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AI-Driven Computational Simulation for Enhancing Resilience in Agri-Fresh Food Supply Chains

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Abstract

Agri-Fresh Food Supply Chains (AFFSCs) face increasing disruptions due to climate variability, cold chain fragility, and shifting demand conditions. To address these challenges, recent studies have explored the integration of Artificial Intelligence (AI) techniques with simulation-based approaches to improve supply chain resilience. This paper presents a structured review of 30 peer-reviewed studies that jointly apply AI, simulation paradigms, and resilience concepts in the context of AFFSCs. The analysis classifies simulation types, AI techniques, disruption scenarios, and resilience dimensions, revealing that neural networks, machine learning, and digital twins are the most frequently applied. While adaptability and robustness are the most emphasized resilience strategies, the co-occurrence analysis of keywords highlights a conceptual disconnect between strategic goals and technical modeling approaches. The review concludes with identified research gaps and suggests that future work should focus on embedding resilience metrics directly within AI-enabled simulation frameworks, particularly through digital twins.

Keywords
Agri-Fresh Food Supply Chains, Artificial Intelligence, Simulation Paradigms, Supply Chain Resilience, Disruption Scenarios.

1.Introduction
Agri-Fresh Food Supply Chains (AFFSCs) are highly vulnerable to disruptions due to the perishability of their products and the structural complexity of their logistics networks (Ivanov 2025; Mejía et al. 2019; Zhang 2024). Events such as climate variability, transport failures, and regulatory shifts disrupt their operations, leading to food losses and increased costs (Enayati et al. 2024; Vallejo et al. 2021; Wollenberg et al.2016; Xue et al. 2025). Ensuring

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resilience in AFFSCs is thus essential for securing food availability and enhancing supply chain robustness (Ahmad et al. 2024; Assumpção and Samed 2020). Fragmented logistics systems and institutional voids further marginalize small-scale producers, especially present in emerging economies, limit their access to competitive markets and modernization processes (Marquez F. et al. 2018). While classical analytical approaches, such as modified EOQ models that incorporate perishability (Suárez-Díaz et al.2020), offer valuable insights, they are insufficient to capture adaptive behavior or system learning under disruption scenarios.

Recent research has increasingly emphasized simulation to analyze the resilience of supply chains (Abril et al. 2024; Ivanov, 2025, 2020). Simulation models enable the exploration of various disruption scenarios and adaptive responses. In parallel, the integration of Artificial Intelligence (AI) has expanded the capabilities of these models by enabling data-driven decision-making and predictive analytics (Moosavi and Hosseini 2021; Paternina-Arboleda et al.2023; Shadkam and Irannezhad 2025). However, current literature still lacks a consolidated understanding of how AI is embedded within different simulation paradigms to operationalize resilience strategies in AFFSCs (Saad Al-Naimi, 2025).

This paper addresses that gap by examining the intersection between AI techniques and simulation approaches in resilience-oriented modeling. It synthesizes the modeling patterns found during a structured literature review, highlighting the simulation paradigms applied, the AI methods used, the types of disruptions modeled, and the resilience dimensions represented. The analysis also identifies areas where strategic goals and technical modeling remain disconnected, pointing to opportunities for stronger methodological alignment in future research. The rest of this paper is organized as follows. Section 2 provides background on the role of simulation and AI in AFFSCs and outlines key concepts and recent developments. Section 3 describes the methodological protocol used for the literature review, including the search strategy, inclusion criteria, and data extraction process. Section 4 presents the main findings, structured around five analytical dimensions: AI techniques, simulation paradigms, disruption scenarios, resilience dimensions, and co-occurrence analysis. Finally, Section 5 concludes the paper and highlights future research directions.

1.1 Objectives

This study explores how AI techniques have been integrated into computational simulation paradigms to enhance the resilience of AFFSCs under disruption scenarios. It analytically maps the current literature to identify the AI methods and simulation types most used, examines how disruptions and resilience dimensions are modeled, and highlights key research gaps. The analysis aims to inform future applications of AI-driven simulation models that embed resilience metrics and support adaptive supply chain strategies in perishable food systems.

