ASEAN Entrepreneurship Journal (AEJ)

An Integrated Layered Framework for Digital Transformations in the Agricultural Supply Chain: A Strategic Conceptual Perspective

Ting Ting Chen[1 2], Azilah Binti Anis[3*]
[1] Guangxi Electrical Polytechnic Institute, Xixiangtang District, Nanning, 530007 Guangxi, China.
[2] Faculty of Business and Management, Universiti Teknologi MARA, 42300 Shah Alam, Selangor, Malaysia. Email:chentt2023@gmail.com
[3] Department of Technology and Supply Chain Management, Faculty of Business and Management, Universiti Teknologi MARA, Selangor Branch, 42300 Puncak Alam Campus, Selangor, Malaysia. Email: azilahanis@uitm.edu.my

*Corresponding Author

Abstract
This paper develops a conceptual framework for digital transformation in the agricultural supply chain. Subsequently, it suggests that a comprehensive 'Integrated Layered Framework' be formulated where the six core technologies namely Internet of Things (IoT), Blockchain, Big Data/Cloud Computing, Artificial Intelligence (AI), Machine Learning (ML), Digital Twins and Advanced Monitoring are engaged at the three interconnected layers i.e. Device (data collection), Edge (real-time processing) and Cloud Layers (advanced analytics). This framework maps technology applications across production, processing, logistics and retail stages while outlining a progressive transformation pathway from essential digitalisation to comprehensive intelligence. Bidirectional flows are illustrated in the framework, showing how technologies interact synergistically to address agricultural challenges, including fragmentation, inefficiency, and information asymmetry. However, despite these significant potential benefits, the implementation of this framework faces barriers, including digital literacy gaps, infrastructure limitations and economic constraints. Nonetheless, this framework provides stakeholders with a systematic and structured approach towards implementing digital solutions that guarantee agricultural operations' efficiency, transparency, and sustainability.

Keywords: Digital Technology Applications, Agricultural Supply Chain, Integrated Framework, Digital Transformation.

ARTICLE INFORMATION
Received: 16 Jun 2025
Revised: 29 Jun 2025
Accepted: 01 Jul 2025
Published: 13 Aug 2025

INTRODUCTION

In recent years, the global agricultural sector has been undergoing a profound transformation, driven by the integration of digital technologies into traditional farming practices (Du et al., 2023). This shift comes at a time when global food systems are facing a convergence of critical challenges, including climate change, population growth, the depletion of natural resources, and increasing consumer demands for transparency and sustainability (Klerkx et al., 2019; Deichmann et al., 2016). In response, digital technologies have emerged as key enablers, offering innovative solutions to enhance the efficiency, resilience, and sustainability of agricultural systems.

Nowadays, digital agriculture combines digital technology implementations within the farming systems and supply chain operations under the Agriculture 4.0 or referred to as the Smart Farming protocol (Saiz-Rubio & Rovira-Más, 2023). According to Pathak et al. (2024) and Yadav et al. (2022), modern agriculture actually depends on digital technologies, namely Internet of Things (IoT) alongside Blockchain, Artificial Intelligence (AI), Machine Learning (ML), Big Data analytics, Cloud Computing, Digital Twins, Drones and Remote Sensing. In fact, it is found that the interconnected system of these Digital technologies is capable of making better decisions, optimising resource usage, minimising waste, and enabling precise agricultural methods to be practised fruitfully (Yang et al., 2021).

Generally, the agricultural supply chain operates under unique operational challenges. But it remains fragmented due to information asymmetry and the involvement of multiple stakeholders (Bosona&Gebresenbet, 2013). Unlike the manufacturing or the retail sectors, the agricultural sector requires specialised management in terms of handling perishable goods, seasonal harvesting cycles, geographically dispersed farmers and unpredictable weather and biological factors (Jedermann et al., 2014). It is confirmed that Digital technologies have significantly transformed this landscape by enabling real-time monitoring capabilities, predictive analytics and data-driven decision-making while simultaneously enhancing traceability and monitoring throughout the supply chain processes (Freund et al., 2024).

Recent studies also highlight the transformative strengths of digitalisation. Yang et al. (2021) show how digital technologies improve efficiency, transparency and sustainability while reducing costs. Fu et al. (2020) demonstrate how Blockchain enables farm-to-fork traceability, addresses food safety concerns and builds consumer trust. Brohm (2019) emphasises that digital transformation in agriculture goes beyond technology adoption, which requires cultural, organisational, and operational changes.

Nevertheless, despite growing practices in Digital agriculture, challenges remain to be overcome. These challenges include digital literacy among farmers, infrastructure limitations, data privacy concerns, interoperability issues and the digital divide between large plantation farmers and smallholder farmers (Yadav et al., 2020; Lioutas et al., 2021; Rotz et al., 2022). Additionally, it is noted that the fragmented nature of agricultural innovation systems also hinders coordinated digital transformation efforts (Akbari & Hopkins, 2022).

This research develops a conceptual framework taking advantage of the digital transformation in the agricultural supply chain. It incorporates existing research relating to the subject and consequently is able to understand significant technologies alongside their applications, challenges and anticipate future developments. Therefore, this research focuses on three main goals, namely 1) identify vital digital technologies affecting the agricultural supply chain; 2） investigate how the identified digital technologies are applied across the agricultural supply chain stages; and 3) develop a unifying conceptual framework towards digital transformation in the agricultural supply chain.

LITERATURE REVIEW

Agricultural Supply Chain Management

Agricultural Supply Chain Management (ASCM) involves a systematic management of agricultural product activities beginning from the production stage and ending at the point of consumer consumption (Bosona&Gebresenbet, 2013). In fact, the ASCM differs from the other supply chains because ASCM faces three distinctive challenges related to perishable items, which are seasonal patterns and climate sensitivity (Jedermann et al., 2014). Furthermore, the inherent complexity and susceptibility to interruptions clearly define ASCM because of its unique features.

Building on these inherent vulnerabilities, traditional agricultural supply chains face additional operational challenges that compromise their effectiveness. Fragmented operations among intermediary entities create coordination gaps and information asymmetries throughout the network, directly impacting the system's ability to manage perishable products effectively (Khandelwal et al., 2021; Yadav et al., 2022). Inadequate logistics and storage infrastructure further compound these issues, particularly given the climate sensitivity and seasonal variability inherent to agricultural products (Fu et al., 2020). This combination of structural fragmentation and infrastructure deficits results in reduced visibility, higher costs, and significant resource inefficiencies.

These systemic inefficiencies are compounded by growing environmental pressures that demand more sustainable approaches to agricultural supply chain management. In response, scholars have developed Green Supply Chain Management, which incorporates environmental impact assessment and mitigation strategies throughout the supply chain, and Circular Economy principles, which redesign agricultural systems to eliminate waste through resource reuse and regenerative practices (Akbari & Hopkins, 2022). However, traditional agricultural supply chains, with their fragmented structures and linear operational models, lack the integrated coordination mechanisms necessary to implement these sustainability frameworks effectively, particularly when addressing complex challenges like climate adaptation and resource optimisation (Klerkx et al., 2019).

Given the structural fragmentation that prevents effective coordination and the inability of traditional systems to implement integrated sustainability frameworks, digital transformation emerges as a strategic solution to address these interconnected challenges. Digital technologies offer the potential to create unified platforms that can bridge coordination gaps, enhance infrastructure efficiency, and enable the integrated management required for sustainable practices (Deichmann et al., 2016; Yang et al., 2021). Research demonstrates that digitalisation specifically addresses the operational constraints and sustainability requirements identified in traditional agricultural supply chains.

Digital Technology in the Agricultural Supply Chain Management

The section explains digital technologies as pivotal to reforming Agricultural Supply Chain Management (ASCM) by addressing its significant issues like fragmentation, inefficiency and information asymmetry. This change is called Agriculture 4.0 or Smart Farming, which transforms conventional farming practices into intelligent and interconnected systems (Saiz-Rubio & Rovira-Más, 2023; Klerkx et al., 2019). As a result of digitalisation, studies have shown that farmers or stakeholders can increase transparency, decrease the amount of waste and address other challenges such as climate change and shifting customer needs (Deichmann et al., 2016; Du et al., 2023).

The digitalisation process in Agricultural Supply Chain Management (ASCM) is driven by the need for enhanced visibility and coordination, as emphasised in modern supply chain frameworks (Viswanadham& Kameshwaran, 2013). Due to its nature, where foods and products are often perishable, the agricultural supply chain requires real-time information and decision-making due to the cyclic and contingent factors (Bosona&Gebresenbet, 2013; Jedermann et al., 2014).

