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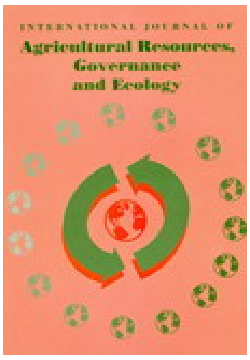


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# Enabling future agriculture: integration of 5G and Metaverse technologies for smart farming innovations

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# Enabling future agriculture: integration of 5G and Metaverse technologies for smart farming innovations


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**Abstract:** The agriculture sector is currently undergoing a significant transformation due to advanced technologies. This review paper explores the integration of 5G and Metaverse technologies for enabling future agriculture, providing a comprehensive overview of technical aspects, applications, challenges, and future developments. It delves into network architecture, data transmission, and digital twin concepts. Additionally, it discusses various applications like precision farming, remote monitoring, and virtual training, supported by case studies. Furthermore, it identifies challenges and limitations such as security risks, technology immaturity, and costs, with proposed future research directions addressing these issues. This review aims to advance 5G and Metaverse technologies in agriculture.

**Keywords:** 5G technology; Metaverse technologies; agriculture; smart farming innovations.

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## 1 Introduction to 5G and Metaverse technologies in agriculture

The world population is growing rapidly (Worldometers, 2023) as shown in Figure 1 to meet this rapid growth of population production of food worldwide has to be increased rapidly. A massive demand needs to be met affordably without wasting resources like water and electricity. In developing economies, food production losses account for 32% of total food losses. Conventional farming methods result in inconsistent yield, excessive resource use, and uncontrolled waste creation (Dora et al., 2020). Farmers require more advanced technologies to produce more with their limited labour and land to meet those needs. Automation is useful in this situation. Due to new rising problems, the agriculture sector has been witnessing a significant transformation with the advent of innovative technologies, such as artificial intelligence, machine learning, and the internet of things (Jha et al., 2023), among these emerging technologies, 5G and Metaverse have the potential to revolutionise agricultural practices and enable smart farming innovations.

### *1.1 5G technology in agriculture*

The emergence of 5G, the fifth-generation wireless technology signifies a fundamental change in the communication network. With its key features like ultra-high-speed data transmission, low latency, and massive device connectivity, 5G enables a range of applications across various sectors including healthcare, smart cities, education, entertainment, and agriculture is also one of them (Li and Li, 2020).

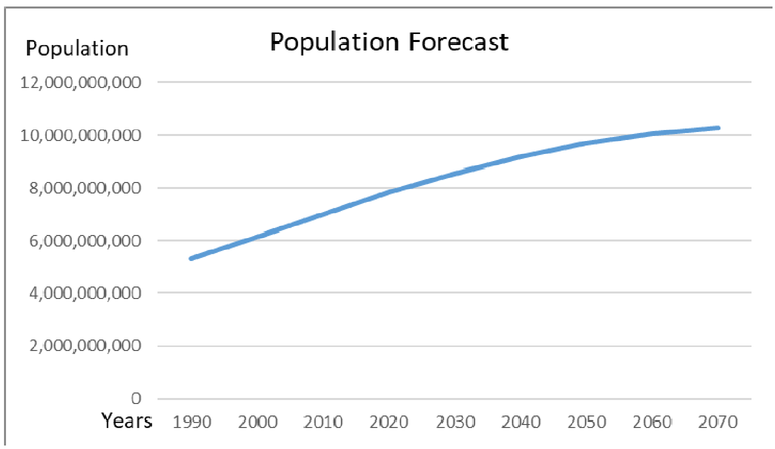
Smart farming systems greatly rely on these capabilities, as they are crucial for their optimal functioning, where time-sensitive decisions based on accurate and up-to-date information can significantly impact productivity and resource management (Avnet, 2023).

Therefore, the following features make 5G an ideal technology for supporting various agricultural applications such as:

- *Real-time monitoring:* with its rapid data transmission, 5G enables real-time monitoring of various agricultural parameters such as soil moisture, temperature, crop growth, crop health, weather patterns, and livestock behaviour. Real-time data collection facilitates early detection of anomalies allowing farmers to take timely preventive measures, optimise resource allocation, and improve overall farm management (Buckmaster et al., 2018; Huynh-The et al., 2022).

