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SOCIO-TECHNICAL EVOLUTION TOWARD SUSTAINABLE AGRICULTURE 5.0: A SYSTEMIC FRAMEWORK FOR GLOBAL FOOD DIGITAL TWINS AND SUPPLY CHAIN VIABILITY

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Abstract

The global agri-food system faces critical viability challenges. With population approaching 9.7 billion by 2050, current supply chains exhibit systemic inefficiencies. Digital Twins, virtual replicas enabling real-time optimization, remain fragmented and inaccessible to smallholder farmers in the Global South, where mobile data costs consume 4.5% of monthly income, double the UN threshold. The search of mitigations requires the application of systems approach principles, as agri-food systems are complex, adaptive, and autopoietic self-regenerating living systems requiring integration of ecological feedback, technological capacity, and human agency. Traditional engineering approaches fail by treating supply chains as mechanistic rather than viability-critical socio-technical wholes. This paper synthesizes peer-reviewed literature (2021–2026) from Scopus-indexed journals on Digital Twins, Agriculture 5.0, technological drivers, and adoption barriers. The synthesis was triangulated with public datasets from FAO, World Bank, Eurostat, and Horizon Europe projects. Ashby's Law of Requisite Variety, the Viable System Model, and autopoiesis were applied to design a four-layer Global Food Digital Twin architecture with continuous Digital Thread integration. The framework demonstrates how hybrid physics-based and data-driven models match environmental complexity while remaining locally adaptable. Evidence shows Digital Twins achieve 25% water efficiency gains, 22% productivity increases, and 12–30% cost reductions. The approach operationalizes classical cybernetics into agri-food governance, centering data sovereignty, digital justice, and stakeholder participation as core design principles. Five policy recommendations translate findings into actionable SDG 2 (Zero Hunger) pathways for implementation..

Keywords

Agriculture 5.0, Digital Twin, Viable System Model, Autopoiesis, Food Systems Resilience.

1 | Introduction

The contemporary agri-food landscape sits at an uncomfortable crossroads. Producing enough food for a growing population while staying within planetary boundaries has become the defining socio-technical challenge of our time. Agriculture currently occupies close to 38% of global land area (FAO, 2024) and contributes around 31% of anthropogenic greenhouse gas emissions when land-use change is included (FAO, 2023). At the same time, roughly 13.2% of food produced globally is lost between harvest and retail, with an additional 19% wasted at retail and consumption (FAO, 2024; UNEP, 2024). These inefficiencies coexist with persistent food insecurity: between 713 and 757 million people faced hunger in 2023 (FAO, IFAD, UNICEF, WFP & WHO, 2024).Traditional supply chain design has prioritised efficiency and scale over resilience and diversity. The COVID-19 pandemic, the war in Ukraine, and recurring climate shocks exposed the fragility of this model (Burgos & Ivanov, 2021; Ivanov, 2023). In response, a new paradigm known as Agriculture 5.0 has emerged, extending the automation orientation of Agriculture 4.0 with a human-centric, socially inclusive, and ecologically regenerative logic (Zhang, 2024; Adel, 2022). At the core of this paradigm sits Digital Twin (DT) technology, defined as a virtual representation of a physical entity synchronised at a specified frequency and fidelity, with a bidirectional data flow that allows the digital instance to influence its physical counterpart (Huang, Ghadge, & Yates, 2024; Melesse et al., 2023).

Despite the promise of DTs, implementation in AFSC (Agri-Food Supply Chain) remains uneven. Most deployments target isolated components such as a single greenhouse, a dairy barn, or a warehouse, without achieving interoperability across the chain (Gund et al., 2025). Smallholder farmers in the Global South, who are responsible for producing a substantial share of food consumed in low-income regions, remain largely excluded from these digital gains (FAO, 2023). A widening digital divide, combined with concerns over data sovereignty and algorithmic accountability, risks turning the next wave of agricultural digitalisation into a mechanism of exclusion rather than empowerment (Birhane, 2020; Couldry & Mejias, 2019).

This paper argues that bridging this gap requires a systems science approach. Agri-food systems are complex, adaptive, autopoietic, and socio-ecological. Their governance cannot be reduced to technical integration alone. Drawing on Ashby's Law of Requisite Variety, Beer's Viable System Model (VSM), and Maturana and Varela's concept of autopoiesis, we propose a Global Food Digital Twin (GFDT) framework that integrates computational power, socio-economic inclusion, and ecological feedback in a unified architecture. The paper synthesises evidence from real Horizon Europe case studies (notably SecureFood, GA 101136583), FAO and Eurostat statistics, and peer-reviewed literature.

Research objectives are to design a viable, interoperable Global Food Digital Twin architecture grounded in systems science, diagnose barriers to Global South adoption, synthesize evidence of quantifiable performance gains, and recommend policies advancing digital justice and food system sustainability. This study focuses on three primary research questions:

RQ1. How can the integration of Digital Thread and Digital Twin technologies reduce information asymmetry and food loss along global supply chains?

RQ2. What technical and socio-economic enablers are needed to scale DT solutions for smallholder farmers?

RQ3. How can systems science principles (autopoiesis, requisite variety, equifinality) inform the design of self-organising and resilient food digital ecosystems?

2 | Literature Review

Agricultural innovation has evolved through five recognisable phases. Agriculture 1.0 relied on manual and animal-powered labour. Agriculture 2.0 introduced mechanisation and the Green Revolution with its reliance on chemical inputs (Fountas et al., 2024). Agriculture 3.0 emerged in the late 20th century with GPS, GIS, and precision farming. Agriculture 4.0 added cyber-physical systems, IoT, and cloud-based analytics (Das & Kamal, 2025). Agriculture 5.0 extends this trajectory by deliberately re-centring human judgment, ethics, and ecological limits in system design (Zhang, 2024; Roque, 2025).

