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Digital Twins for Food Supply Chain Sustainability: Rapid Literature Review and Conceptual Model

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Abstract

Digital Twin (DT) technology offers significant potential to enhance supply chains performances. Thus, the adoption of DTs in food supply chains (FSCs), will have enormous promise for improving sustainability, efficiency, and resilience This paper presents a conceptual framework based on a rapid review of DT applications in FSCs and divided into three sections. The first section provides a literature review on DT components, and FSC sustainability challenges. The second section explores the implementations of DT in FSCs, examining integration levels, key findings, benefits such as waste reduction and improved traceability. Building on these insights, this article develops a comprehensive framework for integrating DT into FSC sustainability, emphasizing its application in pre-adoption, adoption, and post-adoption phases. The framework identifies DT capabilities, technological enablers, barriers, and the economic, social, and environmental impacts of DT adoption, in the context of FSC sustainability. This study highlights critical opportunities in the field, contributing to advancing the application of DT as a strategic enabler of resilient and sustainable food systems.

Keywords
Digital Twin, Sustainability, Food Supply Chain, Simulation, Optimization.

1. Introduction
The FSC is, in essence, the heart of food security and sustainability. Some of the most significant challenges faced by it include inefficiencies, food loss and waste, and environmental influences. Global pressures, such as climate change and a growing population, are growing in magnitude and conspicuously excruciating vulnerabilities in contemporary FSC models due to such disruptive occurrences as the US-China Trade war, the COVID-19 pandemic, and the Russian invasion of Ukraine. Integrating innovative technologies is essential to enhance the sustainability and resilience of the FSC (Ivanov & Dolgui 2021). Among these innovations, Digital Twin (DT) technology is considered promising solutions. A DT is a virtual representation of a physical thing enabling real-time monitoring, simulation, and

optimization of processes (Tao et al. 2019). Since DTs provide insights into complex systems, they then support improved decision-making, predictive maintenance, and resource optimization.

Despite the growing interest in DTs, their application in FSCs is still nascent and underexplored. Existing literature underscores the potential of DTs to transform FSC operations by improving traceability, reducing waste, and enhancing responsiveness to disruptions (Kamble et al. 2019). However, practical implementations face challenges such as data integration, interoperability, and high implementation costs (Verdouw et al. 2021).This article aims to bridge these gaps by conducting a rapid review of 28 academic articles to analyze the current state of DT applications in FSCs.

The article includes the following bases: A synopsis of the DTC foundational concepts, including its key components and how they fit in the FSC sustainability aspirations. The second section presents the practical applications of DTCs in the FSC, with specific emphasis on integration, findings, benefits, challenges, and lessons learned from case studies and frameworks. Finally, the article offers a conceptual framework for leveraging DTC in the FSC for sustainability enhancement and potential future research directions.

2. Literature Review

2.1. Digital Twin

Digital twins (DTs), introduced by Dr. Michel Grieves in 2002 (Grieves 2023), offer transformative solutions for supply chains. A DT is a virtual representation of a physical entity or process, continuously updated with real-time data to enable monitoring, simulation, and optimization. The core features of DTs include:
Connectivity: Seamless communication with physical counterparts and external systemsAutonomy: Independent operation and decision-making based on data inputs.
Traceability: Tracking changes and impacts in real time.
Customizability: Adaptability to different contexts and requirements.
Simulation: Predicting outcomes and testing scenarios.

Based on the digital twin levels of integration of (Sai et al. 2024), we can propose a categorization in the context of supply chain as follow [Figure. 1]:

Asset Twin: The double of an individual asset pertaining to vehicles, machines, or tools. Example: A digital twin for a delivery truck or a production robot.
Process Twin: A specific process, i.e., production, distribution, or inventory management based on SCOR (Supply Chain Operations Reference) processes. Example: A digital twin for the production line processes.
Enterprise Twin: The internal supply chain or procurement, production inside a single organization. Example: A digital twin of a manufacturer's entire supply chain operations.
Collaborative Twin: The supply chain links between an organization and its service providers, suppliers, and inventory service providers, e.g. Logistics or Inventory providers. Example: A digital twin to show how a manufacturer interacts with its third-party logistics providers.

