for managing interconnected global supply networks.

Traditional engineering approaches primarily improve resilience through physical redundancy. Strategies such as safety stock accumulation, supplier diversification, production capacity buffering, and postponement provide manufacturing systems with sufficient operational flexibility to absorb temporary disruptions without immediate production failure (Christopher & Peck, 2004; Tang, 2006). These approaches remain particularly valuable in textile and apparel manufacturing because they reduce dependency on individual suppliers and maintain production continuity during short-term logistics interruptions. However, the comparative evidence consistently indicates that physical redundancy alone becomes progressively less effective as disruptions increase in scale, duration, and geographical extent. Maintaining large inventory buffers and redundant production capacity also introduces considerable financial costs, making such approaches difficult to sustain within an industry characterized by intense price competition and relatively low operating margins (Blackhurst et al., 2005; Sreedevi & Saranga, 2017).

In contrast, digital resilience strategies focus on improving engineering decision-making through continuous data acquisition, predictive modelling, and real-time operational visibility. Predictive analytics enables organizations to identify disruption patterns before they develop into operational failures by analysing historical production data together with continuously updated operational information (Choi et al., 2018; Wahab et al., 2021). Similarly, digital twin technologies provide engineering teams with dynamic simulation environments that evaluate alternative production schedules, logistics routes, and inventory allocation decisions under changing operational conditions (Ivanov & Dolgui, 2021; Ivanov et al., 2019). Rather than increasing physical redundancy, these technologies improve the quality and speed of engineering decisions, allowing manufacturing systems to respond proactively to emerging disruptions.

The reviewed studies consistently demonstrate that physical and digital resilience should not be viewed as competing approaches. Instead, they perform complementary engineering functions within resilient manufacturing systems. Physical flexibility provides the operational capacity required to accommodate unexpected disturbances, whereas digital technologies improve the effectiveness with which that capacity is utilized. For example, supplier diversification remains significantly more effective when predictive analytics identifies potential supplier disruptions before production schedules are affected. Likewise, postponement strategies achieve greater operational efficiency when digital twin simulations evaluate multiple manufacturing scenarios using real-time production information. Consequently, digital technologies enhance the engineering value of traditional resilience mechanisms rather than replacing them.

Another important finding concerns the trade-off between implementation complexity and operational benefit. Conventional resilience strategies generally require relatively simple organizational changes and limited technological infrastructure, making them suitable for small and medium-sized manufacturers. Conversely, predictive analytics, digital twins, and integrated Industry 4.0 platforms require substantial investments in digital infrastructure, data integration, and technical expertise (Hofmann & Rüsch, 2017; Luthra & Mangla, 2018). Although these technologies offer considerably greater operational visibility and decision-support capabilities, their implementation remains challenging for many apparel manufacturers operating within fragmented global supply networks. This observation suggests that the practical adoption of digital resilience should be viewed as a gradual engineering transition rather than a complete replacement of conventional manufacturing practices.

Collectively, the comparative evidence indicates that resilient apparel supply chains are increasingly characterized by hybrid engineering architectures that combine physical flexibility with digital intelligence (Table 2 and Figure 7). Such integrated systems maintain sufficient manufacturing adaptability while simultaneously utilizing predictive analytics and cyber-physical technologies to improve operational awareness, optimize engineering decisions, and reduce disruption recovery time. Therefore, future engineering development should prioritize the integration of physical manufacturing capabilities with intelligent digital decision-support systems rather than focusing exclusively on either physical redundancy or technological innovation.

Table 2. Comparative Engineering Assessment of Supply Chain Resilience Strategies

Engineering Strategy	**Primary Engineering Function**	**Advantages**	**Limitations**	**Engineering Contribution**
Safety Stock	Inventory buffering	Immediate disruption absorption	High inventory cost	Improves short-term robustness
Supplier Diversification	Supply continuity	Reduces supplier dependency	Increased coordination complexity	Enhances sourcing flexibility
Capacity Redundancy	Production flexibility	Maintains manufacturing continuity	Underutilized resources	Supports rapid production recovery
Postponement Strategy	Production flexibility	Reduces demand uncertainty	Requires flexible manufacturing systems	Improves production responsiveness
Predictive Analytics	Demand and disruption forecasting	Early risk identification	Data quality dependency	Enables proactive decision making
Digital Twin	Real-time system simulation	Scenario evaluation and optimization	High implementation complexity	Supports adaptive engineering decisions