2. Background and Related Work

AFFSCs operate under high vulnerability to disruptions due to product perishability, logistical fragmentation, and limited infrastructure in rural settings. These factors are further exacerbated in emerging economies by institutional gaps and restricted access to technology and markets, particularly for smallholder farmers (Jubiz-Diaz et al. 2021; Marquez F. et al. 2018).Simulation modeling has become a dominant approach to analyzing operational disruptions in AFFSCs. Models have been used to represent the impacts of climate change, natural disasters, pandemics and other major events (Balezentis et al. 2024; Clavijo-Buritica et al. 2023; Rabah et al. 2025). Paradigms such as Agent-Based Simulation (ABS), Discrete-Event Simulation (DES), System Dynamics (SD), and Hybrid Simulation have proven useful for capturing complex dynamics, feedback loops, and heterogeneity in supply chain behavior (Badiee et al. 2024; González-Hernández et al., 2020; Paredes-Rodríguez et al. 2024; Vempiliyath et al. 2020). These methods allow researchers to model adaptation mechanisms and assess resilience under different disruption scenarios.

On the other hand, AI techniques have become increasingly integrated into modeling frameworks, expanding their capacity for prediction, optimization, and autonomous decision-making. Techniques such as machine learning, fuzzy logic, reinforcement learning, and neural networks have been used to support cold chain monitoring, demand forecasting, route optimization, and risk classification in AFFSCs (Kapici et al. 2022; Lin and Block 2009; Monteiro and Barata 2021; Vilas-Boas et al. 2023; Xu et al. 2022).

Despite these advances, a comprehensive understanding of how AI is embedded into simulation paradigms to explicitly model resilience dimensions in AFFSCs remains underdeveloped. Prior reviews have explored AI in agriculture or simulation in logistics independently, but few have addressed their integration in a resilience context. In fact, Saad Al-Naimi (2025) highlights the methodological disconnect between technical modeling and strategic

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goals in AFFSCs resilience.This review builds on that gap by conducting a structured literature review that combines both technologies in the context of AFFSCs disruptions. It focuses on understanding how AI techniques are embedded within simulation paradigms, and how this integration supports the explicit modeling of resilience dimensions such as adaptability, robustness, and recovery.

3. Methods

This study follows a structured literature review methodology adapted from Sauer and Seuring (2023), with the aim of analyzing how AI approaches have been integrated into simulation paradigms to strengthen the resilience of AFFSCs. The review was conducted in six main steps:Defining the research question: The research question guiding this review was: What are the leading artificial intelligence approaches and simulation paradigms applied in Agri-Fresh Food Supply Chains, and how have these been used to support supply chain management processes under disruption scenarios? The question reflects a deductive approach guided by the concepts of resilience and digital transformation in AFFSCs. Determining the characteristics of primary studies: Inclusion criteria required papers to apply AI-supported simulation methods to food supply chains, present methodological detail.

Table 1. Search Protocol

Criteria	**Description**			
Database	Scopus and Web of Science (WoS)			
Document Types	Peer-reviewed journal articles, conference papers, reviews			
Search Date	Apr 27, 2025			
Search String – Scopus	`TITLE-ABS-KEY (("artificial intelligence" OR "ai" OR "machine learning" OR "deep learning" OR "reinforcement learning" OR "predictive analytics" OR "neural networks" OR "AI paradigms") AND ("simulation" OR "modeling" OR "computational modeling" OR "agent-based simulation" OR "discrete-event simulation" OR "system dynamics" OR "hybrid simulation" OR "digital twin") AND ("agri-food" OR "perishable food" OR "fresh food" OR "cold chain") AND ("supply chain" OR "logistics" OR "distribution" OR "inventory management" OR "distribution network" OR "network design" OR "supply planning" OR "transportation" OR "warehousing" OR "storage")) AND (EXCLUDE (PREFNAMEAUID,"Undefined")) AND (EXCLUDE (SUBJAREA,"NEUR") OR EXCLUDE (SUBJAREA,"PHAR") OR EXCLUDE (SUBJAREA,"PSYC") OR EXCLUDE (SUBJAREA,"HEAL") OR EXCLUDE (SUBJAREA,"MATE"))`			
Search String – WoS	`Similar logic adapted to WoS syntax`			
Exclusion Filters	Subject areas not relevant to operations or food systems: medicine, psychology, health sciences, materials science.			
Initially retrieved	Scopus 84	WoS 13	Duplicates 5	Total unique records 92
Screening	Title/abstract screening 59			
Full text assessment	Papers that: (1) use both AI and simulation methods; (2) address at least one supply chain function; (3) model or discuss disruption scenarios; (4) point at least one resilience dimension.			
Selection Outcome	Selected for review 30			