- *Data-driven decision making:* the high bandwidth and minimal delay of 5G facilitate the collection and analysis of large volumes of data instantaneously. This data can be used to generate insights and support data-driven decision making in areas such as irrigation management, pest control, and crop optimisation (Whang et al., 2022)
- *Remote control of farming equipment:* 5G enables remote control and monitoring of farming equipment, such as drones and autonomous vehicles. This capability enhances operational efficiency, reduces labour costs, and improves overall productivity (Verma, 2023).

**Figure 1** World population forecast (see online version for colours)




### *1.2 Metaverse technology in agriculture*

The Metaverse, a virtual reality space where users can interact with digital environments and other users, has been gaining traction in various industries (Jha et al., 2023). Metaverse technologies encompass virtual reality (VR), augmented reality (AR), and mixed reality (MR) platforms that provide immersive and interactive experiences. These technologies enable users to interact with digital representations of the physical world, blurring the line between virtual and real environments (McKinsey & Company, 2022). Metaverse platforms offer potential applications in various domains, including healthcare, education, entertainment, and now agriculture as well (Plechatá et al., 2022).

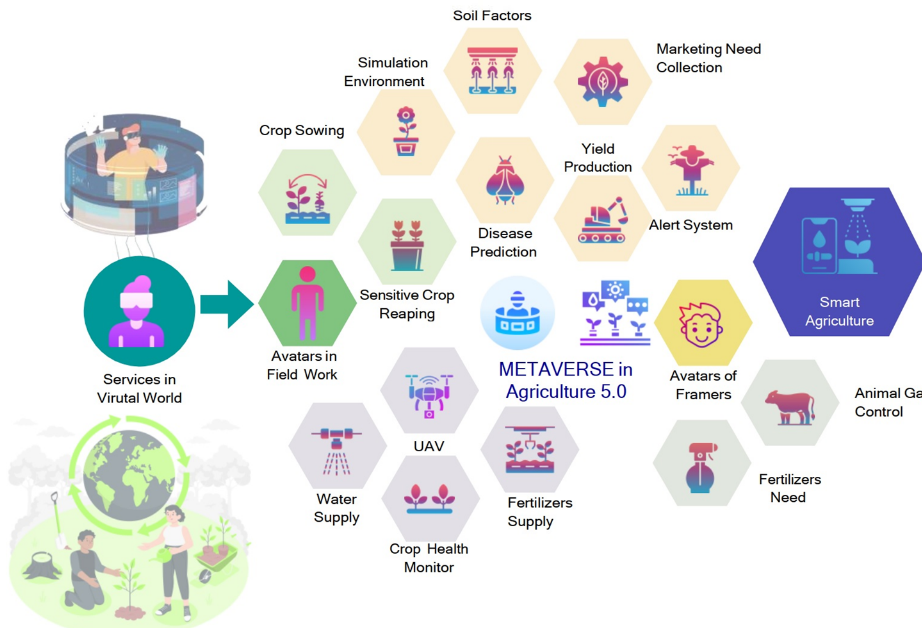
In agriculture, the Metaverse can provide immersive experiences such as:

- *Immersive training and simulation:* the Metaverse provides immersive experiences for training farmers in various agricultural practices, such as crop management, equipment operation, and pest identification. This virtual training environment allows farmers to acquire new skills and knowledge without the need for physical presence (Khansulivong et al., 2022).
- *Digital twin creation:* the Metaverse enables the creation of digital twins, virtual representations of physical assets or processes. In agriculture, digital twins can be used to monitor and optimise farming operations, simulate crop growth, and predict

yield. This technology helps farmers make data-driven decisions and improve overall efficiency (Purcell and Neubauer, 2023).

- *Remote collaboration and knowledge sharing:* the Metaverse facilitates remote collaboration among agricultural stakeholders, allowing them to share knowledge, exchange best practices, and solve problems collectively. This virtual collaboration environment transcends geographical boundaries and enables efficient communication and cooperation (Federal Communications Commission, 2020).

