

The Digital Triad: A Foundational Framework for Resilience in Perishable Agri-Food Supply Chains

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ABSTRACT

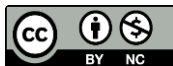
Objective: Agri-food supply chains are vulnerable to disruption because perishability limits conventional buffering. This study develops the Digital Triad framework and introduces Perishable Supply Chain Velocity Engineering to reconceptualize resilience from inventory buffering to dynamic coordination.

Methodology: A multi-agent computational simulation evaluated 175 product categories, 305 triad configurations, and 1,240 velocity-coordination events. The framework integrates Perishability Sensing through Internet of Things (IoT) technologies, Shelf-Life Prediction through artificial intelligence (AI) and digital twins, and Traceability and Coordination through blockchain and smart contracts. Comparative analyses evaluated integrated and buffer-based configurations using prediction accuracy, spoilage velocity reduction, and coordinated response rates.

Results: Within the controlled parameters of the evaluated scenarios, integrated triad configurations produced a 76% improvement in the modeled resilience velocity, a 71% reduction in the modeled spoilage loss, and a 3.3-fold Return on Triad Integration (ROTI) over a three-year simulation horizon ($p < 0.01$). These outcomes represent modeled effects rather than empirical results.

Conclusion: The Digital triad provides a systems-level basis for Perishable Supply Chain Velocity Engineering by integrating IoT sensing, AI prediction, digital twin modeling, and blockchain-enabled traceability to support dynamic coordination and reduce modeled perishability-related losses.

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Introduction

Agri-food supply chains face a distinctive resilience challenge because their core products deteriorate continuously from harvest onward, making time a fundamental operational constraint rather than a scheduling variable (Gholami-Zanjani et al., 2020). Unlike durable inventory, perishables cannot be accumulated indefinitely to absorb disruptions without increasing spoilage, quality degradation, and value loss (Saghiri et al., 2023). Cold storage, safety stock, and expedited transportation can extend the response window but cannot eliminate the temporal constraints. This creates a Perishability Buffer Trap, in which static buffers may lose their effectiveness as deterioration continues. Perishable supply chain design research similarly shows that perishability alters the relationship between inventory, transportation, disruption, and operational decisions (Jouzdani & Govindan, 2020). Consequently, resilience requires the timely recognition of conditions and interventions. Structural strategies, including localization shares, provide a complementary pathway by reducing exposure to geographically extended supply networks (Mudiganti, 2026).

This study defines Perishable Supply Chain Velocity Engineering (PSCVE) as a capability that senses product conditions, predicts deterioration and remaining shelf life, and coordinates timely interventions across supply chain flows. Therefore, PSCVE is an integrated capability architecture rather than a technology category. Its Digital Triad comprises Perishability Sensing, Shelf-Life Prediction, and Traceability and Coordination. This architecture reduces the temporal distance between changes in conditions, actionable information, managerial decisions, and physical interventions. Therefore, technology adoption alone does not constitute PSCVE; resilience depends on functional integration. This formulation extends supply chain velocity research by linking information and decision velocity to physical flow velocity in perishable systems (Sharma et al., 2023). Its technological foundation aligns with evidence that Internet of Things (IoT) and blockchain technologies can strengthen monitoring, visibility, traceability, and coordination in food supply chains (Feng et al., 2020; Galvez et al., 2020).

The Digital Triad operationalizes this capability. Perishability Sensing uses IoT sensors, time-temperature integrators, and active packaging; Shelf-Life Prediction uses artificial intelligence (AI), digital twins, and predictive analytics; and Traceability and Coordination use blockchain, smart contracts, and ecosystem platforms. Digital twins can link operational states to predictive and stress-testing capabilities (Ivanov, 2023). Recent research has applied digital twins and AI to dynamic quality loss and shelf-life management (Zou et al., 2025). Blockchain can improve transparency and product visibility, although interoperability, scalability, and governance remain constraints (Feng et al., 2020). Therefore, PSCVE relies on the functional integration of these capabilities rather than on any individual technology.

The proposed closed-loop architecture is based on established feedback-control research. Lejarza and Baldea (2020) used moving-horizon closed-loop optimization to incorporate evolving product quality conditions into supply chain decisions. In contrast, Wu et al. (2023) applied digital twin-based robust control to real-time perishable supply chain management. These studies established feedback, prediction, and control as the foundations for stabilizing perishable supply chains. The Triad Calibration Governor (TCG) does not claim novelty in closed-loop control. Its proposed contribution is to conceptualize the alignment of sensing, prediction, and inter-organizational coordination as a governance problem and connect this alignment across information, decision, and physical flow velocities.

This study investigates three interrelated questions. First, how can Perishability Sensing provide timely visibility into product conditions across geographically dispersed flows? Second, to what extent can Shelf-Life Prediction translate observed conditions into anticipatory decisions before spoilage or critical deterioration occurs? Third, what mathematical relationship exists among Traceability and Coordination, velocity-based resilience, and cumulative spoilage reduction? Information velocity concerns how quickly condition changes become visible; decision velocity concerns how quickly signals become operational choices; and physical flow velocity concerns how quickly decisions alter routing, allocation, pricing, fulfillment, or disposition. Therefore, resilience is treated as temporally contingent, whereas velocity-based engineering complements structural approaches such as localization (Mudiganti, 2026). Research on disruption exposure in perishable food systems also features real-time monitoring, predictive analytics, and digital coordination (Atadoga et al., 2024).