Retrieving the literature sample: he search strategy was structured around four thematic clusters: (i) AI techniques (e.g., machine learning, deep learning, reinforcement learning), (ii) simulation paradigms (agent-based, discrete-event, system dynamics, hybrid, digital twins), (iii) application context (e.g., agri-food, perishable or fresh food, cold chain), and (iv) supply chain functions (e.g., logistics, inventory, network design, transportation). Boolean logic was used to ensure comprehensive coverage. This broad scope allowed the inclusion of papers relevant to resilience even if not explicitly labeled as such. The search protocol is summarized in Table 1.Selecting the literature: After removing duplicates, we screened 92 unique records by title and abstract. Full texts were reviewed when needed. A final set of 60 documents was selected.

Synthesizing the literature: Data extraction focused on simulation paradigm, AI technique, supply chain function, type of disruption addressed, and reported outcomes. Classification was done iteratively to ensure internal consistency and

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coverage.Reporting the results: The findings are presented thematically in the results section, highlighting key methodological trends, strengths and limitations of current approaches, and future research opportunities.

4. Results and Discussion

The following section presents the findings of the structured literature review, focusing on how AI techniques and simulation paradigms are applied to enhance resilience in AFFSCs. The analysis is structured around five key dimensions: AI techniques, simulation paradigms, disruption scenarios, resilience dimensions, and keyword co-occurrence patterns. This multi-dimensional approach enables the identification of dominant modeling strategies, thematic clusters, and conceptual disconnects that shape the current research landscape.

4.1 AI and Simulation Integration in AFFSCs

Among the selected studies, neural networks emerged as the most frequently applied AI technique, particularly in tasks related to prediction, shelf-life estimation, and temperature-sensitive inventory control. For instance, one study developed and validated neural network models to predict the remaining shelf life of dairy products under fluctuating cold chain conditions, with the goal of supporting quality assurance and inventory decision-making (Lin and Block, 2009). Machine learning (ML) methods followed closely, often integrated with evolutionary algorithms or ensemble approaches to optimize multiple functions such as routing, scheduling, and inventory management.

Table 2. Overview of AI and Simulation Integration in AFFSCs

AI Technique	**Refs.**
Neural Networks (ANN)	(Bhatt et al., 2024; Bhavana et al., 2023; Gallego-García et al., 2022; Li and Lu, 2024; Lin and Block, 2009; Liu et al., 2023; Loisel et al., 2022; Melesse et al., 2022; Mercier and Uysal, 2018; Miao, 2023; Nath et al., 2024; Pattanaik et al., 2023; Qi, 2023; Tao, 2018; Xu et al., 2022; Zhang et al., 2024)
Machine Learning (ML)	(Bhatt et al., 2024; Fuentes et al., 2024; Gallego-García et al., 2022; Hassoun et al., 2023; Kapici et al., 2022; Krupitzer, 2024; Loisel et al., 2022; Melesse et al., 2022; Nath et al., 2024; Sutar et al., 2023; Vedashree et al., 2024; Vilas-Boas et al., 2023; Xu et al., 2022; Zhang et al., 2024)
Deep Learning (DL)	(Bhatt et al., 2024; Fuentes et al., 2024; Hassoun et al., 2023; Li and Lu, 2024; Nath et al., 2024; Vedashree et al., 2024; Wu et al., 2023; Xu et al., 2022; Zhan et al., 2022; Zhang et al., 2024; Zou et al., 2025)
Decision Trees and Ensembles	(Bhavana et al., 2023; Goel et al., 2024; Kapici et al., 2022; Pattanaik et al., 2023; Sutar et al., 2023; Xu et al., 2022)
Reinforcement Learning (RL)	(Gallego-García et al., 2022; Melesse et al., 2022; Vilas-Boas et al., 2023; Zhang et al., 2024; Zou et al., 2024)
Evolutionary and Swarm Algorithms	(Bhavana et al., 2023; Li and Lu, 2024; Miao, 2023; Qi, 2023; Vilas-Boas et al., 2023)
Support Vector Machines (SVM)	(Bhavana et al., 2023; Goel et al., 2024; Sutar et al., 2023; Xu et al., 2022)
Fuzzy Logic and Systems	(Bhavana et al., 2023; Kapici et al., 2022; Vilas-Boas et al., 2023)
Ensemble Methods	(Mercier and Uysal, 2018)