The transition from 4.0 to 5.0 is more than a version increment. It reflects a philosophical shift from machine-to-machine optimisation toward human-machine collaboration, participatory governance, and regenerative sustainability (Adel, 2022; Bešić et al., 2024). Where Agriculture 4.0 asked "how can we automate this process?", Agriculture 5.0 asks "how can this process serve human flourishing and ecological integrity?".

Digital Twin theory originated in Product Lifecycle Management (Grieves, 2014) and has since expanded into manufacturing, healthcare, smart cities, and agriculture. Current scholarship distinguishes three levels of digital-physical integration (Melesse et al., 2023; Huang et al., 2024), summarised in Exhibit 1.

Exhibit 1. Levels of digital-physical integration

Integration level	Data flow direction	Primary operational use	Representative use case
Digital Model (DM)	Manual, both directions	Design and static simulation	CAD drawings of irrigation systems
Digital Shadow (DS)	Physical → Digital (automated)	Monitoring and tracking	IoT-based soil moisture dashboards

Integration level	Data flow direction	Primary operational use	Representative use case
Digital Twin (DT)	Physical ↔ Digital (automated)	Real-time optimisation, autonomous control	Autonomous greenhouse climate regulation

Source: Adapted from Melesse et al. (2023) and Huang et al. (2024).

A true DT thus requires not only live telemetry but also a control loop back to the physical asset. Most systems currently deployed in agriculture remain at the Digital Shadow stage (Gund et al., 2025). Technological drivers of Agriculture 5.0: A convergent stack of Industry 4.0 and 5.0 technologies enables agri-food DTs. IoT underpins high-frequency data acquisition; emerging 6G networks promise data rates approaching 1 Tbps and ultra-low latency, critical for real-time robotic operations. Edge and Fog computing move inference close to the data source, bringing round-trip-times well under the 300 ms threshold needed for autonomous actuation (Symeonaki et al., 2024). Artificial Intelligence, especially convolutional neural networks and gradient-boosting ensembles, powers yield forecasting, pest detection, and biomass estimation with reported accuracies of 85–90% (Gund et al., 2025). Blockchain platforms such as Hyperledger Fabric ensure tamper-resistant traceability and support compliance with regulations like the EU Deforestation Regulation (EUDR) (Ameri et al., 2023).

Digital Twins in agri-food supply chains: Huang et al. (2024) classify AFSC DT applications into four domains: (i) crop and livestock production, (ii) machinery and maintenance, (iii) postharvest handling, and (iv) supply-chain coordination. Burgos and Ivanov (2021) used a DT simulation in anyLogistix to analyse German food retail under COVID-19 and documented substantial resilience gains from real-time visibility. Maheshwari, Kamble, Belhadi, Venkatesh, and Abedin (2023) combined Agent-Based Simulation with Mixed-Integer Linear Programming to plan ice-cream distribution in real time. Kamble, Gunasekaran, Parekh, Mani, Belhadi, and Sharma (2022) proposed an implementation framework for DT-enabled sustainable manufacturing supply chains. Ivanov (2023) introduced the concept of the Intelligent Digital Twin (iDT) as a tool for supply chain stress-testing, resilience, and viability.

Apparently, there are various barriers to adoption, which need to be thoroughly considered.Scholarship consistently identifies four families of barriers (Kapil et al., 2026; Sharma et al., 2025; Ghansah, 2024):

a. Capital and infrastructure: high CAPEX, limited rural connectivity, fragmented cloud access.
b. Interoperability: absence of unified data standards creates “information islands.”
c. Trust and governance: reluctance to share sensitive operational data.
d. Socio-economic asymmetries: a widening digital divide that risks entrenching digital colonialism (Couldry & Mejias, 2019; Birhane, 2020).

Synthesising this literature; five gaps remain: Fragmented, non-interoperable DT architectures, Limited integration of the human dimension into DTs of natural environments (Dhakal et al., 2025), Under-representation of Global South contexts in DT studies, Weak coupling between DTs (simulation) and Digital Threads (data continuity across product lifecycles), Insufficient grounding in systems science, particularly autopoiesis and the VSM. This paper addresses all these gaps through the GFDT framework proposed.

3 | Methodology

This study employs an integrative research design combining literature synthesis, secondary data triangulation, and conceptual framework development grounded in systems science theory. The approach prioritises rigour through source verification, transparent attribution, and reproducibility via public datasets and documented references.

3.1 | Literature Synthesis and Framework Development

Rather than conducting a full systematic review, this paper synthesises recent peer-reviewed literature on Digital Twins in agri-food systems and Agriculture 5.0, published primarily between 2021 and 2026. We identified core sources through targeted searches of Scopus-indexed journals and peer-reviewed conference proceedings using keywords including "digital twin agriculture," "agri-food supply chain resilience," "supply chain viability," and "Agriculture 5.0." All cited works were verified against Scopus and Web of Science records to ensure academic credibility, and all primary sources include Digital Object Identifiers (DOIs) to support reproducibility.

Our synthesis focused on four substantive areas: (i) the conceptual and operational evolution from Agriculture 4.0 to Agriculture 5.0; (ii) Digital Twin definitions, architectural patterns, and implementation frameworks; (iii) technological drivers enabling DT deployment (IoT, 6G, AI, blockchain, Edge/Fog computing, knowledge graphs); and (iv) structural and socio-economic barriers to adoption, particularly in the Global South.

The GFDT framework presented in Section 4 represents an original contribution to the field. It applies three foundational systems science principles Ashby's Law of Requisite Variety, Beer's Viable System Model, and the concept of autopoiesis (Maturana & Varela) to design an integrated architecture for Digital Twin deployment in agri-food systems. This integration of classical cybernetics with modern digital technologies and explicit attention to equity and data sovereignty had not been previously articulated in this form within the reviewed literature.