It has also been discovered that digital tools have been extended to almost all segments of the agricultural supply chain. For instance, Blockchain provides better traceability, which helps solve food safety issues and increases consumer trust (Fu et al., 2020; Baralla et al., 2021). In production, precision agriculture ensures the proper utilisation of resources through statistics (Saiz-Rubio & Rovira-Más, 2023). In fact, Logistic systems have been found to execute monitoring systems that minimise spoilage, mainly in real-time systems (Jedermann et al., 2014). Moreover, retailers of the agricultural supply chain increasingly adopt digital technologies to facilitate direct transactions between producers and consumers, thereby reducing or eliminating the role of intermediaries (Kittipanya-Ngam & Tan, 2020).

Nevertheless, there is still a significant research gap regarding technology applications in the context of the agricultural supply chain. Most prior studies have focused on individual technologies or isolated stages of the agricultural supply chain, rather than providing a comprehensive analysis of their interdependencies, comparative functionalities, and potential for integration and cooperation (Yadav et al., 2022; Freund et al., 2024). While existing frameworks often overlook critical socio-technical considerations (Klerkx et al., 2019; Rotz et al., 2022). Therefore, this study attempts to develop a mechanism to address these gaps by creating an integrated conceptual framework via (1) identifying the core digital technologies that influence agricultural supply chain transformation, (2) mapping their cross-stage applications, and (3) establishing scalable pathways for technology synergy. This approach is considered by this study as most appropriate in providing a comprehensive foundation for understanding digital transformation potentials in the ASCM.

KEY DIGITAL TECHNOLOGY IN AGRICULTURAL SUPPLY CHAIN

The Agricultural supply chain is being transformed by several innovative technologies that solve common issues and foster new advantages in its networks. Each technology has features that could be used at various stages in the supply chain management,i.e., from production to consumption. The following are six common technological advancements fuelling change in the agricultural supply chain.

Internet of Things

The Internet of Things (IoT) is an essential technology platform for the contemporary supply chain in the agricultural industry. There are three significant elements of IoT, namely, sensors, communication networks and data processing platforms. These components collect and transmit environmental and operational data related to crops and their surroundings, including soil moisture content, crop health status, and the performance of farming equipment. Communication protocols such as LoRaWAN* and ZigBee** enable long-range, low-power data transmission across large-scale agricultural fields. The collected data is then processed through digital platforms to support data-driven decision-making, enabling precise resource management, improved yield forecasting, and timely interventions in farming operations (Abi et al., 2024; Wan Mohamad &Rakiman, 2023).

A key strength of IoT lies in its ability to enable precision agriculture. For instance, the moisture control system integrated within the irrigation systems ensures that water is conserved because the irrigation processes are scheduled based on the moisture content of the soil. Likewise, multiple spectral sensors installed on Drones produce crop health maps that, in turn, enable farmers to identify sections of the fields that require fertilisation or pest control (Ardhy et al., 2024). These applications reveal how IoT can be used to achieve efficiency in the use of resources and reduce the harmful effects of resource usage.

However, the current adoption of IoT is characterised by technical issues. Bluetooth, Wi-Fi and cellular networks on the same device are some of the problems that make devices incompatible. Energy scarcity in remote regions means that any kind of sensors or energy harvesting solutions must be low-power consumption-based to support continuous and long-term operations. The threats to data security and susceptibility to counterattacks require sound encryption mechanisms to secure delicate data in the agricultural sector (Garrido-López et al., 2024; Sun & Zhang, 2024). As such, to make IoT truly useful in the agricultural supply chain, some practical solutions are required to overcome the barriers that hinder saleable IoT implementation.

Blockchain

Blockchain is an innovative technology that can create a decentralised and secure system to address the issues in the Agri-supply chain. Generally, a Blockchain contains a record of a series of transactions and is based on a distributed ledger that utilises cryptographic hashing to make the transactions sequential and unalterable (Bermeo-Almeida et al., 2018). The network members approve every record, including the crop yield data or product authentication, eliminating the use of intermediaries and any risk of fraud (Leng et al., 2018).

The biggest strength of the Blockchain is that it can improve traceability. It also records the origin of products and the steps to be taken in processing and transportation. The Blockchain records also allow stakeholders to check the authenticity and compliance with safety standards (Baralla et al., 2021). For instance, smart contracts and self-executing contracts written on Blockchain ensure that payment is made once the delivery is confirmed (Shahid et al., 2020).

Nevertheless, there are some technical challenges in the implementation of Blockchain. The scalability issue persists, as the growing number of transactions causes delay in validation, especially in the public Blockchains (Longo et al., 2020). The use of Proof of Work (PoW) consensus mechanisms is another setback due to the large amount of energy needed to validate transactions, especially in public blockchains. As a result, researchers and developers have shifted focus toward more energy-efficient alternatives such as Proof of Stake (PoS), which requires significantly less computational power (Padma et al., 2024). Also, integrating Blockchain platforms and networks must have a standard format to exchange information and data (Yadav & Singh, 2019).

Big Data and Cloud Computing

Big Data and Cloud Computing are two different technologies that play significant roles in solving major issues in the agricultural supply chain. Big Data refers to massive volumes of data collected from various sources such as IoT devices, satellite images and transactions. Cloud Computing is the platform that supports data storage of these datasets and high-level computations through distributed computing capabilities (Kamilaris et al., 2017; Kulikov et al.,2024).

Big Data holds significant value due to its ability to extract useful insights from various and large information sources. For instance, combining weather forecasts with historical crop yield data allows farmers to predict likely outcomes and strategically plan planting times and resource allocation (Bendre et al., 2021). However, the sheer volume and complexity of agricultural data require advanced tools for meaningful analysis, making Cloud Computing platforms essential for effective data processing and storage.

Cloud Computing increases flexibility and reduces costs in agricultural business processes. Cloud Computing enables farmers and agribusiness enterprises to access powerful computing resources as a service without capital investment in hardware (Phasinam et al., 2022). Consequently, smallholder farmers can use a Cloud-based dashboard for live market prices or weather forecasts through mobile devices (Coble et al., 2018). In the same way, Cloud Systems enhance the sharing of data across the supply chain nodes, improving the flow of information and coordination (Liu et al., 2019).

Combining Big Data with other technologies, especially Cloud Computing, intensifies the effect. Cloud platforms provide scalable infrastructure to store and process vast amounts of agricultural data. When integrated with IoT devices, these platforms can collect real-time data from multiple farms, enabling regional-level analysis of factors such as pest outbreaks or water usage patterns (Weraikat et al., 2024). To ensure that this shared data remains secure and trustworthy, Blockchain technology can be used to protect records stored in the Cloud. This enhances auditability and compliance, which is especially important in multi-stakeholder agricultural systems involving farmers, suppliers, regulators, and distributors (Kumar et al., 2020).

Admittedly, despite these advantages, technical challenges still persist. In the case of farm data, there is always the risk of data leakage or theft because the data is stored in third-party Cloud servers. Hence, there is a need to encrypt the data and control access to the data (Evstatiev& Gabrovska-Evstatieva, 2021). Moreover, internet connectivity is still a problem in some rural areas, which poses a challenge in real-time Cloud-based analytics. Due to that, there is a need for Edge Computing to pre-process the data before forwarding it to the Cloud (Bronson & Knezevic, 2016). There is also an issue of interoperability between different formats of information and Cloud systems, where there must be standardisation for integration (Fuentes et al., 2024).

Artificial Intelligence and Machine Learning

Artificial Intelligence (AI) and Machine Learning (ML) enable technologies to develop self-optimising and self-learning solutions in the Agricultural Supply Chain. AI can be described as systems that can carry out activities like human beings, such as decision-making, choice-making, and identification. In contrast, ML is the study of algorithms that can learn by themselves through data (Javaid et al., 2023). These technologies use Big Data from different sources, such as satellite images and sensors, to gain insights, to get better outcomes and to minimise operational hazards.

There is no doubt that the use of AI is most prevalent in predictive applications in agriculture. For example, AI models can forecast crop yields by analysing historical weather patterns, soil conditions, and planting schedules. Meanwhile, Neural networks and decision trees are some of the ML algorithms that can be used to estimate crop yields based on climate data, type of soil and market trends (Bestelmeyer et al., 2020). For example, Deep Learning algorithms analyse multispectral Drone imagery to identify signs of pest infestation or nutrient deficiency to make interventions (Zheng et al., 2019). Likewise, using Natural Language Processing (NLP) techniques produces demand patterns in the social media platform and market reports and can be used in determining the increase or decrease in demand; thus, improving inventory management (Kanyepe et al., 2024).

Supply chain automation has also been improved by AI. Post-harvest processing involves using a computer vision system with IoT devices to check for any defects in fruits or grains with accuracy above 95% (Oliveira et al., 2021). Reinforcement Learning algorithms learn to adapt to real-time traffic, fuel price and delivery time, which reduces transportation costs by 20% (Cheng et al., 2023).