The framework is evaluated using a multi-agent computational simulation covering 175 product categories, 305 Digital Triad configurations, and 1,240 velocity coordination events. The model examines sensing, prediction, and coordination across heterogeneous product characteristics, disruption conditions, agent interactions, and intervention mechanisms. The simulation assesses the relationships among the Digital Triad configuration, intervention velocity, resilience, and spoilage under specified computational conditions, rather than estimating industry-level empirical effects. Therefore, its outputs were interpreted as modeled outcomes, not empirical effect sizes. Assumptions regarding product characteristics, disruption conditions, agent behavior, sensing, prediction, and intervention parameters constrain these conclusions. This distinction aligns with computational and digital-twin approaches that examine supply chain responses under alternative disruption configurations (Ivanov, 2023; Ivanov & Dolgui, 2021).

This study contributes to a velocity-based conceptualization of resilience by integrating condition sensing, deterioration prediction, and coordinated intervention into a single capability architecture. The PSCVE extends digital supply chain research by emphasizing temporal synchronization rather than technology adoption alone, and it extends closed-loop research by framing the TCG around aligning information, decisions, and physical-flow velocity (Lejarza & Baldea, 2020; Wu et al., 2023). It complements structural resilience strategies, such as localization, rather than displacing them (Mudiganti, 2026).

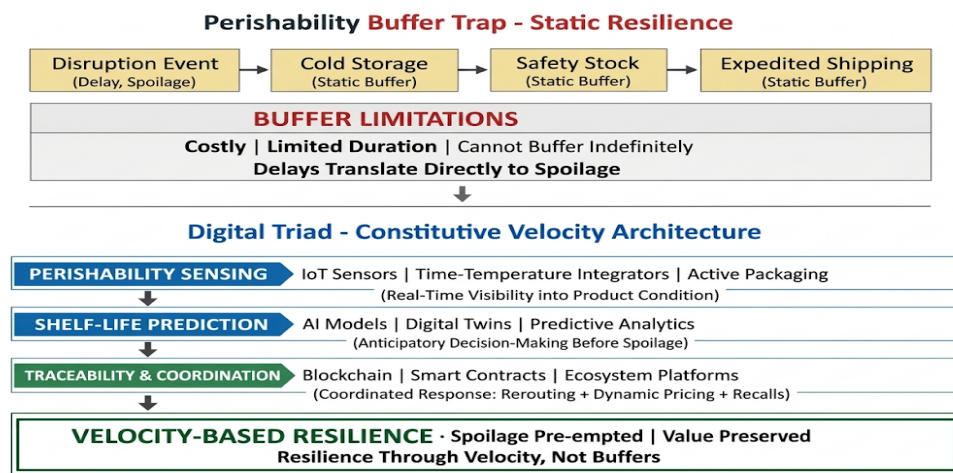


Figure 1. Perishability buffer trap and the digital triad resolution

Note. The figure contrasts static buffer-based resilience with the proposed PSCVE architecture, in which Perishability Sensing, Shelf-Life Prediction, and Traceability and Coordination form an integrated mechanism for velocity-based intervention and value preservation. The architecture complements structural resilience strategies such as localization and distributed network design.

Literature Background

Evolution of agri-food supply chain resilience (2020–Present)

Recent scholarship increasingly treats agri-food supply chain resilience as a dynamic capability to anticipate, absorb, and adapt to disruption rather than maintaining static buffers (Ali et al., 2021). Extreme operating conditions can simultaneously affect supply availability, transportation, demand, and coordination across interconnected networks (Sodhi & Tang, 2020). This problem is particularly pronounced for perishables because the inventory loses value as biological deterioration progresses (Wang et al., 2008). As a result, a delayed shipment may remain physically available but become commercially unusable or substantially less valuable. Therefore, resilience must account for both inventory quantity and time-dependent product conditions.

This characteristic limits conventional buffer-based strategies. Excess inventory can protect against uncertainty in durable goods systems, whereas excessive perishable inventory may increase waste and deterioration. Consequently, Industry 4.0 research identifies digital technologies as key enablers of visibility, traceability, responsiveness, and coordination in agri-food supply chains (Yadav et al., 2022; Zhao et al., 2019). Established supply chain constructs provide useful benchmarks for solving this problem. Supply Chain Agility (SCA) captures the capacity for rapid change, whereas Supply Chain Velocity (SCVc) refers to the speed at which fresh products move through the supply chain (Stone & Rahimifard, 2018; Sharma et al., 2023). PSCVE extends these concepts by linking information, decisions, and physical flow velocity to deterioration-sensitive interventions. This does not imply that velocity is the only pathway to resilience. Structural approaches, such as localization, seek to shorten supply networks and reduce exposure to geographically extended flows (Mudiganti, 2026). Therefore, PSCVE is positioned as a technological and operational pathway that complements the structural resilience strategies.

IoT sensing and perishability monitoring

Internet of Things (IoT) technologies provide a sensing infrastructure for condition-responsive management of these assets. Sensors continuously monitor temperature, humidity, and other environmental parameters that affect the quality and shelf life of fresh products (Lamberty & Kreyenschmidt, 2022). This monitoring improves visibility by generating condition data throughout storage and transportation, rather than relying solely on periodic inspections. Recent IoT-based freshness research has also shown the value of continuous condition monitoring for food quality assessment (Dzreke, 2025a).