**Figure 2** Metaverse technology in agriculture (see online version for colours)




## 1.3 Integration of 5G and Metaverse technologies

One of the fundamental aspects of integrating 5G and Metaverse technologies into smart farming is the establishment of robust connectivity. 5G networks provide high-speed, low-latency connections, enabling seamless data exchange between farming devices, sensors, and Metaverse platforms (Ericsson, 2022). This interconnection facilitates immediate monitoring and control of agricultural operations, allowing farmers to make timely decisions and respond to changing conditions which will result in saving cost and increasing efficiencies. Furthermore, 5G networks enable the transmission of large volumes of data, such as high-resolution imagery and sensor readings, which are essential for accurate analysis and modelling in Metaverse environments (Kang et al., 2023).

Integrating 5G and Metaverse technologies involves a careful orchestration of hardware, software, and network infrastructure to create a seamless and synergistic environment for smart farming. Here is a detailed breakdown of the steps and considerations required to successfully integrate these technologies:

### 1.3.1 Infrastructure development

Ensuring the farming area is covered by a reliable 5G network. Collaborating with telecommunication providers to establish the necessary infrastructure for high-speed and low delay in communication (Vidal, 2023). Deployment of a network of sensors, drones, cameras, and other IOT devices across the farm to collect and transmit real-time data. These devices provide crucial insights into crop health, soil conditions, weather patterns, and machinery status (Consumer Goods Technology, 2023).

### 1.3.2 Data collection and analysis

Data gathering utilising IoT devices to gather data from various sources, including soil moisture sensors, weather stations, and crop health sensors. This data is transmitted over the 5G network to central databases for analysis (Payero et al., 2021). Then integrating data from different sources into a unified platform. This platform should support interoperability and compatibility between various types of sensors and devices, and finally leveraging advanced analytics and AI algorithms to process the collected data. AI can identify patterns, predict outcomes, and offer actionable insights to optimise farming practices (Navarro et al., 2020).

### 1.3.3 Metaverse integration

First develop AR applications that overlay real-time data onto the physical environment. Hurst et al. (2021) proposed farmers can use AR glasses or mobile devices to view information about crop health, nutrient levels, and irrigation requirements as they walk through the fields. Then create immersive VR environments for training, simulations, and planning. Farmers can virtually experience different scenarios, such as planting strategies or machinery configurations, before implementing them in real life (Ponnusamy and Natarajan, 2021; Visartech, 2023). Finally, design user-friendly interfaces for AR and VR applications. The interfaces should be intuitive and easy to navigate, especially for those less familiar with technology.

### 1.3.4 Remote control and automation

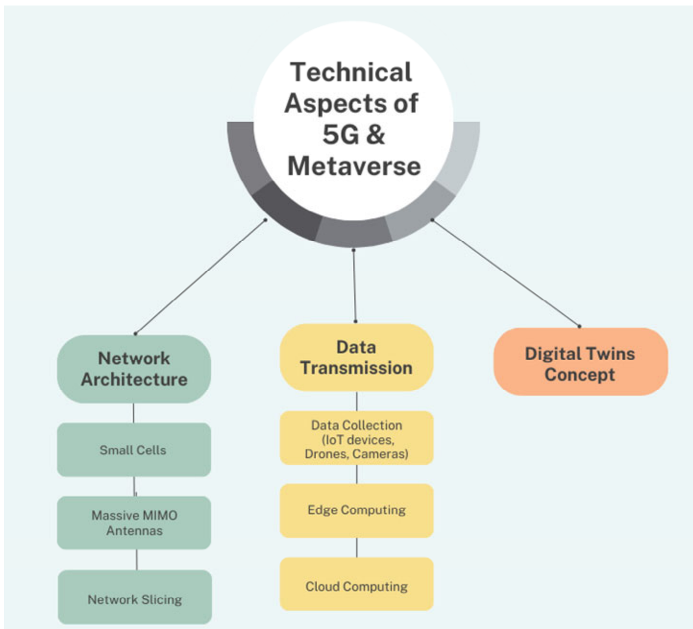
Prabadevi et al. (2023) discusses about developing autonomous farming equipment, such as robotic planters and harvesters that can be controlled remotely using Metaverse interfaces. These devices can carry out tasks with precision, reducing the need for manual labour. Enabling remote monitoring and control of equipment and machinery through Metaverse technologies. Farmers can receive real-time notifications and adjust operations as needed.

By following these steps and taking into account the considerations outlined above, the integration of 5G and Metaverse technologies can be achieved effectively, leading to a transformative shift in the way agriculture is practised through smart farming innovations.