However, the use of AI is not without some technical issues. Good-quality tagged agricultural datasets are needed to train accurate models which are limited or unavailable (Smith, 2018). Such bias may be expected if the training data source is skewed towards large-scale farms, thus overshadowing smallholder conditions (Lioutas et al., 2021). Computational complexity also requires large Cloud or Edge resources and therefore, suffers from scalability problems in resource-constrained environments (Qazi et al., 2022). To address these challenges, collaborative efforts are needed to establish standardised data acquisition formats and develop lightweight AI frameworks.

Digital Twin

Digital Twin technology creates dynamic virtual replicas of physical agricultural systems, enabling real-time monitoring, simulation and optimisation. A Digital Twin consists of four core components, i.e.,(1) physical entities (e.g., farms, machinery, crops), (2) virtual models built using computational algorithms, (3) bidirectional data flows connecting physical and virtual systems and (4) simulation engines for predictive analysis (Pylianidis et al., 2021). Digital Twin turns operational reality into Big Data and makes it easier to make decisions on behaviours in agricultural processes.

As such, the primary use of Digital Twins is in testing various scenarios. Digital Twins also use IoT sensors, weather stations and satellite imagery to test outcomes under different conditions in real-time. For instance, irrigation can be scheduled based on soil moisture simulation, and rainfall and irrigation water use efficiency can be enhanced by 15-25% without compromising production rates (Gefraeye et al., 2021). Likewise, virtual storage space models replicate temperature changes to determine efficient cooling measures (Defraeye et al., 2021).

Closed-loop control systems are also made possible by Digital Twins. Autonomous adjustments in physical environments are made by actuators based on commands received from virtual models, enabling precision agriculture applications.

Nevertheless, there are technical challenges that have made the adoption of Digital Twins difficult. High-fidelity modelling involves a large amount of data and computational power, making it difficult for small-scale farms (Pylianidis et al., 2021). The quality of model accuracy is contingent on the data collected by the sensors, where errors are carried through simulations (Defraeye et al., 2021). Cybersecurity threats are also seen when interdependent systems increase the exposure of potential threats. Therefore, there is a need for encryption and access rights (Pylianidis et al., 2021).

Advanced Monitoring Technologies (Drones and Remote Sensing)

Advanced monitoring technologies, including drones and remote sensing systems, provide high-resolution spatial and temporal data essential for precision agriculture and supply chain optimisation. Multispectral, thermal and Light Detection and Ranging (LiDAR) sensors mounted onto Unmanned Aerial Vehicles(UAVs)or Drones provide detailed aerial imagery of the crops, land and facilities. Remote sensing involves using satellite or aircraft-borne sensors to study vast agricultural landscapes with details on vegetation health, water availability and environmental change (Mulla, 2013). These technologies facilitate real-time data acquisition that does not require physical assessment from the field.

The key advantage of Drones is the flexibility and high resolution of the collected data. Crop conditions indicative of stress, like chlorophyll content and water deficit, can be measured by multispectral sensors at the plant level (Ardhy et al., 2024). Thermal imaging also reveals microclimates in a given area, which helps determine the right time to water in water-deficient areas (Guebsi et al., 2024). LiDAR helps produce 3D maps of the terrain, which is helpful for levelling operations and drainage systems (Guebsi et al., 2024). Remote sensing can complement drones since it covers a larger area. NDVI (Normalised Difference Vegetation Index) satellite systems monitor plant health over large areas of the farmlands, and hyperspectral sensors, on the other hand, detect nutrient deficiencies that are not visible to the human eye (Mulla et al., 2013).

However, technical constraints prevent its use in the broader economic activities of society. Constraints include the limited endurance of batteries and their carrying capacity. This significantly limits Drone use, especially in large corporate farms (Guebsi et al., 2024). In fact, Drone sensor accuracy depends on the atmospheric conditions, and the performance of the sensor needs to be validated from time to time (Guebsi et al., 2024). Data processing requires significant computing power, especially when analysing large volumes of high-resolution data in real-time (Guebsi et al., 2024). Two challenges critical for scalability include the standardisation of data formats and the reduction of the cost of sensors. The standardisation challenge stems from proprietary data formats used by different manufacturers, which create integration barriers and prevent seamless data exchange across agricultural systems. Cost barriers particularly affect smaller agricultural operations, as advanced sensing equipment requires substantial capital investments that many farmers cannot afford, thus limiting the technology's reach and overall impact on agricultural transformation.

Summary on Digital Technologies in The Agricultural Supply Chain

Table 1 presents the core digital technologies applicable to the agricultural supply chain, as identified through the review of relevant literature conducted in this study.

Table 1: Summary of Core Digital Technologies in Agricultural Supply Chains

Technology	Core Function	Key Synergistic Technologies	Primary Challenges	Representative Studies
Internet of Things (IoT)	Real-time data acquisition (environmental/equipment status), automated control	Blockchain, AI, Cloud Computing	Network heterogeneity, energy constraints, cybersecurity vulnerabilities	Ardhy et al. (2024); Sun & Zhang (2024)
Blockchain	Immutable data recording, brilliant contract execution, end-to-end traceability	Blockchain, AI, Cloud Computing	Scalability limitations, energy-intensive consensus, cross-chain interoperability	Baralla et al. (2021); Leng et al. (2018)
Big Data & Cloud Computing	Large-scale data storage, distributed computing, predictive modelling	IoT, AI, Blockchain	Data privacy risks, network latency, system interoperability	Kamilaris et al. (2017); Coble et al. (2018)
AI & Machine Learning	Predictive analytics (yield/demand), automated decision-making (routing/QC)	IoT, Digital Twins, Blockchain	Data quality dependency, algorithmic bias, computational complexity	Zheng et al. (2019); Kanyepe et al. (2024)
Digital Twin	Virtual simulation, real-time optimisation, predictive maintenance	IoT, AI, Blockchain	High-fidelity modelling costs, error propagation, cybersecurity risks	Pylianidis et al. (2021); Defraeye et al. (2021)
Advanced Monitoring	High-resolution data capture (drones), large-scale environmental sensing (remote sensing)	IoT, AI, Blockchain	Drone battery limits, sensor calibration demands, computational load	Mulla (2013); Guebsi et al. (2024)

DIGITAL TECHNOLOGY APPLICATIONS ACROSS THE AGRICULTURAL SUPPLY CHAIN STAGES

This section will explain digital technology applications that are applied in the agricultural supply chain stages.

Production Stage

The production phase of the supply chain in agriculture has unique factors such as resource utilisation, climatic factors, pest control and yield issues. Since digital technologies are multi-layered, it becomes possible to support precision farming and data-driven decision-making for the industry.

Layered Technology Implementation

Generally, digital technologies in agricultural production operate across three interconnected layers. They are:

a) **The Device Layer –** In line with section 3.1, these field devices lay the groundwork for precision agriculture by providing highly detailed, real-time data. Ardhy et al. (2024) provided a way forth monitoring systems by using IoT to identify the fluctuations in the soil moisture across the different field zones with an accuracy of more than 95% for efficient irrigation scheduling.

b) **The Edge Layer -** This layer is responsible for data gathering, initial processing and controlling the system's interaction with other systems. This layer processes real-time data before transmitting data to the Cloud systems, which minimises the amount of data transmitted and offers a timely response to field conditions. Sun and Zhang (2024) designed an agricultural logistics control system based on the MQTT protocol, Edge computing, and can quickly determine the required irrigation for multiple field locations within several seconds instead of hours.

c) **The Cloud Layer -** Computation-wise, rich capabilities at the Cloud layer support complex modelling, data warehousing, and forecasting. The AI models of agriculture involve using yield data, climate data and market data to make decisions on resource allocation and prognosis. Fuentes et al. (2024) explained that AI systems based on Cloud technology are capable of incorporating historical weather data for five years, and that data from sensors could predict the required irrigation level at 92% precision.