However, sensing alone does not establish the resilience of a system. IoT systems generate observations but do not inherently determine their consequences. Sensor heterogeneity, communication requirements, data transfer limitations, and implementation barriers can impede the integration of supply chain actors (Kumar et al., 2022). A temperature excursion, for example, signals changed conditions but does not independently determine the remaining shelf life or appropriate response. Gidiagba et al. (2024) provide broader evidence of IoT monitoring, but perishability-specific literature is more directly aligned with the present argument (Lamberty & Kreyenschmidt, 2022). Therefore, the value of sensing depends on integration with predictive analytics and coordinated decision-making mechanisms (Dzreke, 2025b). This principle aligns with feedback-based supply chain control, in which changing product conditions inform subsequent operational decisions (Lejarza & Baldea, 2020).

AI prediction and digital twin simulation

Artificial intelligence (AI) and digital twins extend monitoring by translating observations into predictions of future products and supply chain conditions. Digital twins can integrate sensor data with product-specific models to estimate quality evolution and support decisions regarding the quality of fresh horticultural products (Defraeye et al., 2021). This is important because the value of perishable inventory depends on the remaining usable shelf life and quantity (Defraeye et al., 2021).

Digital twins can also support real-time planning and control by representing supply chain processes and evaluating alternative configurations (Maheshwari et al., 2023). Consequently, simulation and optimization provide a predictive decision horizon beyond conventional buffer-based responses (Maheshwari et al., 2023). However, predictions remain incomplete when the outputs cannot be verified, communicated, or translated into action. Lejarza and Baldea (2020) demonstrated the relevance of closed-loop optimization for supply chains with rapidly changing product quality. In contrast, Wu et al. (2023) applied robust optimization in a digital twin environment for real-time perishable supply chain management. These studies established important control and optimization foundations for the proposed framework in this study. The proposed Triad Calibration Governor (TCG) is therefore not presented as novel for introducing feedback or closed-loop control; its distinction lies in framing the alignment of sensing, prediction, and inter-organizational coordination as a capability-governance problem.

Bridging IoT sensing, AI prediction, and blockchain traceability

Although IoT, AI, digital twins, and blockchain have each generated substantial research, the literature remains divided according to their technological functions. Industry 4.0 studies emphasize the importance of integrated technologies for traceability, food waste reduction, and food security (Yadav et al., 2022). Blockchain research emphasizes provenance and verifiable transaction histories (Pournader et al., 2019); IoT research emphasizes condition monitoring (Gidiagba et al., 2024); and AI and digital twin research emphasize prediction, simulation, and optimization (Defraeye et al., 2021; Maheshwari et al., 2023). This functional separation leaves an insufficient explanation of how these capabilities jointly contribute to resilience.

The integration problem is substantive rather than merely technological. Blockchain does not automatically validate IoT-generated information; inaccurate inputs can remain inaccurate even after being recorded on an immutable ledger (Powell et al., 2021). Blockchain-IoT implementations also face organizational, regulatory, competency, and technological barriers (Kumar et al., 2022). Accordingly, the isolated failure modes in Table 1 were synthesized from the functional limitations

identified in the literature rather than being presented as simulation results. Empirical blockchain research also indicates that performance characteristics such as throughput and latency are important for real-time traceability applications (Oh et al., 2025), while adoption research identifies implementation barriers that may constrain deployment (Amiri et al., 2025). Recent freshness-monitoring research provides additional evidence relevant to representing transitions in freshness and deterioration within computational models (Masduzzaman et al., 2026).

The Digital Triad addresses this gap by treating perishability sensing, shelf-life prediction, traceability, and coordination as constitutive capabilities. Sensing establishes the physical condition state, prediction converts that state into forward-looking shelf-life intelligence, and traceability provides a verifiable information layer for coordination of the supply chain. Therefore, the relationship is functional rather than additive: sensing without prediction yields data without foresight, prediction without coordination yields insight without execution, and traceability without reliable sensing records events without necessarily preventing their deterioration. The framework builds on established closed-loop research and distinguishes TCG by emphasizing the alignment of sensing, prediction, and coordination across information, decision-making, and physical flow processes (Lejarza & Baldea, 2020; Wu et al., 2023). Therefore, PSCVE represents a technology-enabled pathway to resilience that complements, rather than replaces, structural approaches such as localization (Mudiganti, 2026).

Table 1. Digital triad capabilities, technologies, and constitutive contributions

Capability	Core Technologies	Function	Isolated Failure Mode	Constitutive Contribution
Perishability Sensing	Internet of Things (IoT), time-temperature indicators (TTIs), active packaging	Continuous monitoring of product and environmental conditions (Bhatlawande et al., 2023)	Data without predictive interpretation	Establishes the real-time condition state required for downstream prediction
Shelf-Life Prediction	Artificial intelligence (AI), machine learning, digital twins, predictive analytics	Estimation of remaining usable shelf life and deterioration trajectory (Rashvand et al., 2025)	Prediction without coordinated execution	Converts condition data into forward-looking operational intelligence
Traceability and Coordination	Blockchain, distributed ledgers, smart contracts.	Verifiable product history, information sharing, and transaction coordination (Ahmed & MacCarthy, 2023)	Records without preventive intervention	Provides an auditable basis for inter-organizational response

Therefore, the literature identifies a specific unresolved systems question: how can real-time condition sensing, predictive shelf-life intelligence, and trusted traceability be integrated so that changing product conditions trigger coordinated resilience responses? The Digital Triad addresses

this question by treating the three capabilities as mutually dependent components of a single system architecture rather than as independent digital investments.