Integrated Physical–Digital Strategy	Combined operational flexibility and intelligence	High resilience and operational efficiency	Requires organizational and technological integration	Enables adaptive and resilient manufacturing systems

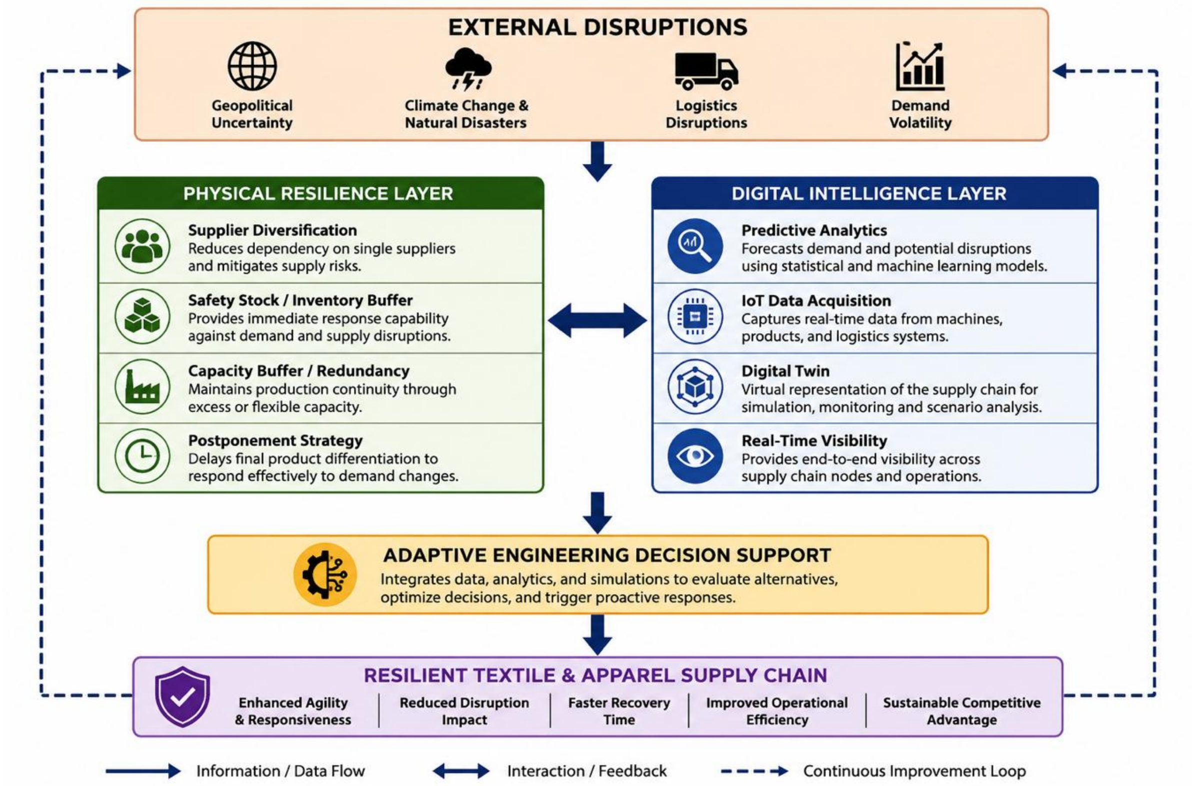

Figure 7. Comparative framework of conventional and digitally enabled resilience strategies. *The reviewed literature suggests that resilient manufacturing systems are achieved by combining conventional physical flexibility mechanisms with digitally enabled predictive analytics and engineering decision-support technologies. Physical resilience provides operational capacity, whereas digital intelligence improves the effectiveness, responsiveness, and adaptability of engineering decisions under disruption.*

4.4 Technology Readiness and Engineering Challenges

The comparative evaluation of the reviewed studies indicates that the maturity of resilience technologies varies considerably across the textile and apparel industry. While predictive analytics, digital twins, and Industry 4.0 technologies have demonstrated substantial engineering potential, their industrial implementation remains uneven due to differences in digital infrastructure, organizational capability, and manufacturing complexity. Consequently, the current challenge is no longer the conceptual validation of these technologies but their practical deployment within highly fragmented and cost-sensitive production environments.