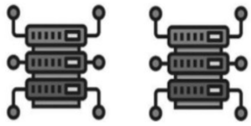
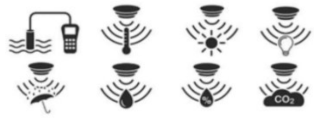
Cloud Layer	• Long-term Data Storage • AI-driven Agricultural Modelling • Remote Monitoring & Optimization • Predictive Analytics Cloud Computing, Machine Learning, Big Data Fuentes et al. (2024), Weraikat et al. (2024)	
Edge Layer	• Real-time Data Analysis • Data Collection & Storage • Device & Cloud Layer Communication Edge Computing, Gateway Devices, Local Servers Sun & Zhang (2024), Akter et al. (2024)	
Device Layer	• Environmental data collection,e.g.soil, weather • Physical interaction with the field • Device to Edge Communication IoT Sensors, Drones, Smart Farm Ardhy et al. (2024), Kawre et al. (2024)	

Figure 1: Layered Digital Architecture for Agricultural Production Stage Management.(Source: Authors' Elaboration)

Key Applications in Production

The integration across these layers facilitates several critical applications especially in the areas listed below:

a) **Precision Resource Management: Internet of Things (IoT) -** Essentially, IoT sensor networks for water and fertilisers through edge computing to cloud analytics. In the study by Phasinam et al. (2022), various cases of using soil moisture sensors interfaced with an automatic irrigation system showed that water use can be cut by 28 percent while ensuring yields remain constant. The experiment incorporated wireless sensor nodes, commonly known as the Device layer. It relayed data to local processing units, known as the Edge layer and then to Cloud-based predictive models to produce efficient irrigation programs. It has also been discovered that precision fertilisation that utilised nutrient sensors regulated the application rates and reduced chemical inputs by 15 to 20 percent while increasing the yield variability (Abiri et al., 2023). These systems show that the layered system can address the issue of responsive resource management depending on the field conditions.

b) **Continuous Monitoring and Early Detection -** Continuous monitoring feeds the Edge and the Cloud layer to detect anomalies before they can be observed. Kawre et al. (2024) designed an IoT-based crop monitoring system while incorporating distributed sensors to monitor small changes in the plant transpiration rates and determine the water stress period. This data was pre-processed at the Edge layer to remove anomalies to avoid overwhelming Cloud-based analytical systems and correlate them with the typical stress patterns. Multispectral cameras mounted on Drones improved monitoring. Guebsi et al. (2024) noted that Drones detected early infections up to two weeks before scouts did the visual inspections.

c) **Decision Support Systems -** The Cloud layer comprises data from sources good for decision-making in the management of farms. Savaliya et al. (2024) proposed a Cloud-based crop prediction system that computed the crop production of previous years. While the current year crop sensor values and future forecasted crop conditions provide guides on optimal planting period, which helps farmers to increase crop production by 8 to 12%. Other platforms capture agricultural practices and production data through the Blockchain, and data analysis leads to a set of suggested actions (Fu et al., 2020).

Jakarbet et al. (2024) showed that by integrating ML algorithms with field sensor networks, it was possible to predict suitable crops according to present environmental conditions, therefore assisting farmers in choosing the right variety and time to plant them.

The framework depicted in Figure 1 shows a clear and logical structure that can be used to study how digital technologies produce agriculture via the Device, Edge and Cloud layers. This approach allows for the enhancement and complexity of the analysis and optimisation throughout the growing season, which results in the rational use of resources, less negative impact on the environment and higher production. Favourably, with the reduction in technologies and a general enhancement in understanding their implementation in agriculture, these systems are becoming more popular among operational establishments.

Processing and Storage Stages

Agricultural supply chains' processing and storage phases concern perishability, quality issues and waste. Digital technologies usually solve these challenges via effective monitoring, automated processing and data-driven storage management systems (Iftekhar et al., 2020; Grecuccio et al., 2020).

Layered Technology Implementation

Like in the production phase, Modern digital technologies used in the processing and storing of agricultural products operate on the three interrelated layers that allow for monitoring, analysis and optimisation. The framework, as shown in Figure 2, facilitates efficient data flow from physical operations to decision-making systems.

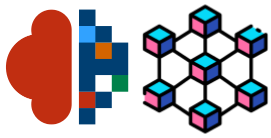
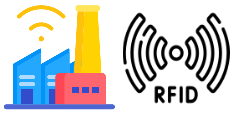
Cloud Layer	• Quality prediction modelling • Inventory optimisation • Supply-demand matching • Traceability management Machine learning Blockchain, Big Data Padma et al. (2024), Weraikat et al. (2024)	
Edge Layer	• Real-time quality assessment • Environmental control • Local data filtering Edge Computing, Gateway Devices, Local Servers Lohith Kumar & Raj (2022), Casino et al. (2020), Defraeye et al. (2021)	
Device Layer	• Product quality sensing • Environmental monitoring • Storage condition monitoring IoT Sensors, Drones, RFID, Smart equipment Garrido-López et al. (2024), Jagtap et al. (2020)	

Figure 2: Layered Digital Framework for Agricultural Processing and Storage Stages (Source: Authors' Elaboration)

The Device layer provides the base through dedicated sensing and monitoring equipment. Garrido-López et al. (2024) explained that wireless sensor networks in storage facilities are where temperature, humidity, ethylene and other factors are closely monitored with a precision of less than ±0.3°C of temperature. In terms of processing facilities, Casino et al. (2020) found that IoT sensors enhance the quality deviation in the dairy production line. These technologies help to form an extensive system of creating digital replicas of the physical parameters.

At the Edge layer, computing infrastructure in the local area deals with data received from sensors to facilitate a timely response. Solutions provided by Edge computing in horticultural storage that convert sensor data into real-time environmental control were experimented with by Defraeye et al. (2021), and they found a significant increase in product freshness. For processing operations, Qian et al. (2020) found that the Edge system was able to analyse characteristics of incoming shipments and produce self-optimising yield and energy consumption.

The Cloud layer provides high-end computational capabilities for analytical and system administration. The authors Fuentes et al. (2024) showed how AI in the Cloud uses performance data and operation data to increase storage savings by minimising loss. According to Padma et al. (2024), established Blockchain implementations regulate the records through processing and storage operations and decrease the time during contamination investigations from days to minutes.

Key Applications in Processing and Storage

In processing and storage operations, digital technologies have made it possible to solve some problems that have been persistent while opening up new value propositions. Computer vision systems are more effective regarding quality management than conventional inspection strategies. Jagtap et al. (2020), managed to portray cases where the use of automated visual inspection systems increased the defect detection rate compared to manual inspection. These systems allow for constant surveillance rather than just taking snapshot samples. Therefore, the quality issues are detected almost immediately, thus minimising wastage.

Predictive analytics improve storage management since they provide information on possible trends in the quality of products. Weraikat et al. (2024) reviewed ML systems employed on past and present data for the estimation of conditions and duration of storage. This makes managing the facility's inventory possible by moving products with certain risk factors into the market before they get spoiled. According to Defraeye et al. (2021), several applications of the Digital Twin technology in storage have revealed considerable potential for optimising temperature fluctuations and product perishability.

One of the most significant advantages of using Blockchain technology is that it provides transparency and non-reversible records in processing and storage activities. Barilla et al. (2021) discussed several case studies on food processing facilities where multiple parameters were captured for each batch, thereby cutting down the time taken to verify the quality of the batches as well as improving efficiency in the availability of information downstream. During safety incidents, Blockchain systems effectively identify the impacted products. Casino et al. (2020) reveal that Blockchain enabled specific recalls, which had much lower costs than traditional traceability systems.

The combination of IoT and Blockchain has led to the development of more reliable automated documentation systems. Lohith Kumar and Raj (2022) discovered that effective implementations in which storage condition sensors captured the data and stored it in a Blockchain-based ledger reduce the need for manual recording and maintain the record's authenticity. Shahid et al. (2020) also explained that compliance verification was automated through smart contracts, raising alerts when storage conditions were not as required, but could provide full audit trails that reduced verification time.

Consumer applications acquire the benefits of traceability to the end consumers in the food chain. According to Qian et al. (2020), Blockchain systems were applied to link the processing and storage of information with consumer applications, where product information was authenticated. This helped to open market segments and make it possible for traceability to be rewarded through higher prices in specific markets. These examples prove that digital technologies could effectively replace conventional handling and archiving of records by practising innovative and efficient processes.

Logistics and Distribution Stage

The agricultural supply chains' logistics and distribution stage involves moving, handling and delivering agrarian products from processing facilities to retail markets. This stage encompasses transportation management, cold chain logistics, route optimisation, warehouse operations and inventory distribution (Jedermann et al., 2014; Drljača & Sesar, 2023). Remarkably, IT solutions have provided solutions to some of the concerns, such as product deterioration, transport, lack of visibility and distribution issues (Wang et al., 2024).

\

Layered Technology Implementation

Integrated digital technologies in the agricultural logistics and distribution systems exist in the Three-Tier Logistics Model that facilitates product flow control, enhancement and orchestration. This framework provides real-time tracking, timely decision-making and cooperation within the logistics networks as illustrated in Figure 3.

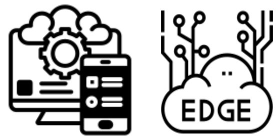
Cloud Layer	• Supply chain optimisation • Route and logistics planning • Multi-stakeholder coordination • Traceability management Machine Learning, Blockchain, Big Data K et al. (2023), Wang et al. (2024)	
Edge Layer	• Real-time vehicle/shipment monitoring • Environmental control adaptation • Route optimisation Edge Computing, Mobile Computing Platforms Sun & Zhang (2024), Raj et al. (2024)	
Device Layer	• Location and condition tracking • Product quality sensing • Vehicle/equipment monitoring IoT Sensors, RFID, GPS Trackers Garrido-López et al. (2024), Wan Mohamad & Rakiman (2023)	

Figure 3: Layered Digital *Framework for* Agricultural Logistics and Distribution(Source: Authors' Elaboration)

Logistics operations use various sensors and tracking systems at the Device layer to manage their activities. Garrido-López et al. (2024) identified cellular IoT solutions used to track perishable commodities during transportation, where they continually report temperature, humidity and shock data with a transmission frequency of 15-minute intervals. Wan Mohamad and Rakiman (2023) discuss RFID systems that enabled item-level tracking in every channel of distribution. This improves the product's condition and location information, which finally leads to the minimisation of product losses. These technologies provide digital transparency concerning the physical assets throughout the movement and handling processes.