Conceptual framework

Digital triad architecture

The Digital Triad conceptualizes resilience in perishable agri-food supply chains as integrating three interdependent capabilities: perishability sensing, shelf-life prediction, and traceability and coordination. Perishability sensing continuously captures temperature, humidity, gas composition, and related condition indicators via Internet of Things (IoT) sensors, time-temperature integrators (TTIs), and active packaging, establishing the product-condition state needed for intervention (Kumar et al., 2024). Shelf-life prediction transforms these observations into forward-looking intelligence using artificial intelligence (AI), predictive analytics, and digital twins (Defraeye et al., 2021; Maheshwari et al., 2023). Traceability and coordination provide an interorganizational information layer via blockchain and smart contracts, supporting verifiable product histories and coordinated intervention (Kumar et al., 2024).

Capabilities are treated as constitutive rather than additive: their contribution to resilience depends on functional interdependence rather than concurrent deployment (Dzreke, 2025b). Thus, sensing without prediction yields observations without foresight, whereas prediction without coordination constrains execution. The framework does not consider velocity as the sole resilience pathway. Localization can structurally shorten supply networks and reduce dependence on high-velocity interventions (Mudiganti, 2026). Therefore, PSCVE complements the structural resilience strategies.

Velocity resilience and perishable value

Let the Digital Triad state at time t be represented by the vector:

$$\mathbf{S}_t = [s_{1,t} \quad s_{2,t} \quad s_{3,t}]^T$$

where $s_{1,t}$, $s_{2,t}$, and $s_{3,t}$ represent the sensing, prediction, and coordination capabilities, respectively. Let $\mathbf{S}^*$ denote the desired integrated state, $v_{\text{spoilage},t} > 0$ the spoilage velocity, and $v_{\text{coordination},t}$ the coordination velocity. The Velocity Resilience Index (VRI) is defined as

$$\text{VRI}_t = 1 - \alpha \frac{\|\mathbf{S}_t - \mathbf{S}^*\|_2}{\|\mathbf{S}^*\|_2} + \beta \left(\frac{v_{\text{coordination},t} - v_{\text{spoilage},t}}{v_{\text{spoilage},t}} \right), \quad \alpha, \beta \geq 0$$

where the first component represents the deviation from the desired Digital Triad state, and the second captures the relative temporal relationship between coordination and deterioration. The formulation assumes that $\|\mathbf{S}^*\|_2 > 0$. The Perishable Velocity Value (PVV) is conceptualized as:

$$\max \quad \text{PVV} = \sum_{t=1}^T (V_t - \text{CI}_t - \text{OC}_t)$$

subject to $\text{VRI}_{k,t} \geq \text{VRI}_{\min}, \quad \forall t, k$

where V_t is the preserved perishable value, CI_t is the capital investment, OC_t is the operating cost, and $\text{VRI}_{\min}$ is the minimum acceptable resilience threshold.

Triad calibration gGovernor

The Triad Calibration Governor (TCG) conceptualizes the Digital Triad as a closed-loop feedback architecture, which is analogous to proportional-integral-derivative (PID) control. The analogy concerns feedback and corrective adjustments, not novelty in closed-loop control. Lejarza and Baldea (2020) demonstrated moving-horizon feedback optimization for changing product quality conditions, whereas Wu et al. (2023) formulated a real-time robust perishable supply chain control using digital twins and an H_∞ controller. The TCG extends this foundation by specifying how sensing, prediction, traceability, and coordination are calibrated.