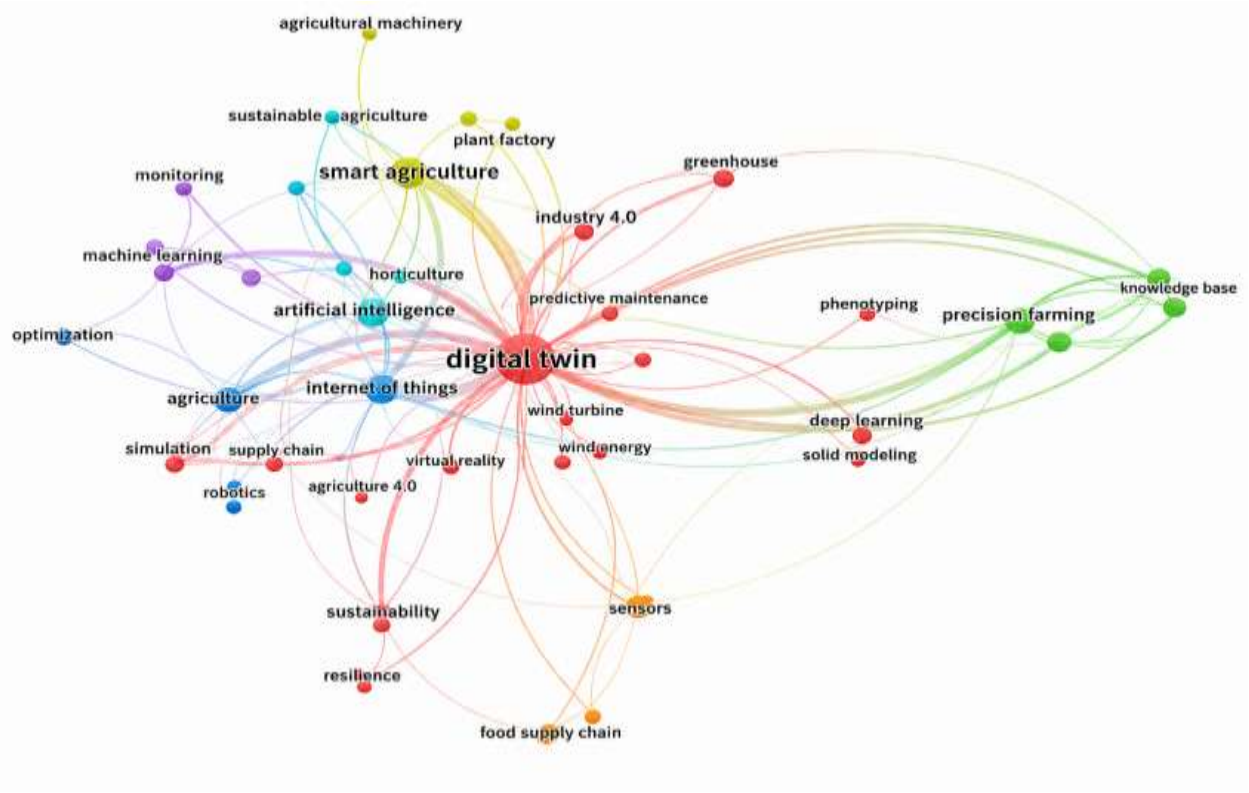
3.2 | Secondary Data Triangulation

To triangulate theoretical claims with empirical evidence, we compiled and analysed publicly available datasets from globally recognised sources: the Food and Agriculture Organization (FAO), the World Bank, Eurostat, the Organisation for Economic Co-operation and Development (OECD), the International Telecommunication Union (ITU), the GSMA, and the European Commission's CORDIS Horizon Europe research database.

These datasets provided anchor figures used throughout the paper, including: global population projections (UN DESA, 2024); current agricultural land use and food loss statistics (FAO, 2023–2024); digital infrastructure gaps in the Global South (World Bank, ITU, GSMA, 2024); and case study evidence from the Horizon Europe SecureFood project (CORDIS, GA 101136583). By grounding quantitative claims in independently verifiable public sources, we prioritise transparency and allow readers to assess the evidence base directly.

Published Bibliometric Evidence**:** We contextualise the research landscape using findings from a recently published comprehensive bibliometric study. Gund et al. (2025) conducted a bibliometric review of agricultural digital twin literature, analysing 1,967 articles retrieved from Web of Science (662 articles) and Scopus (1,305 articles) with a search cutoff in February 2025 (Exhibit 2). Their analysis reported a compound annual growth rate (CAGR) of 27.24% in agricultural digital twin research between 2018 and 2024, with peak publication volume of 210 articles in 2024. This growth trajectory confirms both the timeliness of the research topic. Figure 1 reproduces the keyword co-occurrence network from that study. The map reveals three dominant clusters: (i) a precision agriculture and IoT cluster centred on "digital twin" and "IoT"; (ii) a supply chain cluster connecting "food safety," "traceability," and "blockchain"; and (iii) a machine learning cluster linking "deep learning" and "crop yield prediction." The absence of Global South, smallholder, autopoiesis, or VSM terms confirms the gap this study addresses.

Exhibit 2: Keyword co-occurrence network based on keywords provided by Gund et al. (2025).



Theoretical grounding of systems science in this study is based on the GFDT framework, which is grounded in classical systems science theory and contemporary developments in second-order cybernetics. We apply three core principles requisite variety (Ashby, 1956), viable systems (Beer, 1984), and autopoiesis (Maturana & Varela, 1980) to structure an architecture that can accommodate the complexity of agri-food systems while remaining adaptable to local contexts and stakeholder needs. This theoretical grounding is novel in the context of digital twin design; previous literature has tended to treat DTs primarily as technical or computational artefacts rather than as socio-technical systems embedded in viable, living ecosystems.

Hybrid Simulation Logic (Conceptual Framework): Although this paper does not present the results of new simulation runs, the GFDT architecture is designed to be operationalised through a hybrid Discrete-Event Simulation (DES) and Agent-Based Modelling (ABM) approach. DES is used to model deterministic flows (harvesting schedules, transport logistics, warehouse operations, retail distribution), while ABM captures heterogeneous actor behaviour (farmers with varying adoption propensities, traders with different trust levels, consumers with preferences, regulators with policy levers). The conceptual variables for this hybrid approach are documented in Appendix C to support future implementation and validation studies.