The Edge layer processes data in real time, facilitating logistics decision-making. Sun and Zhang (2024) emphasise that Edge computing has been applied in agricultural logistics control systems, where environmental and location data were used to determine the best route to deliver locally and to adjust the time of the delivery schedule. Raj et al. (2024) described mobile computing platforms based on how large vehicle condition monitoring data could be processed and what corrective actions to be taken as soon as the environmental conditions exceeded the stipulated limits. These Edge capabilities also enable the management of the Cloud with short bursts of connectivity into the Cloud environment.

Cloud layer systems are used to optimise logistics management at all layers of the procedures. Shanmugapriyaa et al. (2023) examined Cloud platforms that utilised the supply chain data from different sources to establish the best distribution networks to enhance vehicle productivity without increasing empty miles. Wang et al. (2024) reported that the Blockchain-based systems had consistent records of transport and handling points, thus developing authenticated records of custody. These Cloud capabilities take the complicated and disintegrated logistics processes and turn them into unified, information-based systems.

Key Applications in Logistics and Distribution

Digital technologies put into place various possibilities that help solve the problems of agricultural logistics' duration and quality preservation, thereby creating new management activities to improve agricultural pursuits.

The control of the cold chain has been improved through continuous monitoring and control. In their study, Garrido-López et al. (2024) stressed IoT solutions that provide constant temperature records from the processing level up to the delivery at the retail outlets. These systems provided real-time monitoring of temperature excursions so that timely measures could be taken before the quality of the products was affected. This resulted in temperature monitoring that gave only 4-6 data points, while IoT-based systems gave visibility throughout the transport process, reducing spoilage cases.

Transportation optimisation then entails the use of real-time information to improve this aspect and, at the same time, minimise the side effects on the environment. TÜRKSOY (2023) reveals that Drones acquire the route's condition and feed this information to the AI-based routing systems. The latter minimised the delivery time and fuel usage by adapting routings to the current situation instead of pre-planned routings. Undre and Jokonya (2024) discussed some implementations where weather, traffic and product conditions were incorporated in the choice of the mode of transport and time of transfer to minimise both cost and carbon footprint. Advanced distribution coordination shifts from the traditional dispersed supply chain logistics into integrated flexible systems. Shanmugapriyaa et al. (2023) discussed the Blockchain-based distribution platforms that ensured the constant availability of the product for visibility and the automation of the documentation of transactions between the logistics partners. They provided an excellent opportunity to optimise the work of managers and improve cooperation between different services. Daw (2024) demonstrated how Drone-based image processing enables agricultural forecasting that provides real-time visibility of crop yields and inventories. This results in more responsive allocation decisions that reduce stockouts and oversupply situations in distribution networks.

Last-mile delivery solves the last and most complex and expensive link in the supply chain of agriculture. According to Raj et al. (2024), UAV applications in agricultural logistics enable the timely delivery of products in remote areas. They greatly enhanced the quality of service for perishable commodities, especially in developing business environments. According to Casino et al. (2020), other mobile-enabled delivery verifications were those that confirmed the condition of the delivered product with transfer documents that were believed to limit conflict while at the same time ensuring quality assurance in the supply chain.

Retail and Consumption Stage

Agricultural supply chains' retail and consumption stage refers to the last point where consumers acquire products through outlets, including physical stores, online shops and direct selling. This stage includes inventory management, consumer interaction, product display and promotion (Wang & Ng, 2018; Cho et al., 2019). Digital technologies help solve the problems associated with food waste, lack of trust between buyers and sellers, accelerate inventory management and facilitate new customer interactions (Zhang et al., 2018; Yeo et al., 2017).

Layered Technology Implementation

Digital technologies in the retail and consumption stage operate within a three-layer framework that connects physical products with data-driven consumer experiences and business optimisation systems. This integrated approach enables responsive inventory management, enhanced consumer engagement, and improved data-driven retail operations as illustrated in Figure 4.

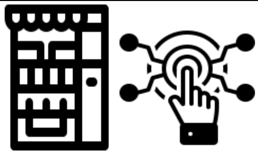
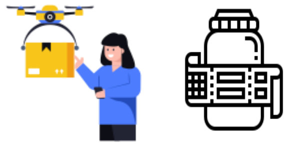
Cloud Layer	• Demand forecasting • Inventory optimisation • Omnichannel coordination • Consumer behaviour analytics Machine Learning, Big Data Analytics Wang & Ng (2018), Li et al. (2021)	
Edge Layer	• Real-time inventory management • Interaction systems • Digital product information Smart Shelving, Interactive Kiosks Zhang et al. (2018), Yeo et al. (2017)	
Device Layer	• Smart packaging • Freshness monitoring • Consumer interaction tools NFC Tags, Smart Labels, Mobile Apps Baralla et al. (2021), Iftekhar et al. (2020)	

Figure 4: Layered Digital Framework for Agricultural Retail and Consumption (Source: Authors' Elaboration)

The Device layer develops tangible link between products and digital technology. Barilla et al. (2021) highlighted the innovative packaging with NFC tags that let consumers use their smartphones to get reliable product information. Such system enables consumers to check the origin of the products, how they were produced and their handling history. Iftekhar et al. (2020) discussed freshness monitoring sensors installed into packages which give a message about the product's freshness and remaining shelf life so that consumers can use the product at the right time, avoiding wastage and spoilage.

The Edge layer is responsible for processing data concerning the store's operation and consumer experience. Zhang et al. (2018) investigated intelligent shelving systems that used weight sensors and computer vision for real-time inventory visibility to cut down the issues of stockouts by 30% as opposed to the conventional inventory systems. Yeo et al. (2017) described the kiosk systems that provide information about the products, usage and preparation tips depending on consumers' choices.

The Cloud layer enables the optimisation of all the systems and coordination across different channels. Wang and Ng (2018) defined AI in supply chains as demand forecasting systems that are able to predict consumers' buying behaviours with much higher levels of precision, with a view to eliminating stock-out and overstock situations in the retail chain. In their study, Li et al. (2021) focused on e-commerce platforms that connected online and offline stores, which provided customers with similar experiences and also ensured efficient inventory coordination between online and brick-and-mortar stores. They found that Cloud capabilities enhance the retail operating model from a system of disconnected parts to a consumer activation system.

Key Applications in Retail and Consumption

Digital technologies have significant implications across retail and consumption processes and issues in creating new forms of consumer interactions and organisational models. Transparency and authentication systems contribute to promoting trust by confirming the information regarding the products. Barilla et al. (2021) described retail use cases based on Blockchain, which enabled consumers to gain reliable information about the product's origin, manufacturing and previous handling. These implementations gave substantial competitive benefits to the participating brands, as consumers were ready to pay a premium price for the products with claimed attributes. It converted passive packaging into active information mediums, which may help with branding and creating customer awareness and trust.

Omni-channel retail means the availability of a fully synchronised online and offline selling interface for consumers. Liu et al. (2021) sampled implementation strategies involving multichannel strategies that incorporated online to offline platforms for e-commerce, where a consumer can research the product online, purchase through an app and pick up the product from a convenient physical store. This integration enabled proper utilisation of inventory and, at the same time, increased the convenience of consumers by providing them with various purchasing options. In their observation, Lu and Reardon (2018) observed how digital platforms disrupted agricultural retail by connecting producers directly to consumers, thereby eliminating intermediaries and creating new markets for quality products peculiar to the regions.

Intelligent retail environments can enrich the shopping experience by using various technologies. Zhang et al. (2018) discussed several cases where physical stores adopted digital signage, product sense and recommendations. These environments helped consumers by offering them detailed product information, usage instructions and recommendations for other related products that could be purchased, thus improving the shopping experience and the purchase value. In a similar study, Cho et al. (2019) pointed out that the use of mobile applications offers recommendations based on past purchases, the consumer's diet preferences and seasonal produce. By and large, these enhance consumer satisfaction and increase basket size.

Subscription and direct-to-consumer models build regular interactions through digital channels. Yeo et al. (2017) described subscription services that offer products based on consumer preference and limited seasons. These implementations help cut wastage by improving demand and supply methods while simultaneously providing producer markets. Wang and Ng (2018) examined direct-farm connection platforms that facilitate consumers to extend their patronage to individual producers.