Echelon Twin: The supply chain network of a single echelon connecting manufacturers to immediate suppliers and retailers. Example: A digital twin to connect a manufacturer with its key supplier and retailer.
Ecosystem Twin: The entire supply chain network spanning across multiple echelons, including suppliers, manufacturers, service providers, and end customers. Example: A comprehensive digital twin of a global supply chain network.

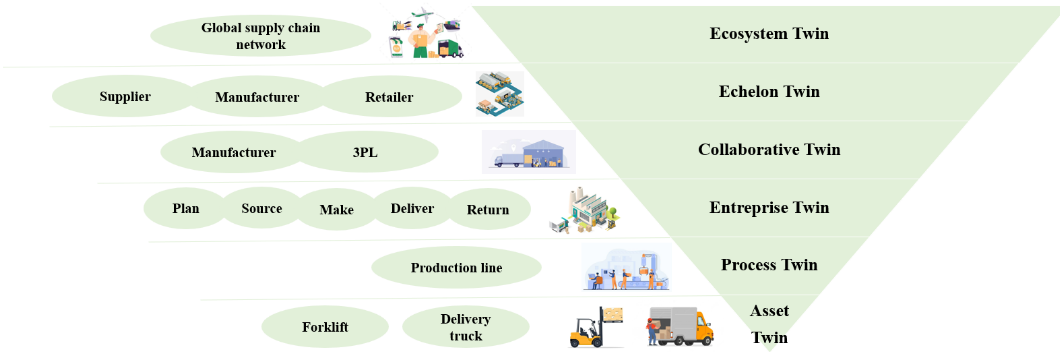

Figure 1. DT Categorization in Supply Chain

According to [7], DTs represents many benefits and drawbacks [Tab. 1]:

Table 1. Digital Twin Benefits and Challenges

Benefits	Challenges
• Allow for the simulation of processes in a virtual environment, identifying inefficiencies and optimizing waste management strategies. • Can predict equipment failures and maintenance needs, reducing downtime and preventing waste. • Provides real-time data and analytics, enabling dynamic adjustments to processes to reduce waste.	• Setting up digital twins could require significant investments in technology and expertise. • The effectiveness of the operation is determined based on the precision with which more accurate input data are obtained; otherwise, the simulation derived may not be correct and will eventually lead to inadequate decision-making. • That technology and infrastructure will not be easy on the pocket and thus not readily available for smaller food companies.

2.2. Food Supply Chain sustainability

The food supply chain represents a complex set of interconnected activities and actors, comprising farmers, processors, distributors, retailers, and consumers, which do ensure the movement of food from production to consumption (Burgos & Ivanov 2021). The general characteristic of these supply chains is therefore seasonality, perishability, and sensitivity with respect to external factors such as climate, market dynamics, and global events; leading to major challenges, namely food loss and waste, logistics inefficiencies, environmental degradation, and social inequalities (Gurrala & Hariga 2022). For instance, global food loss and waste constitute one-third of all food produced and thus pose a critical challenge to managing an FSC (Ishangulyyev et al. 2019). Additionally, disruptions such as the COVID-19 pandemic have exposed vulnerabilities in food systems, highlighting the need for enhanced resilience and adaptability (Ivanov & Dolgui 2021). These challenges underscore the necessity of rethinking traditional FSC models to ensure both efficiency and sustainability.

Sustainability in the FSC context involves meeting current food demands without compromising the ability of future generations to meet theirs. It encompasses three interconnected dimensions: economic viability, environmental stewardship, and social equity. A sustainable FSC minimizes environmental impacts, ensures fair labor practices, and promotes economic resilience across all stages of the supply chain. Strategies for enhancing sustainability include adopting precision agriculture to reduce resource use, optimizing transportation to lower carbon footprints, and implementing circular economy principles to reduce food waste and enhance recycling (Spang et al. 2019). Moreover, fostering collaboration among FSC actors and leveraging technology can improve transparency and traceability, critical for sustainability (Zhang et al. 2024).