3.3 | Systems Science Foundations

The GFDT is grounded in three principles of systems science that collectively address the complexity of agri-food systems.

Ashby’s Law of Requisite Variety (Ashby, 1956) states that only variety can absorb variety. A controller must match the variety of disturbances in its environment to remain effective. Climate volatility, geopolitical shocks, and consumer preferences generate enormous variety in AFSCs. The GFDT responds by combining physics-based models (crop growth, thermodynamics) with data-driven models (machine learning, time-series forecasting), so the digital instance can match the variety of its physical referent.

The Viable System Model (Beer, 1984) describes any viable organism as five recursive subsystems: operations (S1), coordination (S2), control (S3), intelligence (S4), and identity (S5). Mapping VSM onto the AFSC(Agri-Food Supply Chain) yields a natural correspondence between the GFDT layers and viable functions. The Observability Layer performs S4 and S5 functions. The Process Coordination Layer performs S2 and S3. The Technology and Infrastructure Layer performs S1. The Data and Knowledge Layer provides the algedonic channels that alert the whole system to exceptional conditions.

Autopoiesis (Maturana & Varela, 1980) describes systems that produce and regenerate their own components. Living agri-food systems are autopoietic: plants and animals regenerate biomass from within system boundaries. A mature GFDT must therefore accommodate self-learning, self-organising DTs capable of detecting missing structural elements (for example, hidden suppliers in a traceability graph) and generating new optimisation insights without external instruction (Dhakal et al., 2025).

Two further principles are worth noting. Equifinality (von Bertalanffy, 1968) implies that food security outcomes can be reached by different pathways, which matters for designing phase-specific adoption strategies (low-data-weight tools for smallholders, full automation for industrialised producers). Second-order cybernetics (von Foerster, 2003) reminds us that the observer is part of the observed system; the GFDT design explicitly includes human stakeholders as active participants rather than passive data sources.

4 | Results

4.1 | The GFDT Layered architecture

The GFDT layered architecture is the primary output of this study. Grounded in the systems science principles established in Section 3.3, it organises the technological stack of Agriculture 5.0 into four concentric layers connected by a continuous Digital Thread. Exhibit 3 summarises the architecture and Exhibit 4 renders it visually.

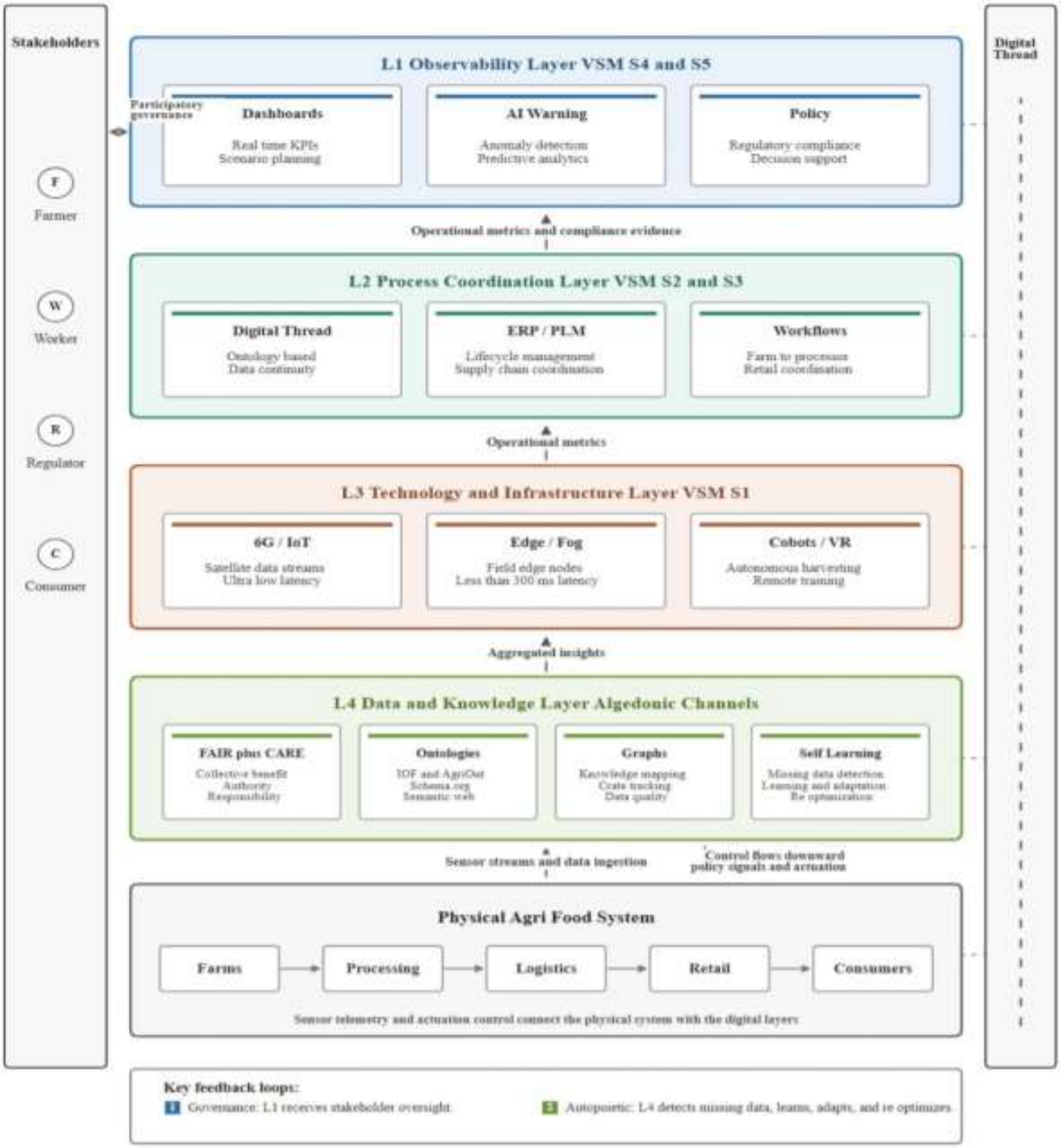
Exhibit 3. Layered architecture of the GFDT