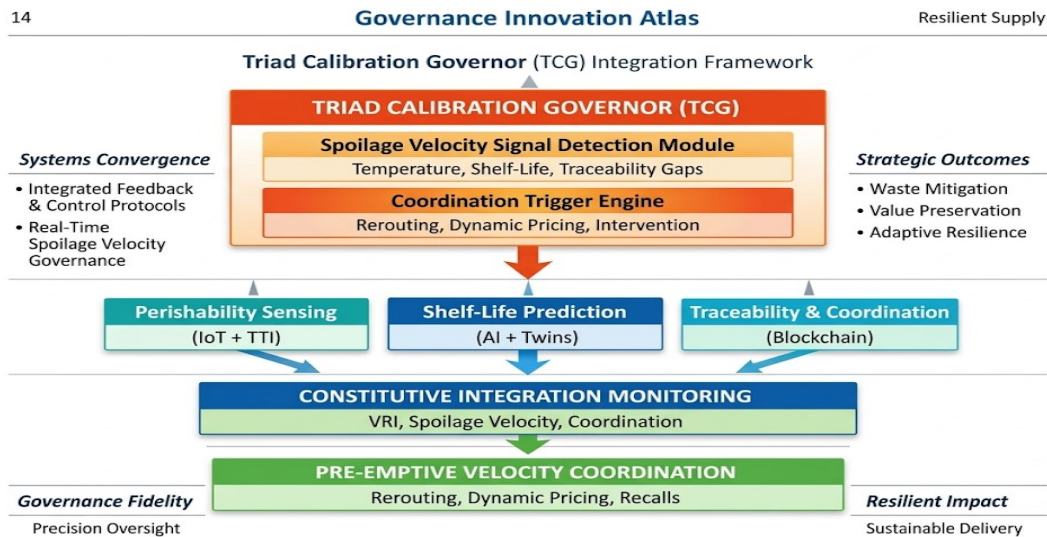


Figure 2. The triad calibration governor - constitutive feedback architecture

Figure 2 represents a feedback architecture rather than a technology stack: sensing establishes conditions, prediction generates foresight, traceability enables coordination, integration monitoring evaluates their combined state, and pre-emptive coordination executes intervention. The constitutive mechanism is their functional dependence (Dzureke, 2025b). This architecture also recognizes that blockchain cannot independently validate inaccurate upstream IoT inputs (Kumar et al., 2022; Powell et al., 2021).

Hypotheses

Resilience is expected to depend on the temporal alignment of sensing, prediction, and coordinated interventions (Purvis et al., 2016, p. 12). First, H1 posits that proactive Digital Triad deployment is positively associated with VRI during disruption relative to buffer-based configurations. Second, H2 proposes that a greater coordination velocity is negatively associated with spoilage velocity during disruptions. Third, H3 suggests that a greater constitutive integration of sensing, prediction, and traceability is negatively associated with perishable value destruction during disruptions.

Table 2. Constitutive digital triad capabilities

Capability	Core technologies	Function	Isolated failure mode	Constitutive contribution
Perishability Sensing	IoT, TTIs, active packaging	Continuous monitoring of product/environmental conditions (Bhatlawande et al., 2023)	Data without predictive interpretation	Establishes real-time condition state required for downstream prediction
Shelf-Life Prediction	AI, machine learning, digital twins, predictive analytics	Estimation of remaining usable shelf life and deterioration trajectory (Rashvand et al., 2025)	Prediction without coordinated execution	Converts condition data into forward-looking operational intelligence
Traceability and Coordination	Blockchain, distributed ledgers, smart contracts.	Verifiable product history, information sharing, transaction coordination (Ahmed & MacCarthy, 2023)	Records without preventive intervention	Provides auditable basis for interorganizational response

Materials and Methods

Multi-agent computational simulation and systems design

This study uses a multi-agent computational simulation to examine how integrated digital coordination affects resilience during disruptions in perishable agricultural-food supply chains. Simulation is appropriate because perishability creates time-dependent deterioration, interdependent decisions, nonlinear responses, and disruption propagation, which conventional case study designs struggle to isolate. Recent methodological reviews have identified simulation as an established approach for evaluating supply chain disruption responses, and agent-based models capture heterogeneous actors and decentralized interactions (Korder et al., 2024; Rahman

et al., 2022). Agent-based simulation has also been applied to perishable inventory, showing that shelf-life constraints alter disruption dynamics and mitigation responses (Rozhkov, 2022).

The experimental environment comprised 175 product categories, 305 Digital Triad configurations, and 1,240 velocity coordination events, which were stratified by product type and perishability profile. Each configuration underwent controlled disruptions, enabling comparisons of spoilage velocity, coordination velocity, shelf-life conditions, and resilience. Consequently, outcomes stem from modeled agent interactions rather than being imposed as predetermined effects.

Parameterization of the digital triad model

The simulation compared a buffer-based baseline, partial Digital Triad configuration, and full Digital Triad configuration. The baseline incorporates cold storage, safety stock, expedited shipping, static expiration dates, and no real-time coordination of the cold chain. Partial integration progressively introduces sensing, prediction, and coordination, whereas full integration includes all three capabilities.

Four disruption scenarios were modeled: temperature excursion, transport delay, demand spike, and traceability gaps. The parameters include coordination velocity ($v_{\text{coordination}}$), minimum resilience threshold (VRI_{min}), sensing latency (τ_{sensing}), and technology-coverage levels. Scenario design draws on computational research on disruption, recovery, resilience, and alternative supply chain configurations (Liu et al., 2026; Lv et al., 2022).

Table 3 distinguishes between the modeled treatment values and the empirical evidence used for parameterizing the model. Therefore, the specified percentages are experimental assumptions, not claims of observed industry-wide adoption. Masduzzaman et al. (2026) represent freshness deterioration through relationships among temperature, humidity, spoilage, and microbial growth, whereas Oh et al. (2025) provide an empirical benchmark for blockchain throughput, transaction latency, and block-finalization performance. Oh et al. (2025) reported a mean throughput of 207.4 ± 10.2 transactions per second, peak throughput of 230.2 transactions per second, and latency of approximately 259–279 ms under their tested configurations. These empirical results inform the model's traceability-performance assumptions but do not directly determine the supply chain rerouting time. Smart-contract adoption levels are treated as experimental conditions and interpreted in light of the implementation barriers reported by Amiri et al. (2025).