In one example, ML was applied in conjunction with digital twin architectures to enhance coordination across blockchain-enabled agri-food supply chains (Vilas-Boas et al., 2023). Deep learning (DL) was employed in a smaller subset of papers, typically in contexts requiring unstructured data handling or dynamic forecasting, such as temperature prediction in refrigerated transport or anomaly detection in IoT-enabled monitoring systems. Table 2 presents a consolidated overview of the main artificial intelligence techniques and simulation paradigms applied across the reviewed studies.

Beyond neural networks, ML, and DL, a smaller set of studies applied AI techniques such as fuzzy logic, reinforcement learning, or evolutionary algorithms, typically selected to address uncertainty, optimization challenges, or interpretability requirements. These techniques were often embedded within simulation models to represent decision rules, generate demand profiles, or guide scenario testing. The integration of AI and simulation was consistently shaped by the specific function being modeled—whether inventory management, routing, or temperature control—and by the type of disruption or operational complexity addressed.

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4.2 Simulation approaches

As shown in Table 3, Digital Twin (DT) models were the most frequently employed simulation paradigm in the reviewed studies. These models were often integrated with real-time sensing and AI components to support predictive control in cold chain logistics or inventory planning (Melesse et al., 2022; Pattanaik et al., 2023; Zou et al., 2024). Agent-Based Simulation (ABS) was also applied in studies focusing on adaptive behavior among supply chain actors under disruption scenarios (Li and Lu, 2024; Loisel et al., 2022), while neural network-based simulations were used to model dynamic relationships in food quality prediction and environmental control (Qi, 2023; Tao, 2018). Other paradigms, such as System Dynamics (Gallego-García et al., 2022) and Discrete-Event Simulation (Sutar et al., 2023), offered suitable frameworks for representing system feedback and process-level variability.

Table 3. Simulation approach

Simulation approach	**Refs.**
Digital Twin (DT)	(Fuentes et al., 2024; Goel et al., 2024; Hassoun et al., 2023; Kapici et al., 2022; Krupitzer, 2024; Melesse et al., 2022; Pattanaik et al., 2023; Sutar et al., 2023; Wu et al., 2023; Zhan et al., 2022; Zhang et al., 2024; Zou et al., 2025)
Agent-Based Simulation (ABS)	(Li and Lu, 2024; Loisel et al., 2022; Miao, 2023; Vedashree et al., 2024)
Neural Network Simulation	(Lin and Block, 2009; Qi, 2023; Tao, 2018)
Computational Fluid Dynamics (CFD)	(Bhatt et al., 2024; Bhavana et al., 2023)
System Dynamics (SD)	(Gallego-García et al., 2022; Zhou et al., 2022)
Discrete-Event Simulation (DES)	(Sutar et al., 2023; Vilas-Boas et al., 2023)
Monte Carlo Simulation	(Balezentis et al., 2024)
Hybrid Simulation	(Liu et al., 2023)
Other AI-based Simulation	(Mercier and Uysal, 2018; Xu et al., 2022; Zou et al., 2024)

While some studies opted for single-paradigm approaches, some combined techniques to leverage their respective strengths.

4.3 Disruption types

The reviewed studies addressed a broad range of disruption types, with climate and environmental events emerging as the most frequently modeled category. These included temperature fluctuations, extreme weather, and humidity-related conditions affecting production or cold chain integrity (Bhatt et al., 2024; Fuentes et al., 2024; Xu et al., 2022). Pandemics and health crises were also commonly explored, often through scenario-based simulations to evaluate the impact of workforce shortages, mobility restrictions, and sudden demand shifts (Hassoun et al., 2023; Vilas-Boas et al., 2023). Cold chain failures were modeled primarily to assess the effect of temperature deviations on food quality and spoilage (Wu et al., 2023; Zhou et al., 2022), while logistics and operational disruptions, such as transport delays or equipment failures, appeared in studies focused on event-driven systems (Goel et al., 2024; Li and Lu, 2024).