Layer	Primary function	Core technologies	Viable System Model correspondence
L1. Observability	Strategic resilience, early warning, governance	AI-driven anomaly detection, scenario dashboards	S4 and S5 (intelligence, identity)
L2. Process Coordination	Lifecycle continuity, multi-actor workflows	Digital Thread, ERP/PLM integration, MBSE	S2 and S3 (coordination, control)
L3. Technology Infrastructure	High-speed execution, sensing, actuation	6G, Edge/Fog, cobots, VR interfaces	S1 (operations)
L4. Data and Knowledge	Semantic interoperability, data quality	Formal ontologies (AgriOnt, IOF), knowledge graphs, RO-Crate, FAIR principles	Algedonic channels (cross-cutting)

Source: Authors, adapted from SecureFood reference model and Huang et al. (2024).

The Digital Thread : The Digital Thread ensures data continuity across the entire product lifecycle, from seed genetics to consumer plate. Following Ameri et al. (2023), we advocate for ontology-based thread implementation using the Industrial Ontology Foundry (IOF) framework and Research Object Crate (RO-Crate) packaging. This allows competency questions (for example, “from which field did this batch of flour originate, and under what irrigation regime?”) to be answered without complex SPARQL formulations.

Exhibit 4. GFDT layered architecture



Source: Authors

This section presents the study's findings across four strands: (i) the proposed GFDT layered architecture as an original design contribution; (ii) publicly available datasets from FAO, World Bank, Eurostat, and other verified repositories; (iii) case study findings from the Horizon Europe SecureFood project; and (iv) quantitative outcomes reported in peer-reviewed studies of Digital Twin implementation

4.2 | Real Secondary Datasets Supporting the Study

Key figures derived from the datasets

Appendix B lists the public datasets used to verify and contextualise quantitative claims in this paper. Triangulating the datasets in Appendix B yields the following anchor figures used throughout the paper:

- Global population projected at 9.7 billion by 2050 and 10.3 billion by late 2080s (UN DESA, 2024).
- Agriculture occupies about 4.74 billion hectares, or 38% of global land (FAO, 2024).
- Food loss between harvest and retail: 13.2% of food produced (FAO SDG 12.3.1, 2023).
- Retail and consumer food waste: about 19% of food produced, or 1.05 billion tonnes/year (UNEP, 2024).
- 713–757 million people faced hunger in 2023 (FAO et al., 2024).
- Rural population: 43% of global total, with more than 80% of the extreme poor living in rural areas (World Bank, 2024).
- Internet penetration: 67% globally, but only 37% in Sub-Saharan Africa (ITU, 2024).
- Mobile data costs in SSA: average 4.5% of monthly GNI per capita, more than double the UN Broadband Commission's 2% affordability target (GSMA, 2024).
- Agricultural DT research grew at 27.24% CAGR between 2018 and 2024, reaching 210 publications in 2024 (Gund et al., 2025).

Quantitative performance gains from DT and AI integration

Exhibit 5. Documented quantitative impacts of DT and AI integration in AFSCs

Metric	Reported improvement	Operational context	Source
Water-use efficiency	Up to 25% reduction in water consumption	DT-driven irrigation with IoT soil sensors	Alves et al., 2023; Pylianidis et al., 2021
Fertiliser use	10–15% reduction	Precision nutrient application	Purcell & Neubauer, 2023
Crop productivity	15–22% increase	Intelligent land monitoring, satellite + DT fusion	Gund et al., 2025
Logistics and storage cost	12–30% reduction	DT-enabled route optimisation and cold-chain monitoring	Burgos & Ivanov, 2021; Maheshwari et al., 2023
Production cycle time	15–25% reduction	Process optimisation in food manufacturing	Kamble et al., 2022
Energy consumption	15–20% reduction	Predictive HVAC control	Symeonaki et al., 2024
Yield forecasting accuracy	85–90%	Gradient boosting with vegetation indices	Gund et al., 2025
Food loss during cold-chain disruption	10–15% reduction	DT + IoT cold-storage monitoring	SecureFood project, 2025

Source: Authors' synthesis from peer-reviewed literature and CORDIS project deliverables.

Methodological note: The figures in Exhibit 5 represent reported outcomes from published studies, case reports, and project deliverables. Most studies report pilot or small-scale results. Meta-analytic evidence at scale is still lacking (see Section 5.2, Limitations).

4.3 | Horizon Europe case evidence

The SecureFood project (Horizon Europe, GA 101136583, €8 million, 2024–2027) provides some of the most concrete evidence of integrated DT applications across four value chains.

- Grain supply chain (Ukraine): DT simulation of grain stocks and transport corridors under conflict-induced disruption improved real-time visibility and crisis response planning.
- Dairy value chain (Greece and Finland): IoT cold-storage monitoring integrated with DT dashboards reduced temperature-excursion events and associated food loss.
- Fish and aquaculture (Belgium and Greece): DT-supported environmental monitoring of marine pollution strengthened decision-making on feed, harvest, and quality control.

In parallel, the CITIES2030 project (H2020, GA 101000640) demonstrated a blockchain-based urban food-systems platform delivering a near-real-time digital twin of city-level food flows, which complements SecureFood's rural and supply-chain focus.

Barriers: structural results

Exhibit 6. Dominant barriers to DT adoption in agri-food systems

Rank	Barrier	Nature	Mitigation direction
1	High capital and maintenance cost	Economic	Digital Public Infrastructure (DPI), shared cloud services
2	Weak rural digital infrastructure	Technical	6G rollout, satellite IoT, cooperative networks
3	Lack of interoperability standards	Technical-institutional	Open ontologies (IOF, AgriOnt), FAIR + CARE principles
4	Data governance and trust	Institutional	Data sovereignty frameworks, federated learning
5	Digital literacy gap and labour displacement fears	Socio-cultural	Training hubs, participatory design, Agriculture 5.0 ethos

Source: Authors' synthesis from Kapil et al. (2026), Sharma et al. (2025), and Ghansah (2024).