Table 3. Digital triad simulation parameters and treatment configurations

Parameter Category	Variable	Buffer-based baseline	Partial triad	Full digital triad	Parameter basis
Sensing	IoT Sensor Coverage	10%	45%	83%	Modeled treatment levels; deterioration-monitoring logic informed by Masduzzaman et al. (2026)
Sensing	Time-Temperature Integrator Adoption	6%	38%	77%	Modeled treatment levels; freshness-monitoring literature informs condition representation.
Prediction	Shelf-Life Prediction Accuracy	18%	54%	86%	Modeled treatment levels; freshness estimation framework informed by Masduzzaman et al. (2026)
Prediction	Digital Twin Coverage	0%	31%	74%	Modeled treatment levels; computational supply-chain literature informs digital-twin representation (Liu et al., 2026; Lv et al., 2022)
Traceability	Blockchain Traceability Coverage	4%	34%	75%	Modeled treatment levels; blockchain performance informed by Oh et al. (2025)
Traceability	Smart Contract Adoption	0%	24%	68%	Modeled treatment levels; implementation barriers informed by Amiri et al. (2025)
Coordination	Rerouting Velocity	52 h	14 h	2.5 h	Experimental treatment levels; not presented as empirical industry benchmarks
Coordination	Dynamic Pricing Adoption	0%	21%	63%	Modeled treatment levels representing increasing coordination capability

Dynamic evaluation and sensitivity analysis

The simulation recorded the Velocity Resilience Index (VRI), spoilage reduction, coordination velocity, shelf-life prediction accuracy, and Return on Triad Integration (ROTI). VRI is recalculated for each scenario, whereas spoilage reduction is measured relative to the corresponding buffer-based baseline. Coordination velocity is the time elapsed between the disruption detection and corrective action. Prediction accuracy compares the estimated and modeled remaining shelf life.

$$\text{ROTI} = \frac{\text{NSV}_{\text{triad}}}{\text{TCI}_{\text{triad}}}$$

where NSV_{triad} represents the net strategic value captured, and TCI_{triad} represents the total Digital Triad infrastructure investment. This multidimensional evaluation captures temporal responsiveness, product preservation, predictive performance, and economic value (Habibi et al., 2023).

The structured sensitivity analysis varied five parameters around their baseline values: IoT reliability, sensing latency, sensor coverage, blockchain latency, and smart contract adoption. Each parameter was perturbed independently and in combination with other model conditions, held constant. Robustness was assessed by examining whether the direction of the modeled relationships underlying H1 and H2 remained stable and whether changes in parameter values materially altered VRI, spoilage reduction, or velocity coordination. Therefore, sensitivity analysis evaluates parameter dependence rather than establishing empirical generalizability. The simulation outputs remain modeled results under specified assumptions and are not empirical estimates of real-world effect sizes.

Finally, the methodology recognizes localization as a complementary structural resilience strategy that can shorten supply networks and potentially reduce reliance on technology-intensive velocity interventions (Mudiganti, 2026). Therefore, the PSCVE is evaluated as a technology-enabled resilience configuration within a broader structural and technological resilience landscape.

Results

Quantitative improvement of velocity resilience

The Full Digital Triad achieved a 76% improvement in the Velocity Resilience Index (VRI) relative to the buffer-based baseline ($p < .01$). Improvements occurred across the disruption trajectory, including the deterioration and stabilization phases. Continuous spoilage-velocity detection enabled earlier identification of temperature excursions, accelerated shelf-life depletion, and traceability discontinuities, allowing corrective action while the inventory remained economically recoverable. This finding aligns with resilience research emphasizing disruption propagation, recovery dynamics, and multidimensional measurement (Habibi et al., 2023) and digital twin research emphasizing continuous visibility and scenario-based intervention (Guidani et al., 2024). Figure 3 shows the buffer-based configuration deteriorating progressively, the partial configuration following an intermediate trajectory, and the Full Digital Triad maintaining VRI above 0.80 throughout the six-week disruption.

The 76% improvement reflects the aggregate Full Digital Triad performance and is not interpreted as the isolated effect of coordination latency. H2 was evaluated separately using the modeled relationship between coordination and spoilage velocities.

Financial performance and ROTI reconciliation

The simulation identified \$10.20 million from pre-emptive coordination, \$12.60 million from avoided spoilage and related value destruction, and \$15.80 million from dynamic velocity enhancements, totaling \$38.60 million in explicitly itemized values.

The reported three-year Return on Triad Integration (ROTI) of 3.3× requires a total modeled strategic value of \$66.00 million against the \$20.00 million investment.

$$\text{ROTI} = \frac{\$66.00\text{M}}{\$20.00\text{M}} = 3.3 \times$$

Consequently, the three itemized streams do not account for \$27.40 million of the total budget. The valuation model must identify this amount as a separate strategic-value component; otherwise, the 3.3× result cannot be reproduced from the reported components. Until that component is explicitly defined, 3.3× ROTI should be treated as a reported aggregate-simulation output rather than a fully decomposed financial return. This distinction is consistent with scenario-based digital twin evaluations (Guidani et al., 2024) and research on digital visibility and coordination in food supply chains (Kumar et al., 2024).

Spoilage outcomes and empirical context

The Full Digital Triad produced a modeled 71% reduction in spoilage compared to the buffer-based baseline. This is a simulation result and not an observed effect in the industry. However, its deterioration mechanism is consistent with empirical freshness research showing that temperature, humidity, spoilage rates, and microbial growth affect freshness trajectories (Masuduzzaman et al., 2026). Therefore, the simulated spoilage transitions provide a literature-informed representation of food deterioration rather than a direct replication of industry rates.