Digital Twins are effecting some stunning transformations in the FSC through the advanced tools and systems that will enhance efficiency optimization, demand forecasting, resilience measures, and enable social impact. They allow complete visibility of the FSC, from which you can gauge where bottlenecks exist and where to mitigate concerns.

As such, effective utilization of fewer resources brings down operating costs and improves process efficiency (Melesse et al. 2023). By simulating various scenarios, DTs assist in accurate demand forecasting, aligning production with market needs, minimizing overproduction, and reducing waste (Guidani et al. 2024). DTs enhance the resilience of the FSC by allowing stakeholders to plan for contingencies and respond swiftly to disruptions, thereby maintaining continuity and reducing potential economic losses (Melesse et al.,2023). Real-time monitoring through DTs ensures adherence to safety standards and maintains product quality, thereby protecting consumer health and increasing public trust in food products (Henrichs et al. 2021). DTs contribute to sustainability by optimizing processes to reduce waste and resource consumption, aligning with societal goals of environmental conservation (Luo & Ball 2024). The adoption of DTs in the FSC creates demand for skilled professionals in technology and data analysis, leading to job creation and the advancement of workforce capabilities (Yadav & Majumdar 2024).

3. Methods

3.1. Search design

This study opted for a rapid review because it effectively summarizes knowledge from various sources in a short timeframe. In fact, such approaches are a mixture between systematic reviews and those that can be done more rapidly, making it very suitable for timeliness in research. Rapid reviews are defined as evidence synthesis in which components of systematic reviews-such as the need for comprehensive search strategies or detailed assessments of study quality-are shortened or even left out to provide information that is timely and can be acted on (Khangura et al. 2012). This methodology has become increasingly popular as a practical solution for researchers and decision-makers looking for relevant insights in emerging or evolving fields.

This paper presents the rapid review on the implementation of DT technologies in food supply chains. Traditional systematic reviews are not exhaustive, but are still efficiently used in unexplored research areas where conducting a full systematic review is time-consuming or where limited literature exists. Methodological rigor for a rapid review is ensured by, among others, a relatively simplified yet structured process comprising targeted literature searches and narrative syntheses of findings (Tricco et al. 2015). This method allows for timely generation of insights while maintaining a balance between comprehensiveness and feasibility (Tricco et al. 2022).

3.2. Search strategy

The search strategy for this rapid review was designed to systematically identify and analyze studies related to Digital Twin (DT) applications in food supply chains (FSCs). The search was with SCOPUS using research query below:
TITLE-ABS-KEY ("digital twin" AND (" food" OR "Agri") AND "supply chain")

The studies included journal and conference articles that covered only the food supply chain applications of DTs (no industrial, manufacturing, or energy-related papers). The initial search yielded 103 sources, which were screened based on relevance and inclusion criteria. Only articles that explicitly included case studies or frameworks of DT applications in FSCs were retained, resulting in a final selection of 28 articles. This targeted approach ensured that the review focused on studies offering practical insights and methodological contributions.

A structured flowchart was used to document this process [Figure 2], providing a transparent overview of the methodology. This approach follows a systematic protocol tailored to this review's focus.

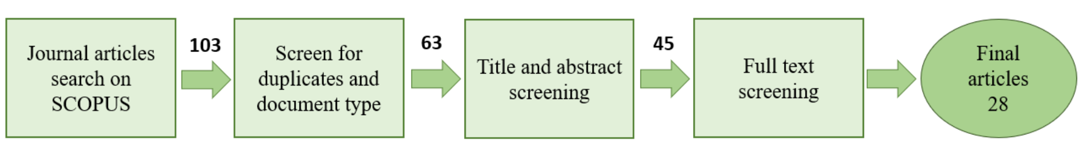

Figure 2. Flow diagram of the article selection process

The inclusion criteria prioritized peer-reviewed journal articles that addressed practical implementations of DT in FSCs, with emphasis on sustainability, operational efficiency, and technological frameworks (Tab.). Studies that lacked substantive discussion of DT applications in FSCs, or were theoretical without practical insights, were excluded [Table 2].