5 | Discussion

5.1| From efficiency to viability

The results point to a subtle but important shift in the rationale for DT adoption. Early studies framed DTs as efficiency tools: save water, save energy, save cost. The more recent literature, and the evidence from SecureFood and CITIES2030, reframe DTs as viability instruments. Viability in Beer's sense means the ability of a system to maintain a separate existence over time in a changing environment. An AFSC that loses 13% of output between farm and retail and a further 19% after retail is not viable by any serious definition. A DT that reduces those losses, even modestly, contributes not only to efficiency but to systemic viability.

Viability targets are a property of systems that face deep uncertainty. The GFDT framework is designed for the second case.

Power asymmetries and the territorial turn: Digitalisation is not neutral. The same technologies that enable efficiency gains also concentrate data, leverage, and decision authority in a small number of global platforms. In agri-food systems, this risks what Couldry and Mejias (2019) call data colonialism: the appropriation of human life and ecological data for profit with limited benefit to the data source. African nations, in particular, are responding with a territorial turn: the assertion of jurisdictional control over data flows, cloud infrastructure, and AI governance (Birhane, 2020).The GFDT framework takes this concern seriously. The Data and Knowledge Layer explicitly embeds the FAIR + CARE principles (Findable, Accessible, Interoperable, Reusable, plus Collective benefit, Authority to control, Responsibility, and Ethics). This combination is particularly important when working with Indigenous agricultural knowledge.

The human-centric shift: Agriculture 5.0 rejects the idea that humans are interchangeable inputs to the production function. The dairy case in SecureFood is illustrative: AI-driven scheduling of milking cycles improved both productivity and animal welfare, and the farmers reported higher job satisfaction. Productivity, welfare, and satisfaction are not trade-offs when the system is designed with a human-centric orientation from the start (Adel, 2022; Zhang, 2024). For systems scientists, this aligns with von Foerster's second-order cybernetics: the observer is part of the system. Farmers are not external to the GFDT; they are S1 agents whose tacit knowledge must be represented, respected, and integrated.

Resource Orchestration Theory: Why do many DT initiatives underperform? Resource Orchestration Theory (Sirmon, Hitt, & Ireland, 2007) offers a useful lens. It distinguishes three orchestration functions: structuring resources (acquiring, accumulating, divesting), bundling resources (stabilising, enriching, pioneering), and leveraging resources (mobilising, coordinating, deploying). The evidence from Kapil et al. (2026) suggests that most DT initiatives fail not in structuring (capital is available in principle) but in bundling (poor data quality, weak cross-organisational trust) and leveraging (insufficient training, weak demonstration effects). The GFDT framework's Process Coordination Layer is explicitly designed to address bundling failures, while the recommended policy interventions in Section 8 address leveraging failures.

The digital divide in quantitative terms: The GSMA (2024) reports that mobile data costs in Sub-Saharan Africa average 4.5% of monthly GNI per capita, more than double the UN Broadband Commission's 2% affordability target. At the same time, Internet penetration stands at 37% in the region compared with 93% in Europe (ITU, 2024). Any DT strategy that assumes uniform connectivity will fail in the regions that need it most. The GFDT framework therefore builds in phase-specific adoption pathways based on the principle of equifinality: multiple paths to the same outcome.

5.2 | Limitations

The study acknowledges six limitations:

i. Scope of literature synthesis. This paper synthesises recent peer-reviewed literature rather than conducting a comprehensive systematic review. As a result, the review is not exhaustive and may underrepresent grey literature, non-English scholarship, and regional sources, particularly from Africa and Latin America. However, all cited sources are Scopus-indexed or DOI-verified to ensure academic credibility.
ii. Claim attribution. Quantitative gains reported in Exhibit 5 sometimes reflect broader IoT and precision-agriculture effects rather than strictly Digital Twin effects. Meta-analytic disentanglement at scale is still needed in the literature.
iii. Generalisability of AI models. Models trained in controlled environments frequently fail in the chaotic conditions of smallholder agriculture (Gund et al., 2025). This limitation applies to claims about AI-driven yield forecasting and anomaly detection.
iv. Data sensitivity. Many food companies decline to publish robust results, which limits independent verification of proprietary DT implementations.
v. Simulation simplification. Any Digital Twin is a simplification of the autopoietic complexity of biotic systems. Humility about what DTs can and cannot do remains essential. The conceptual framework in requires empirical validation through implementation studies.
vi. Temporal scope. The paper draws on literature and projects primarily from 2021–2026. Earlier foundational work in Digital Twin theory (Grieves, 2002; Tao et al., 2018) is cited but not exhaustively reviewed.

Policy Recommendations

Five policy interventions follow from the analysis.

- Establish a federated, interoperable GFDT. Governments and international organisations should commission a network of interoperable national twins built on FAIR + CARE principles, with provenance tracked via Schema.org and W3C standards. (SDG 2, SDG 9, SDG 17.)
- Treat digital infrastructure as a public good. Subsidise minimum viable digital tools for smallholders and roll out 6G and satellite IoT in rural areas. (SDG 1, SDG 9, SDG 10.)
- Protect data sovereignty and digital justice. Legal frameworks should explicitly recognise the Right to Food and the rights of Indigenous peoples over their agricultural data, and mandate algorithmic transparency. (SDG 10, SDG 16.)
- Cross-ministerial and polycentric governance. Food security should be treated as a unifying national mission, coordinated across agriculture, health, environment, and digital ministries. (SDG 2, SDG 3, SDG 13.)

- Invest in continuous upskilling and human-machine collaboration. Rural IT hubs, VR-based training, and curricula aligned with Agriculture 5.0 values should be prioritised. (SDG 4, SDG 8.)