A consistent finding across the reviewed literature is that predictive analytics has reached a relatively advanced level of technological maturity compared with other digital resilience solutions. Machine learning-based forecasting techniques are increasingly capable of processing large volumes of production, logistics, and demand data to improve operational planning and disruption prediction (Choi et al., 2018; Wahab et al., 2021). Nevertheless, forecasting performance remains highly dependent on data availability and quality. The apparel industry presents a particularly difficult environment because short product life cycles, frequent design changes, and seasonal collections often generate limited historical observations for newly introduced products. This "cold-start" condition reduces forecasting reliability and limits the practical effectiveness of conventional predictive models for fashion-oriented manufacturing (Choi, 2020; Hemingray et al., 2023). Consequently, improving prediction under sparse-data conditions remains an important engineering challenge.

Digital twin technology exhibits substantial potential to improve operational resilience through real-time simulation and engineering decision support; however, its industrial maturity remains lower than that of predictive analytics. Successful implementation requires continuous synchronization between physical manufacturing systems and their virtual representations, demanding reliable data acquisition, interoperable information systems, and continuous model updating (Ivanov & Dolgui, 2021; Ivanov et al., 2019). These technical requirements can generally be satisfied within highly automated manufacturing environments but become considerably more difficult in globally distributed apparel supply networks characterized by heterogeneous production technologies and varying levels of digital capability. As a result, many digital twin applications remain confined to pilot implementations or selected operational processes rather than enterprise-wide deployment.

Another challenge emerging consistently from the reviewed studies concerns system interoperability. Modern apparel supply chains comprise multiple independent organizations employing different enterprise systems, planning platforms, and data standards. Integrating operational information across suppliers, manufacturers, logistics providers, and retailers therefore remains technically demanding, particularly when real-time data exchange is required for predictive decision making. Incomplete information sharing reduces the effectiveness of predictive analytics and limits the accuracy of digital twin simulations, thereby constraining the overall engineering performance of digitally enabled resilience systems (Hofmann & Rüsch, 2017; Kshetri, 2018).

Economic feasibility represents an additional engineering constraint. Unlike highly automated industries, many apparel manufacturers operate in low-margin business environments where investment decisions are strongly influenced by implementation costs and expected operational returns (Luthra & Mangla, 2018; Nayak et al., 2023). Although advanced sensing infrastructure, cloud platforms, and cyber-physical systems provide significant improvements in operational visibility, their adoption frequently requires substantial capital investment, specialized technical expertise, and organizational restructuring. Consequently, smaller manufacturers often continue to rely on conventional planning approaches despite the demonstrated benefits of digital resilience technologies.

The reviewed literature further indicates that future resilience engineering should prioritize scalable and economically feasible digital solutions rather than increasingly sophisticated technological architectures alone. The challenge is not simply developing more advanced predictive models or higher-fidelity digital twins but designing engineering solutions that can be effectively deployed across diverse manufacturing environments with varying technological capabilities. Lightweight digital twins, modular analytics platforms, and flexible data integration approaches may therefore represent more practical directions for improving resilience in the textile and apparel industry than highly complex engineering systems that require extensive technological infrastructure.

Overall, the findings demonstrate that the future development of resilient apparel supply chains depends on balancing technological capability with implementation feasibility (Table 3 and Figure 8). Engineering solutions must provide sufficient analytical sophistication to improve operational decision making while remaining economically sustainable and technically deployable across globally distributed manufacturing systems. Addressing this balance will be essential for translating the theoretical benefits of Industry 4.0 technologies into practical improvements in supply chain resilience.

Table 3: Technology Readiness and Engineering Challenges of Digital Resilience Technologies

Technology	Current Engineering Readiness	Principal Engineering Challenge	Practical Implication
Predictive Analytics	High	Limited historical data for new products	Reduced forecasting accuracy under cold-start conditions
Digital Twin	Moderate	Real-time synchronization of physical and virtual systems	Limited large-scale implementation
IoT-enabled Monitoring	Moderate–High	Infrastructure deployment and interoperability	Inconsistent real-time visibility
Cloud-based Information Systems	High	Cross-organizational data integration	Data sharing constraints

Industry 4.0 Integration	Moderate	High implementation cost and organizational complexity	Uneven adoption across manufacturers