Table 2. Inclusion and exclusion criteria

Inclusion criteria	**Exclusion criteria**
• peer-reviewed articles, published in the last 10 years, relevant to supply chains), • Final publication stage, • Case studies or conceptual frameworks.	• Studies published in a language other than English, • Studies types: reviews, short communications, and briefs not reporting the impact of DTs through empirical studies and approaches, studies from other sectors (manufacturing, urbanization,…).

5. Results and Discussion

The rapid review identified a total of 28 peer-reviewed articles that analyze the application of digital twin (DT) technologies in food supply chains (FSCs). These articles range from 2015 to 2023, showing the growing interest in the domain. The research covers different stages of the supply chain: production, processing, storage, transportation, and retail. The focus of most of these studies was on increasing efficiency, minimizing waste, and enhancing the sustainability of food supply chains. In this regard, it is expected that the use of a digital twin would enhance food production while aiding in identifying any failures in the supply chain, understanding their root causes, and streamlining decision processes, thus minimizing food wastage and maintenance time (Guruswamy et al. 2022). Digital Twin (DT) technology is increasingly integrated into food supply chains (FSCs) for increasing efficiency, sustainability, and resilience (Burgos & Ivanov 2021). The summaries below comprise key applications, findings, types of digital twins employed, and sustainability outcomes, with reference points in the academic literature as well as real-world implementations.

Table 3 categorizes the functions of digital twins in food supply chains at different levels of application, from monitoring at the product level to insights at a global scale. Each entry encapsulates the major discoveries concerning the functional aspects of the digital twins, outlining specific abilities in monitoring, optimization, prediction, and resource management. The citations link the reader directly to the studies on which these conclusions are based and show the transformational potential of the new technologies in the context of food supply chains.

Table 3: The summaries below comprise key applications, findings, and benefits

DT Function/ Level	Key Findings	Benefits
Monitoring *Product Level*	Non-physical digital twins with the help of the physics model were used to simulate the temperature distribution within the shipments of fresh produce. 5 °C decrease in shipment temperature increased strawberry and raspberry shelf life by 36 and 73%, respectively. Optimized humidity decreased mass loss by 20%. Such optimizations enhanced the performance and sustainability of the cold chain. (Shoji et al., 2022)	Extended shelf life, reduced waste, improved efficiency

Simulation *Supply chain level*	The study delineated the emerging roles of Industry 4.0 technologies, including artificial intelligence and the Internet of Things, for digitalization in agri-food supply chains. Digital twins enabled real-time monitoring and predictive analytics to allocate resources better. Challenges include bridging the gap between legacy systems and addressing issues related to data quality. (Hassoun et al., 2023)	Real-time monitoring, predictive analytics, better resource allocation
Optimization *System level*	The study proposed a digital twin, which is regarded as a virtual framework providing full visibility of food supply chains from farm to consumer. It emphasized combining consumer awareness with digital twin modeling for food quality and waste reduction. The simulations showed fewer delays, with improved decision-making contributing to fresher product delivery. (Guidani et al., 2024)	Improved decision-making, reduced delays, enhanced supply chain visibility
Prediction *Hybrid level*	Real-time digital twins allowed dynamic planning and monitoring of supply chain operations and disruption management. Predictive analytics was to foresee demand fluctuations to optimize inventory levels. The study expressed cost savings and enhanced supply chain resilience as benefits. (Maheshwari et al., 2023)	Dynamic planning, reduced disruptions, optimized inventory
Risk Management *Entreprise level*	This research utilized biophysical digital twins to simulate the impact of cooling strategies on food quality. Temperature reductions during refrigerated storage greatly benefited product quality. Digital twins provided insightful evaluation of biocontrol treatments to reduce spoilage.(Defraeye et al., 2019)	Improved food quality, reduced spoilage during storage
Quality Assurance *Retail level*	Digital twins integrated sustainability assessments, including energy use and emissions of greenhouse gases. Real-time data integration permitted the sociological assessment of the environmental impacts. The findings support a move toward more green supply chains. (Defraeye et al., 2021)	Sustainability metrics integration, greener supply chain practices
Resource Allocation *Farm level*	Cold chain digital twins simulated the transport and storage environment. Optimized temperature and humidity management decreased food spoilage. The study pointed out the role of digital twins in the shelf life extension and energy savings. (Hu et al., 2023)	Reduced food loss, optimized energy consumption