## 2 Technical aspects of 5G and Metaverse integration for smart farming

In this section we will provide a comprehensive overview of the technical aspects of integrating 5G and Metaverse technologies for smart farming. We will begin by discussing the network architecture, including smart cells, massive MIMO, and network slicing. Next, we will examine data transmission and processing, including data collection, edge computing, and cloud computing. Finally, we will introduce the digital twin concept, including key concepts, types, and applications of digital twins in smart farming.

**Figure 3** Technical aspects of 5G and Metaverse (see online version for colours)




### *2.1 Network architecture*

The 5G network architecture for smart farming is designed to provide high-speed, minimal latency linkage and support diverse agricultural applications. Key components of this architecture include:

#### *2.1.1 Smart cells*

Small cells are low-power, short-range base stations that extend network coverage and capacity in agricultural areas. They are strategically deployed to ensure high-speed network access and overcome the challenges of signal attenuation and interference in rural environments (TRAI, 2022). Small cells can be used to provide localised coverage for specific agricultural applications, such as precision agriculture, livestock monitoring, and irrigation management. Oughton et al. (2019) proposes they can be deployed in areas where traditional macro-cells are not feasible, such as remote locations or areas with low population density. Small cells can be used in ultra-dense heterogeneous networks (UDHNs) to provide high-capacity and high-speed networking. UDHNs consist of a large number of small cells, each with a coverage range of a few hundred meters. UDHNs can support a wide range of agricultural applications, such as autonomous farming, remote monitoring, and precision agriculture (Kamal et al., 2021). Small cells can be used in conjunction with full-duplex technology to enhance network capacity and spectral efficiency. Full-duplex small cell base stations can transmit and receive data simultaneously, enabling efficient use of the available spectrum (Dangi et al., 2021).

### *2.1.2 Massive MIMO*

Massive multiple input, multiple output (MIMO) antennas use multiple transmitters and receivers to enhance network capacity, coverage, and spectral efficiency. In the context of smart farming (Dangi et al., 2021), discusses massive MIMO antennas enable efficient data transmission and reception from a large number of IoT devices deployed across the farm. The number of antennas in a cell has increased significantly from 10 in 4G to more than 100 in 5G. This increase in the number of antennas enables massive MIMO antennas to support multiple users simultaneously, improving network capacity and spectral efficiency. Beamforming technology allows the antenna to focus the radio signal in a specific direction, improving the signal strength and reducing interference (Pons et al., 2023). Massive MIMO antennas can be used in ultra-dense heterogeneous networks (UDHNs) to provide high-capacity and high-speed connectivity. UDHNs can support a wide range of agricultural applications, such as autonomous farming, remote monitoring, and precision agriculture (US Government Accountability Office, 2020).

### *2.1.3 Network slicing*

The studies conducted in (5G-PPP, 2023) suggests network slicing allows the allocation of dedicated virtual networks within the 5G infrastructure, tailored to the specific requirements of different agricultural applications. Each network slice is allocated a portion of the available network resources, including bandwidth, latency, and reliability, ensuring optimised resource allocation and efficient data transmission. In the context of smart farming, network slicing enables the customisation of network performance parameters to meet the unique needs of various agricultural applications. For example, a network slice can be dedicated to autonomous farming operations, ensuring reduced lag and a high-reliability internet connection for real-time control and decision-making. Another network slice can be allocated for remote monitoring and control, prioritising high bandwidth and reliable connectivity for data-intensive applications (Ericsson, 2022).

Network slicing allows for the efficient utilisation of network resources by dynamically allocating them based on the specific requirements of each agricultural application. This flexibility enables farmers to optimise their network usage, ensuring that critical applications receive the necessary resources while minimising resource wastage (Pivoto et al., 2023). With network slicing, smart farming applications can coexist on the same physical infrastructure while maintaining isolation and security. Each network slice operates as an independent virtual network, ensuring data privacy and integrity for different agricultural applications (US Government Accountability Office, 2020).