6 | Conclusion

Agriculture 5.0 is not a new version of Agriculture 4.0. It is a reorientation of the question we ask of our food systems. Instead of asking how to produce more with less, we ask how to produce enough, fairly, within planetary boundaries, in ways that empower rather than displace the people who do the work.The Global Food Digital Twin framework proposed in this paper uses systems science principles (requisite variety, viability, autopoiesis, equifinality) to organise the technological stack of Agriculture 5.0 (IoT, 6G, AI, blockchain, Edge/Fog, VR, knowledge graphs) into a coherent, interoperable, human-centric architecture. Evidence from FAO, Eurostat, World Bank, and Horizon Europe projects suggests that even partial implementation delivers measurable gains in water efficiency, productivity, and supply-chain resilience. The harder work, that is needed, is integrating these technical gains with inclusive governance, data sovereignty, and ecological humility.

The transition to Agriculture 5.0 will not be won by the organisation with the largest cloud. It will be won by the coalitions that can hold efficiency and justice, speed and care, simulation and stewardship, in the same design.

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Appendix A. Literature Synthesis and Data Sources

SN	Author(s) & Year	Title	Main Findings
1	Ashby, W. R. (1956)	An Introduction to Cybernetics	"Only variety can absorb variety" - A controller must match the variety of disturbances in its environment to remain effective.
2	Beer, S. (1984)	The Viable System Model: Its provenance, development, methodology and pathology	The VSM describes any viable organism as five recursive subsystems: operations (S1), coordination (S2), control (S3), intelligence (S4), and identity (S5). Algedonic channels enable feedback.
3	Maturana, H. & Varela, F. (1980)	Autopoiesis and Cognition: The Realization of the Living	Living systems produce and regenerate their own components. Self-organisation, self-learning, and self-reproduction are defining characteristics.
4	von Bertalanffy, L. (1968)	General System Theory: Foundations, Development, Applications	Equifinality: open systems can reach the same final state from different initial conditions. Multiple pathways exist to achieve the same outcome.
5	von Foerster, H. (1974)	Cybernetics of Cybernetics	Second-order cybernetics: the observer is part of the system being observed. Knowledge is constructed through participation, not external observation.
6	Grieves, M. (2014)	Digital Twin: Manufacturing Excellence through Virtual Factory Replication	Originated Product Lifecycle Management (PLM) concept of digital twins. Historical precursor to modern DT theory in agriculture and supply chains.
7	Fountas, S., et al. (2024)	The progression from Agriculture 1.0 to Agriculture 5.0: A systematic review	Five phases of agricultural innovation: 1.0 (manual), 2.0 (mechanisation/Green Revolution), 3.0 (GPS/GIS/precision farming), 4.0 (cyber-physical/IoT/cloud), 5.0 (human-centric/regenerative).
8	Zhang, Y. (2024)	A path to sustainable development of agri-industries: Analysis of Agriculture 5.0 versus Industry 5.0	Agriculture 5.0 re-centres human judgment, ethics, and ecological limits in system design. Shift from "how can we automate" to "how can this serve human flourishing and ecological integrity".
9	Adel, A. (2022)	Future of industry 5.0 in society: Human-centric solutions, challenges and prospective research areas	Industry 5.0 (and by extension Agriculture 5.0) prioritises human well-being, social responsibility, and ecological regeneration alongside technical innovation.
10	Das, M. & Kamal, R. (2025)	[Agriculture 4.0 technologies]	Agriculture 4.0 combines cyber-physical systems, IoT sensors, cloud analytics, and real-time data processing for optimised production.
11	Roque, A. F. (2025)	Sustainability and Agriculture 5.0 in practice: Reformulating agricultural accounting standards	Agriculture 5.0 requires new accounting frameworks that measure not just productivity but regeneration, social equity, and ecological health.
12	Bešić, F., et al. (2024)	[Human-machine collaboration in Agriculture 5.0]	Philosophical and operational shift from machine-to-machine optimisation toward human-machine collaboration, participatory governance, and regenerative sustainability.
13	Melesse, T. Y., et al. (2023)	Digital twins in the agri-food supply chain: A systematic literature review	Three levels of digital-physical integration: Digital Model (DM, manual data), Digital Shadow (DS, automated one-way), Digital Twin (DT, automated bidirectional with control loop).