Traceability *Distribution level*	Digital twins identified supply chain-based critical waste generation points. Utilization of digital twin simulations evaluated various waste management strategies, such as recycling and reusing wastes. It suggested a framework to provide direction through which waste can intervene at a much smaller level by separating waste into the avoidable and unavoidable categories. (Valero et al., 2023)	Targeted waste management, reduced environmental impact
Sustainability Metrics *Global level*	In the baseline analysis, conventionally accepted spoilage levels were taken into account for temperature and humidity variations by machine learning models fed with data from the digital twins. These predictive insights allowed for proactive changes to preserve product quality. Some of the key benefits identified include reduced relevant cost and maintenance of the quality of the products.(A * Udugama et al., 2023)	Proactive storage and transport adjustments, cost savings
Real-time Control *Sector level*	Digital twins simulated the performance impact of supply chain disruptions. Run the scenario analysis so the stakeholders develop proactive strategies to mitigate the risk. The research highlights the importance of DTs as part of this challenge for supply chain resilience and adaptability achievement.(Cimino et al., 2024)	Enhanced resilience, adaptability to disruptions

5.1. State of the Art of DT Usage in FSC

Some applications of digital twins in food supply chains have ranged across many critical challenges:

- Cold Chain Management: The optimization of the cold chain was by far DT's most common application, employed to monitor and control temperature, humidity, and environmental conditions during transportation. (Shoji et al., 2022) highlighted that the shelf life of raspberries and strawberries could be extended by 73% and 36%, respectively, with a 5°C decrease in shipment temperatures.
- Reduction/Prevention of Waste: Digital twins have been used to pinpoint and mitigate waste points in the supply chain. (Hassoun et al., 2023) focused on distinguishing avoidable and unavoidable food wastes, using DTs to potentially assess waste management strategies prevention, reuse, and recycling. Studies have quantified the impact of interventions, such as reducing time taken for shipment, on food quality and waste reduction.
- Sustainability Assessments: Findings have revealed that DTs supported sustainability goals by optimizing resource use and carbon emissions. These inputs included modeling on energy use, greenhouse gas emissions, and water consumption. (Maheshwari et al., 2023) recommended that they could leverage DTs to create a more sustainable food supply chain by merging real-time monitoring with predictive analytics aimed at saving resources.
- Resilience and Risk Management: Digital twins provided real-time visibility and predictive abilities that enhanced the resilience of the supply chain. For instance, (Guidani et al., 2024) simulated some disruptions to predict their probable consequence on supply chain performance using digital twins, thus enabling stakeholders to enact proactive behavior.

5.2. Emerging Trends and Opportunities

Several trends and opportunities to advance the use of digital twins in food supply chains were identified in the review:

- IoT and Blockchain Interfacing: A primary trend consists of the convergence of IoT, blockchain, AI technologies with DTs. Such integrations allow data collection to be more secure and precise, resulting in reliably functioning DT systems (A * Udugama et al., 2023).
- End-to-End Visibility: It may not be unreasonable to predict options for research that may arise in the creation of end-to-end DTs covering the entire supply chain, from farm to fork. In these systems, visibility and coordination among the various stakeholders could be achieved (Maheshwari et al., 2023).
- Collaboration and Standardization: The establishment of standardized structures for DT implementation in FSCs could encourage broad adoption and collaboration among industry players (Defraeye et al., 2021).
- Focus on Sustainability Metrics: Increasing attention is being paid to facilitating and integrating sustainability metrics, including carbon footprint, water usage, and waste alleviation, into DT frameworks. These metrics are reinforced by the global sustainability agenda and stakeholder expectations (Guidani et al., 2024) (Chen et al. 2021).

5.3. DT framework for FSC sustainability

A framework [Fig. 3] was developed to provide a systematic route to the use of Digital Twin technology for enhancing the sustainability of food supply chains (FSCs). Based on a 3-phase stratification-the pre-adoption, adoption, and post-adoption phases-the framework guides the entire implementation process of DT technology.