## 2.2 Data transmission and processing

### 2.2.1 Data collection

By utilising various IoT devices and sensors, farmers can gather real-time data on different parameters, enabling them to make informed decisions and optimise their agricultural practices. Let us dive further into the process of data collection:

#### 2.2.1.1 IoT devices and sensors

- *Temperature sensors:* temperature sensors can be used to monitor the thermal conditions of the farm, providing insights into heating or cooling systems and enabling farmers to adjust them accordingly. These sensors can be placed in soil, water, or air to monitor temperature levels.
- *Humidity sensors:* humidity sensors can measure the moisture levels in the soil, assisting in irrigation management. These sensors can be placed in the soil to monitor moisture levels and ensure optimal irrigation practices.
- *Light sensors:* light sensors can monitor the amount of sunlight received by crops, aiding in optimising growth conditions. These sensors can be placed in the field to monitor light levels and ensure optimal growth conditions
- *Pressure sensors:* pressure sensors can be used to monitor the pressure of irrigation systems, ensuring that they are functioning correctly and efficiently.
- *Presence sensors:* presence sensors can be used to detect the presence of animals or humans on the farm, enabling farmers to monitor their movements and ensure their safety.

#### 2.2.1.2 Drones and cameras

Drones equipped with cameras and sensors are increasingly used in smart farming for data collection. They can capture aerial images, collect data on crop health, and monitor large areas of farmland efficiently (Prabadevi et al., 2023). For instance:

- *Multispectral cameras:* multispectral cameras mounted on drones can capture images in different wavelengths, providing valuable information about crop health, nutrient levels, and pest infestations. This data can be transmitted over the 5G network in real time, allowing farmers to make timely decisions and take appropriate actions.
- *Thermal cameras:* thermal cameras can be used to detect temperature anomalies in crops, enabling farmers to identify potential issues and take corrective actions.
- *RGB cameras:* RGB cameras can be used to capture high-resolution images of crops, enabling farmers to monitor their growth and detect any abnormalities.

#### 2.2.1.3 Central databases

The collected data is transmitted over the 5G network to central databases, where it is stored and processed. Cloud computing resources can be leveraged to store and manage large datasets, providing scalable and secure storage solutions. Advanced data analytics and AI algorithms can be applied to the stored data to derive actionable insights and optimise farming practices. For example, machine learning algorithms can analyse historical data to predict crop yields, helping farmers make informed decisions about planting schedules and resource allocation.

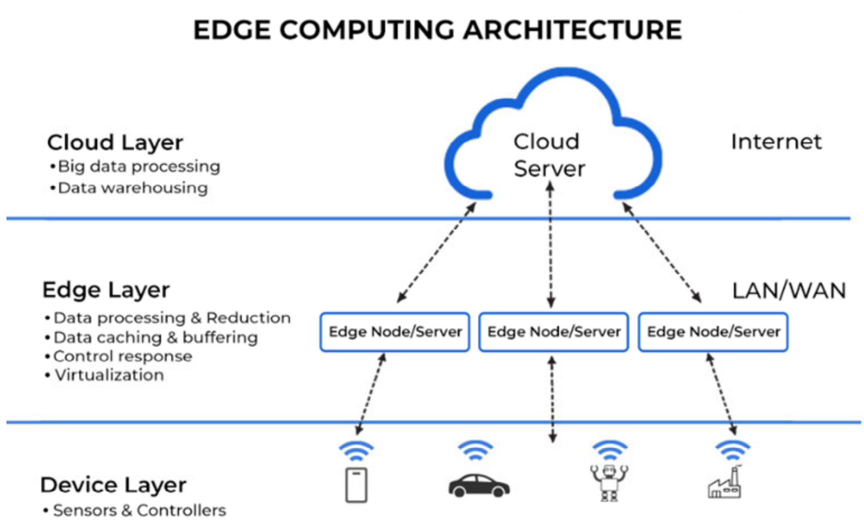
### *2.2.2 Edge computing*

It is a distributed computing paradigm that brings computation and data storage closer to the source of data generation, minimising time delay and enabling real-time analytics (Scale Computing, 2023). It involves processing and analysing data at or near the edge of the network, near where it is generated. In smart farming, edge computing allows for the processing of data at the edge of the network, near IoT devices, sensors, and drones deployed across the farm (IBM, 2023a).

#### *2.2.2.1 Components of edge computing*

- *Edge servers or gateways:* edge servers or gateways are deployed at the edge of the network to process data locally. These servers can be equipped with computing and storage resources, enabling real-time data processing and analysis (Spiceworks, 2023).
- *Edge devices:* edge devices, such as IoT devices, sensors, and drones, are deployed across the farm to collect real-time data on various parameters. These devices are connected to the edge servers or gateways, enabling local data processing and analysis (AWS Amazon, 2023).
- *Edge analytics:* edge analytics refers to the process of analysing data at the edge of the network, near the source of data generation. This approach minimises the need for data transmission to centralised cloud servers, reducing latency and enabling real-time decision making (Microsoft, n.d.).