Table 4. Disruption types

Disruption types	**Refs.**
Climate and Environmental Events	(Balezentis et al., 2024; Bhatt et al., 2024; Fuentes et al., 2024; Mercier and Uysal, 2018; Miao, 2023; Qi, 2023; Vedashree et al., 2024; Xu et al., 2022)
Cold Chain Failures	(Lin and Block, 2009; Wu et al., 2023; Zhan et al., 2022; Zhou et al., 2022)
Pandemics and Health Crises	(Alam et al., 2023; Burgos and Ivanov, 2021; Hassoun et al., 2023; Mishra et al., 2023; Rathod et al., 2022; Vilas-Boas et al., 2023)
Logistics and Operational Disruptions	(Goel et al., 2024; Li and Lu, 2024; Vilas-Boas et al., 2023)
Supply Variability	(Balezentis et al., 2024; Sutar et al., 2023)
Market and Economic Shocks	(Liu et al., 2023; Xu et al., 2022)

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Although less common, some studies addressed supply variability and economic shocks, highlighting structural fragilities linked to supplier reliability and price instability (Liu et al., 2023; Sutar et al., 2023). Across disruption types, the simulation setup influenced which resilience strategies were evaluated—ranging from buffer stock and rerouting to adaptive learning and scenario reconfiguration. The next section examines how these responses were framed conceptually and operationalized through explicit resilience dimensions.

4.4 Resilience Dimensions

The reviewed studies reflect a multidimensional understanding of resilience in agri-food supply chains, with four core dimensions emerging across simulation models: adaptability, robustness, recovery, and flexibility. These dimensions were either explicitly referenced or indirectly operationalized through the modeling of response strategies to disruptions. Adaptability, the most frequently addressed, was typically associated with learning-based systems or dynamic reconfiguration, such as AI-enabled rerouting, inventory adjustments, or policy switching in response to unexpected conditions (Goel et al. 2024; Pattanaik et al. 2023; Zou et al. 2025). Robustness often referred to the system's ability to maintain acceptable performance during perturbations and was reflected in buffer-based strategies or design redundancy (Sutar et al. 2023; Wu et al. 2023).

While recovery and flexibility were less prevalent, they appeared in studies modeling downtime response or reallocation of resources after disruptive events (Hassoun et al. 2023; Vilas-Boas et al. 2023). Some models embedded these dimensions implicitly, even when not labeled as such, particularly in hybrid simulation settings. The consistent presence of adaptability and robustness across scenarios suggests a practical emphasis on resilience as a dynamic capability rather than a fixed state. The following section explores how these resilience concepts align with the broader knowledge structure revealed by bibliometric patterns in literature.

4.5 Co-occurrence analysis and identified gaps

A co-occurrence analysis of author keywords was conducted using VOSviewer, which uses a clustering algorithm based on the strength of co-occurrence links across publications. The resulting map, Figure 1, reveals four distinct clusters. The first cluster (red) includes terms such as artificial intelligence, resilience, supply chain, and sustainability, reflecting high-level concerns about systemic transformation and strategic challenges in agri-food systems. The second cluster (blue) connects cold chain, digital twins, and deep learning, suggesting a concentration of studies oriented toward operational monitoring and digital modeling of perishable food systems. The green cluster features IoT, blockchain, and big data, often linked to traceability and digital infrastructure, while the yellow cluster focuses on machine learning and simulation as applied to perishable foods, representing more algorithmic or method-driven studies.