The pre-adoption phase highlights the foundational capabilities of DT, the technological enablers required, and the barriers to implementation. DT capabilities such as real-time analytics, visualization, simulation, prediction, and optimization enables informed decision-making and process improvement decisions. Supported by advanced technologies like AI, ML, IoT, big data, computer vision, AR, and RFID. However, during this phase, they also note considerable challenges like high investments in purchase technology and expertise, the need for accurate and reliable input data, and limited accessibility for smaller food companies due to resource constraints.

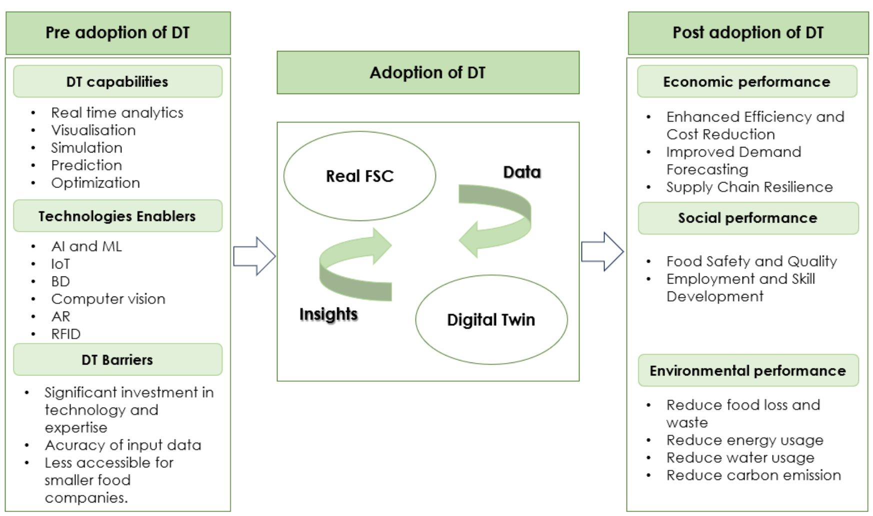

Figure 3. Digital Twin framework for food supply chain sustainability

The adoption phase sits at the heart of the framework--centering on implementation of DT in real FSC operations--and, is given reverence to a data-driven feedback loop comprising feeding the data collected from the real FSC into the DT. The DT processes this data to generate actionable insights that will help in returning positive results towards the optimization and improvements of real-world supply chain operations. This connection between of the real FSC and DT creates a dynamic exchange with the monitoring, forecasting, and optimization of processes occur continuously and in real-time.

The post-adoption phase elucidates the tangible benefits derived from DT technology, divided into three essential dimensions: economic, social, and environmental performance. Economically, DT aids in operational efficiencies and cost reductions while enhancing demand forecasts and improving the resilience of the supply chain. Socially, food safety and quality are enhanced, along with skills and employment opportunities. Environmentally, it adds to impressive sustainability results, including diminished food loss and waste, reduced energy and water use, and lower carbon emissions.

6. Conclusion

This study presents a full review and report on the digital twin applications in food supply chains, showing the transformative potential in solving the immediate issues of sustainability. By analyzing 28 academic articles, the study identifies key components in the DTs-integration of real-time data, predictive analytics, and decision support-toward integrating into the sustainability principles of the FSCs. The review showed DTs would yield many benefits, including better food traceability, reduced food waste, and improved efficiency in the operational processes; however, there still exist challenges, such as technological complexity, data interoperability problems, and high cost to implement.

The conceptual framework laid out points the way forward in employing DT technologies to enhance food supply chain sustainability, placing emphasis on collaborative efforts amongst parties, technological innovation, and supportive policies, thereby accentuating the possible use of DTs as strategic tools in building resilient and sustainable food systems, in synchrony with global goals such as the United Nations Sustainable Development Goals (SDGs). Future research should direct towards addressing technical and organizational barriers, toward establishing standardized frameworks, as well as exploring the role of emerging technologies in DT-enabled food supply chains like blockchain and artificial intelligence. This study will contribute towards a growing understanding and realization of the DTs in food supply chains, thus providing insights for researchers, practitioners, and policy makers.

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