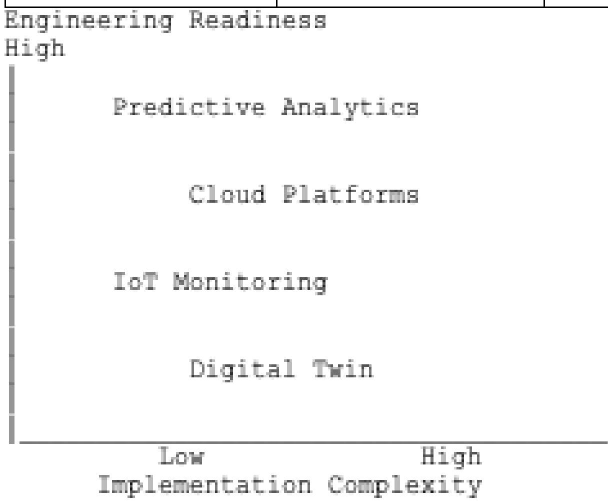

Figure 8. Technology readiness and implementation complexity of engineering resilience technologies. *The reviewed studies indicate that predictive analytics has achieved a comparatively high level of engineering maturity, whereas digital twins remain constrained by implementation complexity and infrastructure requirements. Future research should focus on improving scalability and cost-effective deployment across fragmented manufacturing systems.*

4.5 Integrated Engineering Framework and Future Research Directions

The preceding analysis demonstrates that future advances in supply chain resilience will depend less on the development of individual digital technologies than on their systematic integration within engineering decision-support systems. Although predictive analytics, digital twins, and Industry 4.0 technologies have each demonstrated significant potential to improve operational resilience, the reviewed literature indicates that these technologies are often examined in isolation. Such fragmented approaches fail to leverage the complementary relationships among predictive intelligence, operational simulation, and adaptive engineering control that are necessary to manage complex manufacturing networks amid dynamic disruption.

Based on the synthesis of the reviewed studies, this review proposes an integrated engineering framework that positions supply chain resilience as the outcome of continuous interaction between operational data, analytical intelligence, engineering optimization, and adaptive manufacturing execution. Rather than viewing resilience as a static capability or a collection of isolated risk mitigation strategies, the proposed framework conceptualizes resilience as a dynamic engineering process in which operational decisions are continuously updated according to changing internal and external conditions. Within this process, predictive analytics functions as the primary mechanism for identifying emerging disruption risks, while digital twin technologies evaluate alternative operational responses before physical implementation. Engineering optimization subsequently translates analytical insights into practical production, logistics, and inventory decisions that maintain system performance despite evolving operational uncertainty.

A central finding emerging from this review is that the effectiveness of advanced digital technologies depends fundamentally on the quality of operational integration rather than technological sophistication alone. Predictive models cannot produce reliable forecasts without timely and accurate operational data, while digital twins cannot generate meaningful engineering simulations without continuous synchronization with physical manufacturing systems. Consequently, future research should prioritize the development of interoperable engineering architectures capable of integrating heterogeneous manufacturing information from suppliers, production facilities, logistics providers, and distribution networks into unified decision-support environments. Such integration represents a prerequisite for achieving adaptive and self-regulating supply chain systems.

The review also highlights the importance of developing resilience solutions that are technically scalable and economically feasible. Current engineering research frequently assumes the availability of sophisticated sensing infrastructure, comprehensive digital connectivity, and substantial computational resources. These assumptions are often inconsistent with the operational realities of many textile and apparel manufacturers, particularly those operating within developing economies where digital infrastructure and investment capacity remain limited (Luthra & Mangla, 2018; Nayak et al., 2023). Therefore, future engineering research should focus on designing modular, cost-effective digital solutions that can progressively enhance resilience without requiring a complete technological transformation. Incremental implementation strategies are likely to achieve broader industrial adoption than highly integrated but capital-intensive engineering systems.

Another research priority concerns the integration of engineering optimization with predictive decision support. Although many existing studies demonstrate the forecasting capability of predictive analytics or the simulation capability of digital twins, relatively few investigate how these technologies can collectively support real-time optimization of production scheduling, inventory allocation, transportation planning, and resource utilization under simultaneous disruption scenarios. Future research should therefore move beyond technology evaluation toward the development of integrated engineering decision frameworks that coordinate multiple operational decisions across interconnected manufacturing systems.