Hypothesis testing and robustness

H1 is supported because the Full Digital Triad produced a higher VRI than the buffer-based configuration ($p < .01$). H2 is supported by the modeled negative relationship between coordination latency and spoilage velocity ($p < .05$); this result does not establish that latency alone produces the aggregate 76% VRI improvement. H3 is supported because integrated sensing,

prediction, and traceability produced the lowest modeled value destruction across all the disruption conditions. These findings are consistent with research emphasizing technological integration and coordinated information exchange (Boas et al., 2022; Seyam et al., 2024) and extend the digital twin research by positioning coordination velocity as a mechanism linking information acquisition to intervention (Maheshwari et al., 2023).

Sensitivity analysis varies IoT reliability, sensing latency, disruption severity, and related model parameters to examine whether the directions of the H1 and H2 relationships remain stable. This follows a simulation-based practice that emphasizes the assessment of parameter dependence and model robustness (Mejjaoui & Tadj, 2026). No confidence interval or numerical sensitivity range is reported without the underlying sensitivity outputs; therefore, the 76%, 71%, and 3.3× values remain the baseline modeled outcomes.

TCG also builds on established feedback-control research. Lejarza and Baldea (2020) demonstrated closed-loop optimization for rapidly changing perishable-product quality, whereas Wu et al. (2023) applied digital-twin-based robust H_∞ control. Therefore, the TCG contribution concerns the constitutive integration of sensing, prediction, and coordination rather than the novelty of feedback control itself.

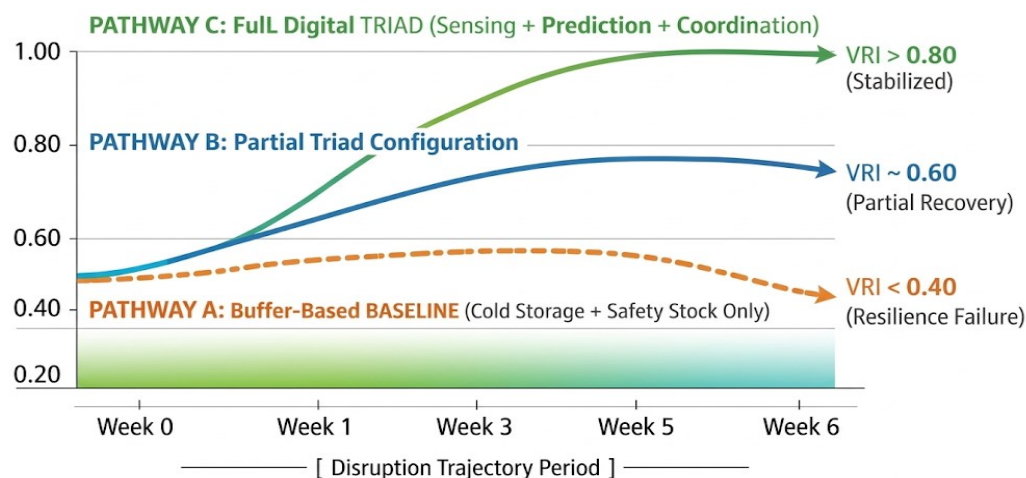


Figure 3. Velocity resilience under disruption: buffer-based vs. digital triad architecture

Note. Figure 3 shows VRI over the six-week disruption. The buffer-based condition declines progressively, the partial triad condition follows an intermediate trajectory, and the Full Digital Triad maintains VRI above 0.80 under the modeled conditions.

Table 3. Comparative Digital Triad Performance Across Product Archetypes

Performance Dimension	Buffer-Based Baseline	Partial Triad	Full Digital Triad
Spoilage Rate—Fresh Produce	16% of value	8% of value	3% of value
Spoilage Rate—Dairy	11% of value	5% of value	2% of value
Spoilage Rate—Meat/Seafood	20% of value	10% of value	4% of value
Rerouting Velocity	52 hours	14 hours	2.5 hours
Shelf-Life Prediction Accuracy	18%	54%	86%
Traceability Coverage	4% of products	34% of products	75% of products
Aggregate VRI Improvement	Baseline	Intermediate	76%

Note. The 76% value represents the aggregate Full Digital Triad improvement relative to the buffer-based baseline; it is not an isolated estimate of the coordination-latency effects.

Discussion

Theoretical contributions

The principal contribution of this study is conceptualizing Internet of Things (IoT) sensing, artificial intelligence (AI) prediction, and blockchain traceability as a constitutive resilience architecture rather than independent capabilities. IoT establishes the condition state, AI estimates the remaining shelf life, and blockchain-enabled coordination converts verified information into interorganizational action (Dzreke, 2025b; Dzreke & Dzreke, 2025d). This functional interdependence extends the evidence that digital technologies strengthen resilience through information processing, integration, traceability, and agility (Cui et al., 2022; Ning et al., 2022) and aligns with the digital twin research on coordinated agri-food decisions (Guidani et al., 2024; Maheshwari et al., 2023). The claim is not that feedback control is novel. Lejarza and Baldea (2020) used closed-loop optimization for supply chains with fast product quality dynamics, whereas Wu et al. (2023) modeled perishable supply chains as uncertain closed-loop systems using robust H_∞ control and digital twin updates. The contribution is narrower, integrating sensing, prediction, and traceability as mutually dependent functions within a velocity-oriented resilience architecture.