The Conceptual Framework for Digital Transformation in the Agricultural Supply Chains

Previous sections discussed the major digital technologies used in various stages of the agricultural supply chain. These technologies are now developed into the Conceptual Model that can transform the agricultural supply chain into Digital systems. The outlined framework, named the Integrated Layered Framework for Digital Technology Application in Agricultural Supply Chain, is elaborated in Figure 5. This approach facilitates analysing, adopting and finally transforming the Agricultural Supply Chains into adopting digital technologies.

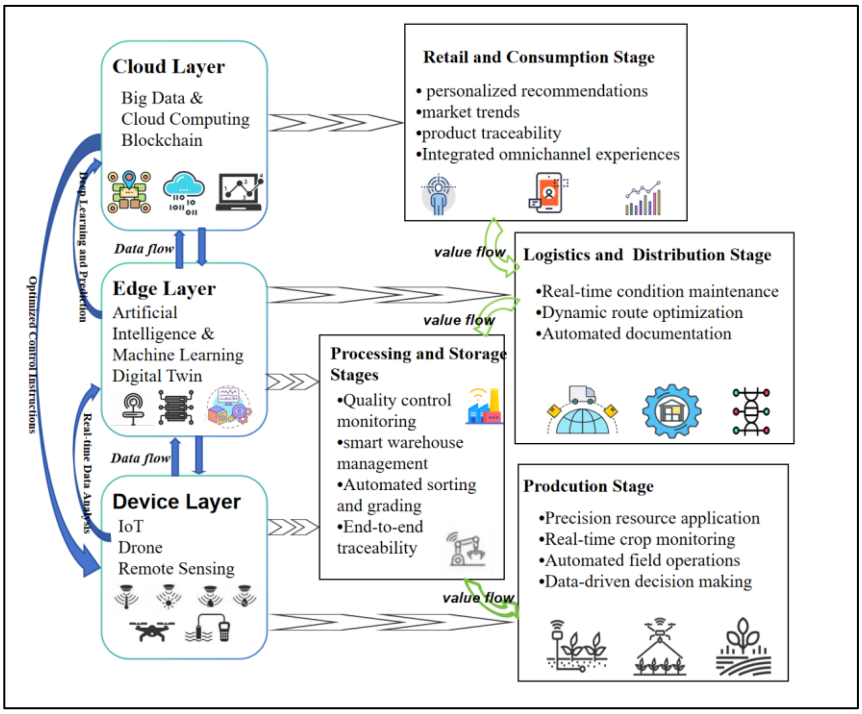


Figure 5: Integrated Layered Framework for Digital Technology Application in the Agricultural Supply Chains (Source: Authors' Elaboration)

Layered Framework

The technological structure of the framework presented in this work is a three-layered structure that can be considered the basis of the digital transformation (explained in Figure 5). Each layer comprises certain technologies related to the various stages of the agricultural supply chain.

a) **Device Layer** - This layer comprises IoT Sensors, Drones and Remote Sensing that provide objective information about the farm environment. These technologies build up the digital platforms by collecting field-level data.

b) **The Edge Layer -** This layer analyses data in real-time and performs preliminary processing. AI, ML, and Digital Twin technologies perform data processing on the collected data at or near the source. Edge computing returns and reduces the amount of data transmitted through the network while providing an almost real-time response to the conditions in the field (Sun & Zhang, 2024). They make it possible to assess the feasibility of particular strategies in the field of agriculture without their actual application.

c) **The Cloud Layer -** This layer offers high-level computational capabilities for data analysis, historical data storage and system management. Big Data, Cloud Computing and Blockchain technologies process accumulated data and provide patterns, trends or forecasts along with efficiency in operations.

Digital Transformation Pathway

This framework involves three gradual steps of the digital transformation process that organisations should adopt depending on the organisation's capabilities and goals. They are:

a) The First level: Basic Digitalisation - This initial level usually involves adopting single technologies in a company, most of which are at the Device level. Companies start with fundamental data acquisition systems, such as IoT sensors or Drones, to measure certain factors. This stage sets digital presence and lays the groundwork for higher-level use. Saiz-Rubio and Rovira-Más (2023) observed that the early stages of digitalisation involve tracking essential parameters that are not very interconnected.

b) The intermediary phase: Integration Step up - This intermediary phase scales up to encompass multiple technologies that operate in harmony and reach the Edge layer. Information exchange between technologies enhances the provision of more information. The IoT sensors and Edge computing integration allow data processing on the local level and make fast decisions. In the study by Fu et al. (2020), they found that using integrated Blockchain-IoT systems enhanced traceability and reduced verification time compared to a single technology.

c) The final stage - This is the integration of all three layers of the comprehensive intelligence. Many technologies are integrated into the supply chain management, i.e. starting from automating decision-making and finally being able to predict. Kittipanya-Ngam and Tan (2020) identified mature implementations in which Cloud analytics, Edge processing and field-level sensing lead to self-optimising agricultural systems which improve performance over time.

Technology Integration and Synergy

This framework also reveals recursive dynamics within the technology layers, where some layers provide support and reinforcement to the other layers. The detailed explanation is as follows:

a) Real-time Analysis - The interaction of the Device and Edge layers makes it possible to process information from the field as it is received.

b) Advanced Analytics and Predictive Modelling - Similarly, the Edge layer and Cloud layers work with processed data flows that can be used for higher-level analysis and prediction.

c) Optimised Control Instructions - Cloud and Device layers are coupled by instruction channels that allow data analysis to be translated into field actions.

d) Value Creation Flow - This framework also includes value-added flow that describes how data creates organisational values.

Overall, this study has developed an Integrated Layered Framework, which is a holistic model that is applicable to all agricultural sectors' digital transformation of supply chain pursuits. Implementing this progressive transformation pathway, especially paying attention to the three layers and their technology synergies, this study is confident that different levels of agricultural organisations can improve their agricultural operations' efficiency and sustainability.

CONCLUSION

This paper formulates a transparent conceptual model that could be used to undertake the digital transformation of supply chains in the agricultural sector. This Integrated Layered Framework is a highly structured approach that integrates digital technologies into the agricultural supply chain by adopting leading present-day digital technologies and their feasible applications at various stages of the chain.

Essentially, this study reveals that six dominant digital technologies arranged in a three-tier structure could expedite the agricultural supply chain. This study reiterates that through the Device layer, it is confirmed that IoT, Drones and Remote Sensing technologies could effectively facilitate the digital base data collection for the framework. Meanwhile, AI and Digital Twin technologies incorporated in the Edge layer could integrate real-time analysis and decision-making to be done simultaneously. In addition, other Cloud layer solutions such as Blockchain, Big Data and Cloud Computing offer advanced analytics and system-wide coordination. Consequently, this framework's digital transformation pathway, i.e., progressing from essential digitalisation via smart digital technology integration and comprehensive intelligence, could finally tackle diverse implementation issues faced by smallholder farms and large agricultural enterprises (Yang et al., 2021).

However, despite the transformative strength of all the digital technologies, other significant implementation challenges remain to be overcome. One of them is Digital literacy issues (Lioutas et al., 2021). This constraint limits access to infrastructure, especially in rural areas (Jedermann et al., 2014) and causes the inability for smallholders to afford the cost of e-commerce (Yadav et al., 2020). Therefore, affordability is another significant issue that limits e-commerce uptake. This study concurs with another study that there is a dire need to focus not only on digital technologies but also on human-centric technologies (Chutcheva, 2025). Hence, interoperability frameworks (Pathak et al., 2024), and technologies that promote sustainability in the environment as well as the supply chain (Ibrahim et al., 2024) are duly examined. Indeed, the conceptual framework outlined in this study could play its role in overcoming the flaws in the existing agricultural supply chain and could enhance current practices to be more effective, accountable and sustainable in the long run.

Author Contributions: Ting Ting Chen: Writing-Original draft preparation, Conceptualisation, Project administration. Azilah Binti Anis: Writing-Original draft preparation, Supervision.

Funding: This research received no external funding.

Acknowledgements: I would like to express my heartfelt gratitude to Fan Zhang from Universiti Teknologi MARA for his insightful guidance and valuable suggestions during the writing process. His thoughtful input greatly contributed to shaping the ideas and structure of this paper, and his support was instrumental in improving the overall quality of the research.

Conflicts of Interest: The authors declared no conflicts of interest regarding this work.

REFERENCES

Abi, A., Abdullahi, H. O., Ali, A. F., & Ahmed, M. M. (2024). Internet of Things in Agriculture: A Systematic Review of Applications, Benefits, and Challenges. *Journal of System and Management Sciences.*

Abiri, R., Rizan, N., Balasundram, S. K., Shahbazi, A. B., & Abdul-Hamid, H. (2023). Application of digital technologies for ensuring agricultural productivity. *Heliyon, 9*(12).