Overall, the evidence synthesized in this review suggests that future resilient supply chains will increasingly operate as adaptive cyber-physical systems in which operational information continuously drives engineering decision making (Figure 9 and Table 4). Rather than replacing conventional manufacturing capabilities, digital technologies should augment physical flexibility through predictive intelligence, dynamic simulation, and optimization-based decision support. The proposed framework, therefore, provides a conceptual roadmap for future engineering research by emphasizing the integration of operational data, analytical capability, engineering optimization, and adaptive manufacturing control as the principal components of resilient textile and apparel supply chains.

Integrated Engineering Framework for Adaptive Supply Chain Resilience

External Disruptions

(Demand • Climate • Logistics • Geopolitical)

|

▼

Operational Data Acquisition

(Production • Inventory • Logistics • Suppliers)

|

▼

Predictive Analytics Engine

(Demand Forecasting • Risk Prediction)

|

▼

Digital Twin Simulation Layer

(Scenario Analysis • Capacity Evaluation • Routing)

|

▼

Engineering Optimization Layer

(Production Scheduling • Inventory Allocation

Resource Planning • Logistics Coordination)

|

▼

Adaptive Manufacturing Execution

|

▼

Supply Chain Resilience Outcomes

Operational Continuity; Rapid Recovery; Flexible Manufacturing; Improved Visibility; Engineering Efficiency

Figure 9. Integrated engineering framework for adaptive supply chain resilience in the textile and apparel industry. *The proposed framework synthesizes the findings of the reviewed literature by illustrating how operational data, predictive analytics, digital twin simulation, and engineering optimization interact to support adaptive manufacturing decisions and improve supply chain resilience under dynamic disruption conditions.*

Table 4: Future Engineering Research Priorities

Research Area	Current Limitation	Future Engineering Direction
Predictive Analytics	Cold-start forecasting	Hybrid prediction models for sparse data
Digital Twin	High implementation complexity	Lightweight and modular digital twins
Data Integration	Fragmented information systems	Interoperable engineering platforms
Engineering Optimization	Limited integration with AI	Real-time adaptive optimization
Manufacturing Systems	Low digital maturity	Scalable Industry 4.0 implementation
Supply Chain Resilience	Independent technology adoption	Integrated cyber-physical resilience systems

5. Conclusion

This narrative review critically synthesized recent advances in supply chain resilience engineering within the textile and apparel industry, with particular emphasis on the integration of predictive analytics, digital twin technologies, and Industry 4.0 systems. The reviewed evidence demonstrates that resilience has evolved from a traditional reliance on inventory redundancy and supplier diversification toward adaptive engineering systems capable of continuously monitoring operational conditions, predicting disruption risks, and supporting dynamic manufacturing and logistics decisions. Rather than replacing conventional resilience strategies, digital technologies increasingly complement physical manufacturing flexibility by enhancing operational visibility, engineering decision support, and system adaptability across complex supply networks. The comparative analysis further indicates that predictive analytics and digital twins represent complementary engineering capabilities rather than independent technological solutions. Predictive analytics enables proactive identification of operational risks and demand variability, whereas digital twins provide virtual simulation environments that support scenario evaluation, production scheduling, and resource optimization before implementing operational changes. Their combined application enables resilient manufacturing systems to respond more effectively to disruptions, improve operational efficiency, and reduce recovery time. However, the review also highlights that successful implementation depends on reliable data integration, interoperable information systems, and scalable digital infrastructures, challenges that remain particularly significant for low-margin and digitally fragmented apparel manufacturing environments.

A principal contribution of this review is the development of an integrated engineering framework that conceptualizes resilience as a dynamic interaction between operational data, predictive analytics, digital twin simulation, engineering optimization, and adaptive manufacturing execution. This framework extends existing resilience research by demonstrating that sustainable operational performance is achieved through the coordinated integration of physical flexibility and digital intelligence rather than through isolated technological or organizational interventions. By synthesizing engineering evidence across multiple research streams, the proposed framework provides a structured foundation for understanding how emerging digital technologies can collectively strengthen manufacturing resilience. The review also identifies several important directions for future engineering research. These include the development of lightweight and economically scalable digital twin architectures, improved predictive models for cold-start forecasting under limited historical data, interoperable data integration platforms across multi-tier supply networks, and optimization-driven decision-support systems capable of coordinating production, inventory, and logistics under simultaneous disruption scenarios. Addressing these challenges will be essential for translating the theoretical capabilities of Industry 4.0 technologies into practical engineering solutions applicable across diverse manufacturing environments.