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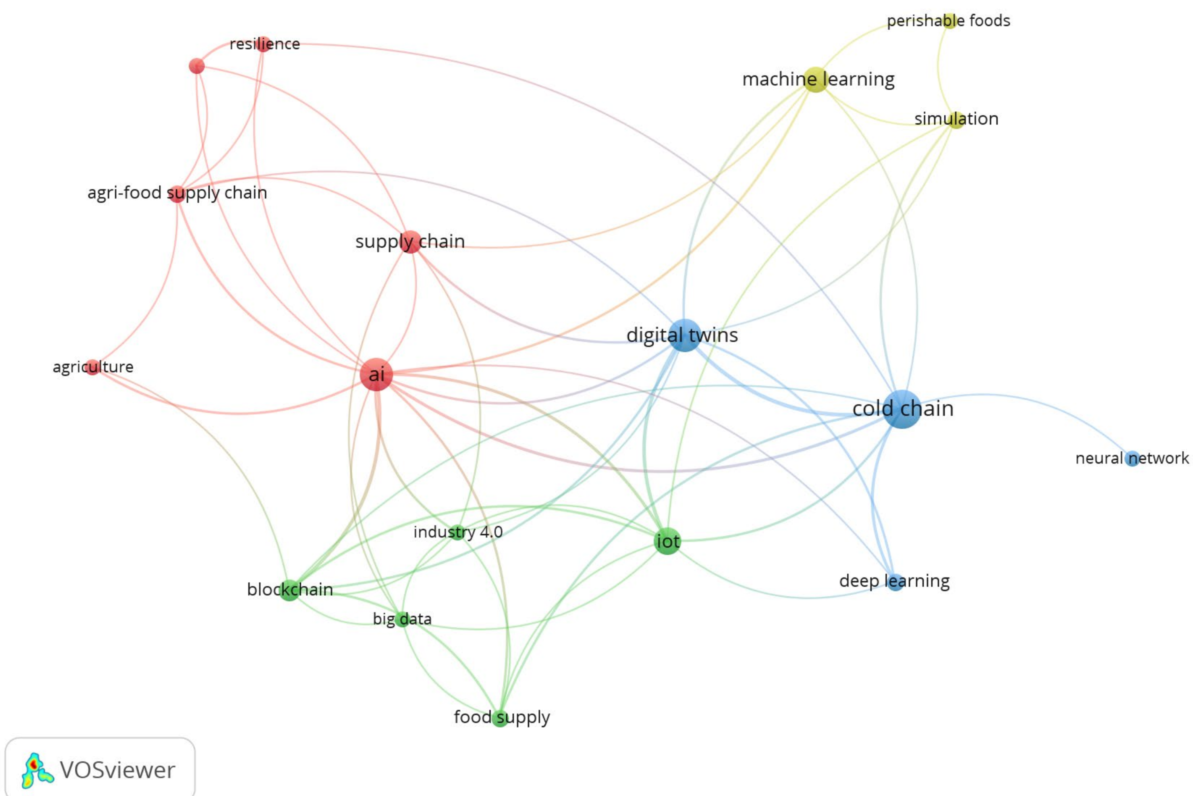

Figure 1. Co-occurrence map of keywords

It is evidenced that terms like resilience and sustainability are more closely associated with strategic keywords than with technical or modeling terms. In contrast, digital twin, machine learning, and simulation are more central within the methodological and technological clusters but exhibit weaker ties to resilience. This suggests that, while simulation and AI are indeed used in resilience-focused studies, the role of resilience is often contextualized as an overarching objective rather than operationalized through explicit simulation constructs. Bridging this conceptual-methodological divide presents an opportunity for future work, particularly in the integration of AI-enabled simulation architectures, such as digital twins, to model and quantify resilience more directly.

5. Conclusion and future work

This study reviewed 30 research articles that integrate artificial intelligence techniques with computational simulation to enhance resilience in AFFSCs. By systematically analyzing simulation paradigms, AI methods, disruption types, and resilience dimensions, the review revealed consistent patterns as well as conceptual gaps. The most frequently applied AI techniques were neural networks, machine learning, and deep learning, often embedded in digital twin or agent-based simulation architectures. Disruptions were primarily modeled as environmental events, cold chain failures, or pandemic-related constraints, with adaptability and robustness emerging as the most addressed resilience dimensions.

The co-occurrence analysis of author keywords confirmed a fragmented knowledge structure, where resilience is more strongly linked to strategic terms than to simulation paradigms or digital infrastructures. This disconnect suggests that, while AI and simulation are increasingly adopted to improve resilience, their integration is still limited in methodological depth. Future research should aim to bridge this gap by developing hybrid simulation models, particularly digital twin frameworks, that embed resilience metrics as core simulation outputs rather than contextual

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assumptions. In addition, expanding the use of AI for adaptive control, scenario learning, and dynamic policy evaluation could enhance the responsiveness of agri-food supply chains to complex disruptions.

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