Akbari, M., & Hopkins, J. L. (2022). Digital technologies as enablers of supply chain sustainability in an emerging economy. *Operations Management Research, 15*(3), 689-710.

Akter, T., Mahmud, T., Chakma, R., Datta, N., Hossain, M. S., & Andersson, K. (2024, June). Iot-based precision agriculture monitoring system: Enhancing agricultural efficiency. In *2024 Second International Conference on Inventive Computing and Informatics (ICICI)* (pp. 749-754). IEEE.

Ardhy, M. M., Sinaga, H. Z., Pratama, M. A., Maulana, A., & Abdullah, A. G. (2024). Optimizing Agricultural Production Through the Internet of Things: Innovative Solutions to Reduce Food Loss and Waste. Inovator, 13(2), 283-303. https://doi.org/10.32832/inovator.v13i2.686

Baralla, G., Ibba, S., Marchesi, M., Tonelli, R., &Missineo, S. (2021). A Blockchain based system to ensure transparency and reliability in food supply chain. *Applied Sciences, 11*(11), 4930.

Bendre, M.R., Thool, R.C., &Thool, V.R. (2021). Big data in precision agriculture: Weather forecasting for future farming. *Big Data Mining and Analytics, 4*(1), 12-22.

Bermeo-Almeida, O., et al. (2018). Blockchain in agriculture: A systematic literature review. *Communications in Computer and Information Science*, 883, 44-56.

Bestelmeyer, B.T., et al. (2020). Scaling up agricultural research with artificial intelligence. *IT Professional, 22*(3), 33-38.

Bosona, T., &Gebresenbet, G. (2013). Food traceability as an integral part of logistics management in food and agricultural supply chain. *Food Control, 33*(1), 32-48.

Brohm, K.A. (2019). The digital transformation of agriculture. *Journal for Advanced Research in Applied Sciences, 5*(5), 43-46.

Bronson, K., & Knezevic, I. (2016). Big Data in food and agriculture. *Big Data & Society, 3*(1), 2053951716648174.

Casino, F., Kanakaris, V., Dasaklis, T.K., Moschuris, S., Stachtiaris, S., Pagoni, M., &Rachaniotis, N.P. (2020). Blockchain-based food supply chain traceability: A case study in the dairy sector. *International Journal of Production Research*, 1-13. https://doi.org/10.1080/00207543.2020.1789238

Cheng, C., Fu, J., Su, H., & Ren, L. (2023). Recent advancements in agriculture robots: Benefits and challenges. *Machines, 11*(1), 48.

Chintamaneni, V., Janipalli, A., Rajaram, J., Devi, T. A., Vajjala, K. V. K., & Vivekanandhan, V. (2024, August). Revolutionizing farming: An analysis of IoT-based smart agriculture monitoring systems. In *2024 5th International Conference on Electronics and Sustainable Communication Systems (ICESC)* (pp. 486-492). IEEE.

Cho, M., Bonn, M.A., & Li, J.J. (2019). Differences in perceptions about food delivery apps between single-person and multi-person households. *International Journal of Hospitality Management*, 77, 108-116.

Chutcheva, Y. V. (2025). Digital transformation of agriculture: from theory to practice. *Russian Journal of Management, 12*(4), 113-123. https://doi.org/10.29039/2500-1469-2024-12-4-113-123

Coble, K. H., Mishra, A. K., Ferrell, S., & Griffin, T. (2018). Big data in agriculture: A challenge for the future. *Applied Economic Perspectives and Policy, 40*(1), 79-96.

Daw, S. (2024). Agricultural Forecasting Through Drone-Based Image Processing: A Future Perspective on Food Supply Chain Management. *International Journal of Computational and Engineering, 6*(7), 73-75. https://doi.org/10.53469/jrse.2024.06(07).14

Defraeye, T., Shrivastava, C., Berry, T., Verboven, P., Onwude, D., Schudel, S., & Rossi, R. M. (2021). Digital twins are coming: Will we need them in supply chains of fresh horticultural produce? *Trends in Food Science & Technology,* 109, 245-258.

Deichmann, U., Goyal, A., & Mishra, D. (2016). Will digital technologies transform agriculture in developing countries? *Agricultural Economics, 47*(S1), 21-33.

Drljača, M., & Sesar, V. (2023). Supply Chain Transportation Management. *Proceedings of the 4th International Scientific Conference "Maritime, Transport and Logistics Science"*, 122-133.

Du, X., Wang, X., & Hatzenbuehler, P. (2023). Digital technology in agriculture: a review of issues, applications and methodologies. *China Agricultural Economic Review, 15*(1), 95-108.

Evstatiev, B. I., & Gabrovska-Evstatieva, K. G. (2021). A review on the methods for big data analysis in agriculture. *IOP Conference Series: Materials Science and Engineering, 1032*(1), 012053.

Freund, A., Jámbor, Z., & Nagy, J. (2024). Evolving Agri-Food Supply Chain Through Digitalisation. *Advances in Logistics, Operations, and Management Science Book Series,* 183-216.

Fu, H., Zhao, C., Cheng, C., & Ma, H. (2020). Blockchain-based agri-food supply chain management: case study in China. *International Food and Agribusiness Management Review, 23*(5), 667-680.

Fuentes, S., Tongson, E., & Viejo, C. G. (2024). Artificial intelligence and Big Data revolution in the agrifood sector. *In Food Industry 4.0* (pp. 171-188). Academic Press.

Garrido-López, J., Jiménez Buendía, M., Toledo, A., Giménez-Gallego, J., & Torres-Sánchez, R. (2024). Monitoring Perishable Commodities Using Cellular IoT: An Intelligent Real-Time Conditions Tracker Design. *Applied Sciences, 14*(23), 11050. https://doi.org/10.3390/app142311050

Grecuccio, J., Giusto, E., Fiori, F., &Rebaudengo, M. (2020). Combining Blockchain and IoT: Food-chain traceability and beyond. *Energies, 13*(15), 3820.

Guebsi, R., Mami, S., &Chokmani, K. (2024). Drones in Precision Agriculture: A Comprehensive Review of Applications, Technologies, and Challenges. *Drones, 8*(11), 686. https://doi.org/10.3390/drones8110686

Iftekhar, A., Cui, X., Hassan, M., & Afzal, W. (2020). Application of Blockchain and Internet of Things to Ensure Tamper-Proof Data Availability for Food Safety. *Journal of Food Quality,* 2020. https://doi.org/10.1155/2020/5385207

Jagtap, S., Bhatt, C., Thik, J., &Rahimifard, S. (2020). Monitoring potato waste in food manufacturing using image processing and Internet of Things approach. *Sustainability, 11*(11), 3173.

Jakarbet, U. P., Suhas, S. P., Savithramma, R. M., & Ashwini, B. P. (2024, October). An Empirical Analysis of Machine Learning Algorithms for Agricultural Crop Prediction. In *2024 8th International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud)(I-SMAC)* (pp. 1782-1790). IEEE.

Javaid, M., Haleem, A., Khan, I. H., & Suman, R. (2023). Understanding the potential applications of Artificial Intelligence in Agriculture Sector. *Advanced Agrochem, 2*(1), 15-30.

Jedermann, R., et al. (2014). Reducing food losses by intelligent food logistics. *Philosophical Transactions of the Royal Society A*, 372(2017).

Kamilaris, A., Kartakoullis, A., &Prenafeta-Boldú, F. X. (2017). A review on the practice of big data analysis in agriculture. *Computers and Electronics in Agriculture*, 143, 23-37.

Kanyepe, J., Chibaro, M., Morima, M., & Moeti-Lysson, J. (2024). AI-Powered Agricultural Supply Chains. *Advances in Marketing, Customer Relationship Management, and e-Services Book Series*, 33–64.

Kawre, A., Bulbule, V., Kherde, H., Chavan, S., Barapatre, A., &Budhe, P. (2024). IoT Based Crop Monitoring System.

Khandelwal, C., Singhal, M., Gaurav, G., Dangayach, G. S., & Meena, M. L. (2021). Agriculture supply chain management: a review (2010–2020). *Materials Today: Proceedings*, 47, 3144-3153.

Kittipanya-Ngam, P., & Tan, K. H. (2020). A framework for food supply chain digitalization: Lessons from Thailand. *Production Planning & Control, 31*(2-3), 158-172.

Klerkx, L., Jakku, E., & Labarthe, P. (2019). A review of social science on digital agriculture, smart farming and agriculture 4.0: New contributions and a future research agenda. *NJAS-Wageningen Journal of Life Sciences*, 90, 100315.

Kulikov, N. I., Kulikova, M. A., Parkhomenko, V. L., & Syrbu, A. P. “Anti-Viral” Digitilization Of Financial Flows In Agribusiness: Opportunities And Challenges. *European Proceedings of Social and Behavioural Sciences.*

Kumar, A., Liu, R., & Shan, Z. (2020). Is Blockchain a silver bullet for supply chain management? Technical challenges and research opportunities. *Decision Sciences, 51*(1), 8-37.