Overall, the findings demonstrate that future textile and apparel supply chains will increasingly operate as adaptive cyber-physical systems in which continuous data acquisition, predictive intelligence, engineering optimization, and real-time decision support function as an integrated resilience architecture. Such engineering systems provide a practical pathway toward improving operational continuity, manufacturing flexibility, and long-term competitiveness under increasingly uncertain global operating conditions.

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References

[1] Al-Okaily, M., Younis, H., & Al-Okaily, A. (2024). The impact of management practices and industry 4.0 technologies on supply chain sustainability: a systematic review. *Heliyon*, *10*(17).
[2] Alghababsheh, M. (2023). Enhancing supply chain resilience in SMEs: The role of business and political ties. *Business Process Management Journal*, *29*(5), 1303-1329.
[3] Barney, J. (1991). Firm resources and sustained competitive advantage. *Journal of management*, *17*(1), 99-120.
[4] Bentze, T., & Wollburg, P. (2025). A longitudinal cross-country dataset on agricultural productivity and welfare in Sub-Saharan Africa. *Scientific Data*, *12*(1), 1843.
[5] Bessant, J. (2020). *Making-up people: Youth, truth and politics*. Routledge.
[6] Blackhurst, J., Craighead, C. W., Elkins, D., & Handfield, R. B. (2005). An empirically derived agenda of critical research issues for managing supply-chain disruptions. *International journal of production research*, *43*(19), 4067-4081.
[7] Choi, T. M. (2020). Innovative "bring-service-near-your-home" operations under corona-virus (COVID-19/SARS-CoV-2) outbreak: can logistics become the messiah?. *Transportation Research Part E: Logistics and Transportation Review*, *140*, 101961.
[8] Choi, T. M., Wallace, S. W., & Wang, Y. (2018). Big data analytics in operations management. *Production and operations management*, *27*(10), 1868-1883.
[9] Christopher, M., & Peck, H. (2004). Building the resilient supply chain. *International Journal of Logistics Management*, 15(2), 1-14.
[10] Durach, C. F., Kembro, J., & Wieland, A. (2017). A new paradigm for systematic literature reviews in supply chain management. *Journal of Supply Chain Management*, *53*(4), 67-85.
[11] Geng, R. (2017). *An investigation of the adoption of green supply chain management practices in manufacturing sector in Asian emerging economies: Guanxi, antecedents and performance* (Doctoral dissertation, Brunel University London).
[12] Gereffi, G. (1999). International trade and industrial upgrading in the apparel commodity chain. *Journal of international economics*, *48*(1), 37-70.
[13] Hemingray, C., Vazirian, M., Kang, Z., & Lyness, R. (2023). Consumer Acceptance of Digital Fashion Garments: A Cross-Generational Study. *TBC*.
[14] Hofmann, E., & Rüsch, M. (2017). Industry 4.0 and the current status as well as future prospects on logistics. *Computers in industry*, *89*, 23-34.
[15] Imtiaz, N., & Rahman, K. (2026). From global EdTech adoption to AI-driven learning equity: A cross-cultural framework for U.S. higher education. *Journal of Adaptive Learning Technologies, 3*(3), 55–69. https://scientificbulletin.com/index.php/JALT/article/view/1979

[16] Imtiaz, N., Kundu, T. R., Roy, A., Bhuiyan, M. I., Rahman, K., & Islam, M. K. (2025). Governance readiness beyond predictive performance: An empirical benchmark for higher-education early warning systems. *Frontiers in Computer Science and Artificial Intelligence, 4*(5), 49–65.

[17] Imtiaz, N., Zannat, F., Vengaladas, M. K., Mahmud, S., & Hasan, M. A. (2025). Transforming business analytics: The impact of machine learning on performance prediction in U.S. financial sectors. *Journal of Business Insight and Innovation, 4*(1), 61–72. https://insightfuljournals.com/index.php/JBII/article/view/45

[18] Islam, A., Miah, M., Akhir, A., Munni, A., Jahan, I., & Nashid, S. (2026). Benchmarking machine learning models for real-time fraud detection in digital banking transactions. *Journal of Posthumanism, 6*(4), 97–135. https://doi.org/10.63332/joph.v6i4.4159

[19] Ivanov, D. (2020). Predicting the impacts of epidemic outbreaks on global supply chains: A simulation-based analysis on the coronavirus outbreak (COVID-19/SARS-CoV-2) case. *Transportation Research Part E: Logistics and Transportation Review*, *136*, 101922.