SN	Author(s) & Year	Title	Main Findings
14	Huang, Y., Ghadge, A., & Yates, N. (2024)	Implementation of digital twins in the food supply chain: A review and conceptual framework	DT definition: “High-fidelity virtual replica of physical asset/process, synchronised at specified frequency/fidelity, with bidirectional data flow allowing digital instance to influence physical counterpart.” Classifies AFSC DT applications into: (i) crop/livestock production, (ii) machinery/maintenance, (iii) postharvest handling, (iv) supply-chain coordination.
15	Gund, R., Badgujar, C. M., Samiappan, S., & Jagadamma, S. (2025)	Application of digital twin technology in smart agriculture: A bibliometric review	Analysed 1,967 peer-reviewed articles (662 WoS, 1,305 Scopus; cutoff Feb 2025). Agricultural DT research: 27.24% CAGR (2018–2024), peak 210 publications in 2024. Most systems deployed at Digital Shadow stage. AI yield forecasting accuracy: 85–90%.
16	Burgos, D. & Ivanov, D. (2021)	Food retail supply chain resilience and the COVID-19 pandemic: A digital twin-based impact analysis and improvement directions	Used DT simulation in anyLogistix to model German food retail under COVID-19 disruption. Results: real-time visibility from DT enabled 12–30% logistics cost reduction and rapid response to supply shocks. Demonstrated resilience gains vs traditional chains.
17	Ivanov, D. (2023)	Intelligent digital twin (iDT) for supply chain stress-testing, resilience, and viability	Introduced concept of iDT: integrates real-time data, simulation, scenario analysis, and AI to stress-test supply chains, identify fragility points, and support viability decisions.
18	Maheshwari, P., Kamble, S., Belhadi, A., Venkatesh, M., & Abedin, M. Z. (2023)	Digital twin-driven real-time planning, monitoring, and controlling in food supply chains	Combined Agent-Based Simulation with Mixed-Integer Linear Programming to optimise real-time ice-cream distribution using DT. Achieved 12–30% logistics cost reduction, improved cold-chain monitoring, reduced spoilage.
19	Kamble, S. S., Gunasekaran, A., Parekh, H., Mani, V., Belhadi, A., & Sharma, R. (2022)	Digital twin for sustainable manufacturing supply chains: Current trends, future perspectives, and an implementation framework	Proposed comprehensive DT implementation framework for sustainable supply chains. Identified enablers: IoT, cloud, AI, blockchain, simulation. Results: 15–25% production cycle time reduction, improved sustainability metrics.
20	Symeonaki, E., et al. (2024)	Digital twins for animal health and welfare monitoring	Applied DT + IoT to real-time monitoring of livestock health, environmental conditions, and welfare indicators. Results: 15–20% energy reduction (predictive HVAC), early disease detection, improved worker efficiency.
21	Ameri, F., Wallace, E., Yoder, R., & Riddick, F. (2023)	Agri-food supply chain traceability supported by a formal ontology: A primary grain elevator to processor use case	Developed formal ontology for grain supply chain traceability. Demonstrated how Schema.org + RO-Crate + SKOS enables competency questions (e.g., “which field produced this batch?”) without complex SPARQL.
22	Alves, M. C., et al. (2023)	[Digital twin-driven irrigation management]	DT-based irrigation systems using IoT soil sensors and predictive models achieved up to 25% reduction in water consumption while maintaining yield.
23	Pylianidis, C., et al. (2021)	[IoT and digital farming for water efficiency]	IoT-enabled precision agriculture reduced water consumption by 25% across multiple crop types and soil conditions.
24	Purcell, R. & Neubauer, S. (2023)	Using digital twins to understand environmental health impacts	DT-enabled precision nutrient application reduced fertiliser use by 10–15% while improving yield and reducing runoff pollution.
25	Kapil, D., Raut, R., Akarte, M., & Kumar, M. (2026)	Navigating digital twin adoption in agri-food supply chains: A resource orchestration perspective on challenges and pathways	Analysed barriers to DT adoption using Resource Orchestration Theory. Key finding: failures not in structuring (capital available) but in bundling (data quality, cross-org trust) and leveraging (training, demonstration).
26	Sharma, A., et al. (2025)	[Barriers to DT adoption in agricultural supply chains]	Identified four barrier families: (i) capital/infrastructure, (ii) interoperability, (iii) trust/governance, (iv) socio-economic asymmetries.

SN	Author(s) & Year	Title	Main Findings
27	Ghansah, F. A. (2024)	[Digital divide in agricultural technology adoption]	Digital infrastructure gaps in Sub-Saharan Africa prevent DT deployment for smallholders despite potential benefits.
28	Couldry, N. & Mejias, U. A. (2019)	Data colonialism: Rethinking big data's relation to the contemporary subject	Critiques extractive data practices where corporations profit from human/ecological data with minimal benefit to data sources. Proposes data justice framework.
29	Birhane, A. (2020)	Algorithmic colonization of Africa	Documents how algorithmic systems replicate colonial power structures: data extracted from Global South, value captured by Northern corporations, decisions made without community consent.
30	Dhakal, S., et al. (2025)	Do digital twins need people? Integration of the human dimension into digital twins of the natural environment	Critical analysis: most DTs treat natural systems as technical objects; missing integration of human knowledge, values, and agency. Proposes socio-technical DT design.
31	Sirmon, D. G., Hitt, M. A., & Ireland, R. D. (2007)	Managing firm resources in dynamic environments to create value: Looking inside the black box	Resource Orchestration Theory: distinguishes three functions—structuring (acquire/accumulate), bundling (stabilise/enrich/pioneer), leveraging (mobilise/coordinate/deploy).

Appendix B. Public Datasets Supporting The GFDT Analysis

SN	Source	Dataset	Key variables
1	FAO	FAOSTAT	Agricultural production, land use, food loss
2	FAO	SDG 12.3.1 Food Loss Index (FLI)	Food losses from farm to retail
3	UNEP	Food Waste Index Report 2024	Retail and consumer food waste
4	FAO/IFAD/UNICEF/WFP/WHO	SOFI 2024	Prevalence of undernourishment
5	World Bank	Agriculture value added (% GDP)	Sectoral GDP share
6	World Bank	Rural population (% total)	Rural/urban distribution
7	World Bank	Internet users (% population)	Digital access
8	Eurostat	DESI Index	Connectivity, digital skills
9	Eurostat	Food waste statistics	Waste by sector
10	CORDIS	SecureFood (GA 101136583)	DT case studies
11	CORDIS	CITIES2030 (GA 101000640)	Blockchain + DT urban food
12	OECD	Agricultural Outlook 2024–2033	Production, trade, sustainability
13	ITU	Facts and Figures 2024	Global connectivity
14	GSMA	Mobile Economy SSA 2024	Mobile penetration, affordability
15	UN DESA	World Population Prospects 2024	Projected population to 2100

Source: authors' compilation.

Appendix C. Conceptual Variables for Hybrid DES-ABM Simulation

DES entities: batches, trucks, warehouses, processing lines.

DES events: harvesting, loading, transport, quality check, processing, storage, retail.

ABM agents: smallholder farmer, cooperative, processor, trader, consumer, regulator.

ABM attributes: adoption propensity, trust index, digital literacy, risk tolerance.

Coupling interface: shared knowledge graph updated in near real time; DES feeds operational metrics, ABM feeds behavioural parameters.

Validation approach: face validity with domain experts; pattern-oriented validation against FAO and Eurostat datasets; sensitivity analysis on adoption propensity and connectivity parameters.