Leng, K., et al. (2018). Research on agricultural supply chain system with double chain architecture based on blockchain technology. *Future Generation Computer Systems*, 86, 641-649.

Li, X., Cao, J., Pan, Z., Fu, Z., Tang, F., Xiong, J., & Huang, G. (2021). Do farmers gain internet dividends from E-commerce adoption? Evidence from China. *Food Policy,* 101, 102024.

Lioutas, E. D., Charatsari, C., & De Rosa, M. (2021). Digitalization of agriculture: A way to solve the food problem or a trolley dilemma? *Technology in Society,* 67, 101744.

Liu, M., Huang, J., Zhang, Q., Gao, S., & Zhu, X. (2021). The adoption and impact of E-commerce in rural China: Application of an endogenous switching regression model. J*ournal of Rural Studies,* 83, 106-116.

Liu, S., Guo, L., Webb, H., Ya, X., & Chang, X. (2019). Internet of Things monitoring system of modern eco-agriculture based on cloud computing. *IEEE Access,* 7, 37050-37058.

Lohith Kumar, B., & Raj, P. A. C. (2022). Implementation of Blockchain Technology in Agricultural Supply Chain Management Using IoT. *Wireless Personal Communications,* 124(1), 805–827.

Longo, F., Nicoletti, L., & Padovano, A. (2020). Estimating the impact of blockchain adoption in the food processing industry and supply chain. *International Journal of Food Engineering, 16*(5-6).

Lu, L., & Reardon, T. (2018). An economic model of the evolution of food retail and supply chains from traditional shops to supermarkets to E-commerce. *American Journal of Agricultural Economics, 100*(5), 1320-1335.

Oliveira, L. F., Moreira, A. P., & Silva, M. F. (2021). Advances in agriculture robotics: A state-of-the-art review and challenges ahead. *Robotics, 10*(2), 52.

Padma, A., Ramaiah, M., & Ravi, V. (2024). Blockchain Technology for Agriculture Supply Chain Management. *In Intelligent Computing and Optimization for Sustainable Development* (pp. 192-210). Chapman and Hall/CRC.

Pathak, P., Damle, M., Dange, P., & Pillai, S. (2024). Application of Digital Technologies in Agri-Supply Chain. *Advances in Logistics, Operations, and Management Science Book Series*, 351-382. https://doi.org/10.4018/979-8-3693-4330-2.ch015

Phasinam, K., Kassanuk, T., Shinde, P. P., Thakar, C. M., Sharma, D. K., Mohiddin, M. K., & Rahmani, A. W. (2022). Application of IoT and cloud computing in automation of agriculture irrigation. *Journal of Food Quality, 2022*(1), 8285969.

Qazi, S., Khawaja, B. A., & Farooq, Q. U. (2022). IoT-equipped and AI-enabled next generation smart agriculture: A critical review, *current challenges and future trends.* IEEE Access, 10, 21219-21235.

Qian, J., Wu, W., Yu, Q., Ruiz-Garcia, L., Xiang, Y., Jiang, L., Shi, Y., Duan, Y., & Yang, P. (2020). Filling the trust gap of food safety in food trade between the EU and China: An interconnected conceptual traceability framework based on Blockchain. *Food and Energy Security, 9*(4).

Raj, E. F. I., Appadurai, M., Jebakumar, V. W., & Thanu, M. C. (2024). Agricultural Logistics Enhancement Using Unmanned Aerial Vehicles. *In Drone Applications for Industry 5.0* (pp. 419-440). IGI Global.

Rotz, S., Gravely, E., Mosby, I., Duncan, E., Finnis, E., Horgan, M., LeBlanc, J., Martin, R., Neufeld, H.T., Nixon, A., & Pant, L. (2022). Automated pastures and the digital divide: How agricultural technologies are shaping labour and rural communities. *Journal of Rural Studies,* 68, 112-122.

Saiz-Rubio, V., & Rovira-Más, F. (2023). From smart farming towards agriculture 5.0: A review on crop data management. *Agronomy, 13*(1), 206.

Savaliya, L., Sapovadiya, M., Garg, D., Patel, P., & Shah, M. (2024, October). Agricultural Analysis of Machine Learning Algorithms for Crop Prediction. In *2024 8th International Conference on I-SMAC (IoT in Social, Mobile, Analytics and Cloud)(I-SMAC)* (pp. 1196-1203). IEEE.

Shahid, A., Almogren, A., Javaid, N., Al-Zahrani, F.A., Zuair, M., & Alam, M. (2020). Blockchain-based agri-food supply chain: A complete solution. *IEEE Access, 8,* 69230-69243.

Shanmugapriyaa, K. R., Swetha, S., Janani, N., Bavithra, K., & Padmavathi, K. (2023, December). Optimizing Supply Chain Efficiency: Integrating Deep Learning and Blockchain Technologies. *In 2023 International Conference on Intelligent Technologies for Sustainable Electric and Communications Systems* (iTech SECOM) (pp. 113-118). IEEE.

Sharma, R., Kamble, S. S., Gunasekaran, A., Kumar, V., & Kumar, A. (2020). A Systematic Literature Review on Machine Learning Applications for Sustainable Agriculture Supply Chain Performance. *Computers & Operations Research,* 119, 104926.

Smith, M. J. (2018). Getting value from artificial intelligence in agriculture. *Animal Production Science, 60*(1), 46-54.

Sun, P., & Zhang, Z. (2024, November). Design and Implementation of an Agricultural Logistics Control System Based on IoT Techology. In *2024 International Conference on Advanced Control Systems and Automation Technologies (ACSAT)* (pp. 40-43). IEEE.

TÜRKSOY, N. (2023). Sustainable Agricultural Supply Chains: The Role of Drones in Improving Efficiency and Reducing Environmental Impact. 7-25. https://doi.org/10.59287/idtscm.67

Undre, H. B., & Jokonya, O. (2024). Factors affecting the adoption of drones in the food supply chain. Frontiers in Sustainable *Food Systems, 8.*https://doi.org/10.3389/fsufs.2024.1497595

Viswanadham, N., & Kameshwaran, S. (2013). The Supply Chain Ecosystem Framework. In Ecosystem-Aware Global Supply Chain Management . *World Scientific Publishing.*17-44.

Wan Mohamad, M., &Rakiman, S. U. (2023). Integrative Review of IoT Implementation in Agri-Food Supply Chain: Findings and Analysis. *International Journal of Entrepreneurship and Management Practices.*https://doi.org/10.35631/ijemp.623003

Wang, G., Li, S., Yi, Y., Wang, Y., & Shin, C. (2024). Digital Technology Increases the Sustainability of Cross-Border Agro-Food Supply Chains: A Review. *Agriculture, 14*(6), 900.

Wang, X., & Ng, C.T. (2018). New retail versus traditional retail in e-commerce: channel establishment, price competition, and consumer recognition. *Annals of Operations Research, 291*(1), 921-937.

Weraikat, D., Šorić, K., Žagar, M., & Sokač, M. (2024). Data Analytics in Agriculture: Enhancing Decision-Making for Crop Yield Optimization and Sustainable Practices. *Sustainability, 16*(17), 7331. https://doi.org/10.3390/su16177331

Yadav, V. S., Singh, A. R., Raut, R. D., Mangla, S. K., Luthra, S., & Kumar, A. (2022). Exploring the application of Industry 4.0 technologies in the agricultural food supply chain: A systematic literature review. *Computers & Industrial Engineering,* 169, 108304.

Yadav, V.S., & Singh, A.R. (2019). A systematic literature review of blockchain technology in agriculture. *Proceedings of the International Conference on Industrial Engineering and Operations Management,* 973-981.

Yadav, V.S., Singh, A.R., Raut, R.D., & Govindarajan, U.H. (2020). Blockchain technology adoption barriers in the Indian agricultural supply chain: An integrated approach. *Resources, Conservation and Recycling,* 161, Article 104877.

Yang, M., Fu, M., & Zhang, Z. (2021). The adoption of digital technologies in supply chains: Drivers, process and impact. *Technological Forecasting and Social Change,* 169, 120795.

Yeo, V.C.S., Goh, S.K., & Rezaei, S. (2017). Consumer experiences, attitude and behavioral intention toward online food delivery (OFD) services. *Journal of Retailing and Consumer Services,* 35, 150-162.

Zhang, A., Liang, C., & Yin, J. (2018). How can dmall do better? Discussion on new retail marketing mode based on 4Cs theory. *Proceedings of the 2018 International Conference on E-Business and Applications,* 98-102.

Zheng, Y.-Y., et al. (2019). CropDeep: The crop vision dataset for deep-learning-based classification and detection in precision agriculture. *Sensors, 19*(5), 1058.