[20] Ivanov, D., & Dolgui, A. (2021). A digital supply chain twin for managing the disruption risks and resilience in the era of Industry 4.0. *Production Planning & Control*, *32*(9), 775-788.

[21] Ivanov, D., Dolgui, A., & Sokolov, B. (2019). The impact of digital technology and Industry 4.0 on the ripple effect and supply chain risk analytics. *International journal of production research*, *57*(3), 829-846.

[22] Johnson, A. R., Johnson, M. E., & Nagarur, N. (2021). Supply chain design under disruptions considering risk mitigation strategies for robustness and resiliency. *International Journal of Logistics Systems and Management*, *38*(1), 1-29.

[23] Kaya, F., Demir, S., Dedeoğlu, M., Başayiğit, L., Ünal, Y., Yürük Sonuç, C., ... & Çakmak, E. G. (2026). Multi-Crop Yield Estimation and Spatial Analysis of Agro-Climatic Indices Based on High-Resolution Climate Simulations in Türkiye's Lakes Region, a Typical Mediterranean Biogeography. *Agronomy*, *16*(3), 321.

[24] Kshetri, N. (2018). 1 Blockchain's roles in meeting key supply chain management objectives. *International Journal of information management*, *39*, 80-89.

[25] Lee, H. L. (2004). The triple-A supply chain. *Harvard business review*, *82*(10), 102-113.

[26] Li, G., Li, L., Choi, T. M., & Sethi, S. P. (2020). Green supply chain management in Chinese firms: Innovative measures and the moderating role of quick response technology. *Journal of Operations Management*, *66*(7-8), 958-988.

[27] Luthra, S., & Mangla, S. K. (2018). Evaluating challenges to Industry 4.0 initiatives for supply chain sustainability in emerging economies. *Process safety and environmental protection*, *117*, 168-179.

[28] MacCarthy, B. L., Blome, C., Olhager, J., Srai, J. S., & Zhao, X. (2016). Supply chain evolution–theory, concepts and science. *International Journal of Operations & Production Management*, *36*(12), 1696-1718.

[29] Magalhaes, M., Bryan, E., Ringler, C., & Nyukuri, E. (2025). *Understanding the policy landscape for climate action in Kenya: Potential for integration of gender, nutrition, and improved impact monitoring*. Intl Food Policy Res Inst.

[30] Min, S., Zacharia, Z. G., & Smith, C. D. (2019). Defining supply chain management: In the past, present, and future. *Journal of business logistics*, *40*(1), 44-55.

[31] Moya, A. A., Tukamuhabwa, B. R., & Kyagante, F. (2026). Enhancing supply chain resilience in agro-food processing firms: investigating the mediating role of supply chain traceability on information technology capabilities in a developing country. *Continuity & Resilience Review*, *8*(1), 54-74.

[32] Munni, A. (2022). Artificial intelligence in project management: A systematic review of applications, challenges, and future directions. *Frontiers in Computer Science and Artificial Intelligence, 1*(1), 68–78.

[33] Munni, A., & Mashaka, G. P. (2026). Machine learning for environmental antimicrobial resistance risk prediction. *International Journal of Digital Health and Telemedicine, 2*(1). https://doi.org/10.51137/wrp.ijdht.550

[34] Nafiz Imtiaz, Zannat, F., Ahmed, S., Hasan, M. A., & Mahmud, S. (2025). Leveraging AI for data-driven decision making and automation in the USA education sector. *Journal of Economics, Management & Business Administration, 4*(1), 87–106. https://www.journals.airsd.org/index.php/jemba/article/view/551

[35] Nayak, D., Singh, M., Pant, M., & Jauhar, S. K. (2023). Efficient supplier selection in the era of industry 4.0. In *Digital transformation and industry 4.0 for sustainable supply chain performance* (pp. 191-205). Cham: Springer International Publishing.