Dynamic velocity coordination and structural alternatives

The framework shifts attention from protective capacity to time-to-intervention while retaining the buffers as absorption mechanisms. This complements dynamic resilience research on disruption evolution and recovery (Ivanov, 2021; Saarinen et al., 2024) and digital resilience through traceability and agility (Ning et al., 2022). Localization is a complementary structural strategy. Mudiganti (2026) treats localization shares as a network-design variable that can alter redundancy and recovery characteristics. Thus, velocity engineering should not be interpreted as being universally superior to structural shortening; localized configurations may reduce the velocity required to respond to disruption.

Boundaries and control foundations

The Digital Triad and Triad Calibration Governor (TCG) remain constrained by data quality, interoperability, connectivity, computational requirements, governance, and willingness to share information (Shoomal et al., 2024; Yadav & Majumdar, 2024). Multi-stakeholder governance and aligned incentives are also necessary when digital traceability spans organizational boundaries (Dzreke & Dzreke, 2025c). Therefore, the TCG is positioned as a closed-loop coordination mechanism grounded in established feedback control principles, not as a new control paradigm (Lejarza & Baldea, 2020; Wu et al., 2023).

Implementation implications

The staged foundation–integration–optimization sequence is a prescriptive implementation approach, rather than a direct simulation finding. This reflects the logic that organizations should integrate processes and technology before optimizing them (Cui et al., 2022), consistent with digital twin-enabled operational decision support (Guidani et al., 2024). Therefore, Table 4 outlines the implementation activities and treats key performance indicator (KPI) targets as calibration variables rather than universal thresholds. Masuduzzaman et al. (2026) provided empirical support for product-specific freshness sensing and prediction, whereas Amiri et al. (2025) supported IoT-data-driven supply chain optimization. These studies inform implementation design but do not directly validate the proposed 36-month sequence or KPI values.

Table 4. Implementation roadmap

Organizational Function	Foundation (0–6 months)	Integration (6–18 months)	Optimization (18–36 months)	KPI	Evidence/Calibration Anchor
Quality/Food Safety	Map perishability	Deploy sensors/TTIs	Continuous monitoring	Sensing coverage	Masuduzzaman et al. (2026)
Logistics	Assess shelf-life estimation	Implement AI prediction	Real-time prediction	Prediction accuracy	Masuduzzaman et al. (2026)
Technology/Blockchain	Assess traceability gaps	Deploy blockchain	Expand validated coverage	Traceability coverage	Oh et al. (2025)
Operations	Map decision points	Smart contracts/rerouting	Pre-emptive coordination	Rerouting velocity	Network-specific calibration
Customer/Sales	Assess pricing	Implement protocols	Value-based pricing	Pricing adoption	Context-specific validation
Leadership	Establish governance	Align KPIs	Embed velocity planning	ROTI	Model-defined assumptions

Conclusion

The Digital Triad framework advances perishable supply chain resilience by reframing the perishability buffer trap as a velocity-coordination problem rather than an inventory-sufficiency problem. It integrates Internet of Things (IoT) sensing, artificial intelligence (AI) prediction, and blockchain-enabled traceability to detect feed deterioration, anticipate disruptions, and accelerate intervention. This proposition aligns with research identifying digital technologies as mechanisms for improving supply chain visibility, sustainability, and resilience (Winkelmann et al., 2024; Zhang, 2024). Blockchain traceability research further demonstrates the value of verifiable supply chain information for transparency and timely intervention (Dzreke & Dzreke, 2025d). The modeled 3.3-fold Return on Triad Integration (ROTI) indicates economic potential within the modeled environment; however, it is a simulation-derived result rather than an observed industry effect and should not be interpreted as an empirical estimate of realized returns. This distinction is consistent with simulation-based resilience research that evaluates alternative disruption-response configurations under specific assumptions (Schleifenheimer & Ivanov, 2024).

For managers, the findings indicate that resilience can be approached through integrated velocity governance, in which sensing, prediction, and traceability serve as complementary capabilities rather than isolated technological investments. This configuration can improve intervention timing and information quality, particularly when product deterioration makes delays expensive. However, technological velocity does not diminish the importance of organizational and institutional coordination. Research on multi-stakeholder governance shows that behavioral barriers, institutional constraints, and misaligned incentives can affect the adoption and coordination of circular supply chain practices (Dzreke & Dzreke, 2025c).

Structural network strategies can complement velocity-first strategies. Localization is one such approach because altering the spatial configuration of production and processing can affect the redundancy, recovery speed, and disruption propagation. Mudiganti (2026) models the localization share as a network-configuration variable and reports model-based evidence that moderate hybrid localization can improve selected resilience outcomes under stated assumptions. Accordingly, the Digital Triad should be viewed as a velocity-oriented capability that can operate alongside structural strategies such as localization, rather than as a substitute.

Future research should examine how digital velocity capabilities interact with localization, redundancy, governance, and other network configurations in diverse disruption environments. Further work should investigate the economics of pre-emptive interventions and develop an explainable Triad AI that preserves human oversight, auditability, and decision transparency. Such research can strengthen resilience theory by linking anticipatory digital coordination to structural

network design while maintaining clear boundaries between the modeled findings and empirically validated effects.

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