[36] Papri, N. K., Haque, M. K. A., & Mouwa, Z. (2022). Climate-adaptive sustainable apparel supply chains: Integrating machine learning, digitalization, and circular economy. *Journal of Primeasia, 3*(1), 1–16. https://doi.org/10.25163/primeasia.3110730

[37] Pettit, T. J., Fiksel, J., & Croxton, K. L. (2010). Ensuring supply chain resilience: development of a conceptual framework. *Journal of business logistics*, *31*(1), 1-21.

[38] Pfohl, H. C., Köhler, H., & Thomas, D. (2010). State of the art in supply chain risk management research: empirical and conceptual findings and a roadmap for the implementation in practice. *Logistics research*, *2*(1), 33-44.

[39] Rahman, M. (2026, March 20). *Sustainable textile materials and their role in shaping contemporary apparel design practices*. SSRN. https://doi.org/10.2139/ssrn.6653078

[40] Rahman, M., & Chowdhary, U. (2024, August 23). *Comparison of 100% cotton and blend for selected performance attributes*. SSRN. https://doi.org/10.2139/ssrn.6365698

[41] Rahman, M., & Forhad, M. R. (2021). Sustainable biomaterials for next-generation textile applications: Emerging fibers, biopolymers, and advanced fabrication strategies—A review. *Journal of Primeasia, 2*(1), 1–8. https://doi.org/10.25163/primeasia.2110698

[42] Rahman, M., & Lee, S.-E. (2024, February 5). *Luxury gaming experiences: An analysis of game design elements within luxury fashion brands*. SSRN. https://doi.org/10.2139/ssrn.6351299

[43] Rao, S., & Goldsby, T. J. (2009). Supply chain risks: a review and typology. *The international journal of logistics management*, *20*(1), 97-123.

[44] Sarker, A., Haque, M. K. A., & Mouwa, Z. (2022). Artificial intelligence for sustainable and climate-resilient apparel supply chains: A narrative review and integrative framework. *Frontiers in Computer Science and Artificial Intelligence, 1*(1), 79–92. https://doi.org/10.32996/fcsai.2022.1.1.9x

[45] Schrauf, S., & Berttram, P. (2016). Industry 4.0: How digitization makes the supply chain more efficient, agile, and customer-focused. *Strategy and PWC*, *9*(2016), 1-32.

[46] Sheffi, Y., & Rice Jr, J. B. (2006, November). The resilient enterprise. In *Conference on National Security, Natural Disasters, Logistics & Transportation: Assessing the Risks & the Responses, University of Rhode Island, RI, September* (pp. 25-26).

[47] Shishodia, A., Sharma, R., Rajesh, R., & Munim, Z. H. (2023). Supply chain resilience: A review, conceptual framework and future research. *The International Journal of Logistics Management*, *34*(4), 879-908.

[48] Soni, U., Jain, V., & Kumar, S. (2014). Measuring supply chain resilience using a deterministic modeling approach. *Computers & Industrial Engineering*, *74*, 11-25.

[49] Sreedevi, R., & Saranga, H. (2017). Uncertainty and supply chain risk: The moderating role of supply chain flexibility in risk mitigation. *International journal of production economics*, *193*, 332-342.

[50] Swierczek, A. (2019). Using the concept of embeddedness to theorise the resource-based competitive advantage of triadic supply chains with a structural hole. *Zeszyty Naukowe. Organizacja i Zarządzanie/Politechnika Śląska*.

[51] Tang, C. S. (2006). Perspectives in supply chain risk management. *International journal of production economics*, *103*(2), 451-488.

[52] Teece, D. J., Pisano, G., & Shuen, A. (1997). Dynamic capabilities and strategic management. *Strategic management journal*, *18*(7), 509-533.

[53] Wahab, S. N., Hamzah, M. I., Sayuti, N. M., Lee, W. C., & Tan, S. Y. (2021). Big data analytics adoption: an empirical study in the Malaysian warehousing sector. *International Journal of Logistics Systems and Management*, *40*(1), 121-144.

[54] Zhu, Z., Du, T., Li, Q., Wang, T., & Xue, Z. (2023). A systematic review of sustainability driven apparel supplier selection. *Journal of Smart Environments and Green Computing*, *3*, 47-65.

[55] Zsidisin, G. A. (2003). A grounded definition of supply risk. *Journal of purchasing and supply management*, *9*(5-6), 217-224.