**Figure 4** The architecture of edge computing (see online version for colours)



#### 2.2.2.2 Applications of edge computing in smart farming

- *Real-time analytics:* edge computing enables real-time analytics of data generated by IoT devices, sensors, and drones. This approach minimises response time and enables timely decision making, allowing farmers to respond quickly to changing conditions and optimise their agricultural practices accordingly (Debauche et al., 2022).
- *Predictive maintenance:* edge computing can be used to predict equipment failures and schedule maintenance proactively. For example, sensors on machines can detect when a machine is about to fail. By using that data at local network at the edge of the network, the system can prognosticate when the machine is likely to fail and proactively schedule conservation, which can reduce timeout and save the money as well (Debauche et al., 2022).
- *Resource optimisation:* edge computing can be used to optimise resource utilisation in smart farming. For example, sensors can monitor soil moisture levels and other environmental factors. By processing that data locally, farmers can make real-time decisions about irrigation and fertiliser application, which can improve crop yields and reduce water waste (Khan et al., 2019).

### 2.2.3 Cloud computing

Cloud computing is a framework that provides widespread, easy-to-access, and on-demand connectivity to a shared collection of customisable computing resources. These resources include networks, servers, storage systems, applications, and various services, all accessible over the internet. This model allows users to efficiently manage and utilise computing power without the need for physical infrastructure (Wang et al., 2016). In smart farming, cloud computing can be leveraged to store and manage large datasets, provide advanced data analytics capabilities, and enable real-time decision making.

#### 2.2.3.1 Key concepts of cloud computing

Following are some of the key concepts of cloud computing:

- *On demand access:* cloud computing allows users to access computing resources and services on-demand, without the need for physical proximity to the hardware or infrastructure. Users can rent access to applications, storage, and other resources from cloud service providers, eliminating the need to own and manage their computing infrastructure (Investopedia, 2023).
- *Scalability:* cloud computing offers scalability, allowing users to easily scale up or down their resource usage based on their needs. This flexibility enables businesses to handle varying workloads efficiently and cost-effectively (Investopedia, 2023).
- *Resource pooling:* cloud computing involves the pooling of computing resources, such as networks, servers, storage, applications, and services, into a shared infrastructure. These resources can be rapidly provisioned and released with minimal management effort or service-provider interaction (Acquisition.gov, 2023).

- *Broad network access:* cloud computing provides broad network access, allowing users to access cloud services and resources over the internet using various devices, such as computers, smartphones, and tablets. This accessibility enables users to work and access their data from anywhere, at any time (Acquisition.gov, 2023).
- *Pay-per-use model:* cloud computing follows a pay-per-use model, where users pay for the resources and services they consume. This cost structure offers flexibility and cost-efficiency, as users only pay for what they use (NIST Computer Security Resource Center, 2021).

#### *2.2.3.2 Types of cloud computing*

- *Infrastructure-as-a-service (IaaS):* IaaS provides virtualised computing resources, such as virtual machines, storage, and networks, allowing users to build and manage their IT infrastructure. Users have control over the operating systems, applications, and configurations, while the cloud service provider manages the underlying infrastructure (Investopedia, 2023).
- *Platform-as-a-service (PaaS):* PaaS provides a platform for users to develop, deploy, and manage applications without the need to manage the underlying infrastructure. Users can focus on application development and deployment, while the cloud service provider manages the platform, including the operating system, runtime environment, and middleware.
- *Software-as-a-service (SaaS):* SaaS offers ready-to-use software applications that are accessed over the internet. Users can use the software without the need for installation or maintenance, as the cloud service provider manages the software and underlying infrastructure (Investopedia, 2023).

## *2.3 Digital twin concept*

IBM (2023b) elaborates that digital twin technology is a virtual representation of a physical object or process that spans its lifecycle, is updated from real-time data, and uses simulation, analytics, and machine learning to optimise its performance. Digital twins play a significant role in the integration of 5G and Metaverse technologies in smart farming.

### *2.3.1 Key concepts of digital twins*

#### *2.3.1.1 Virtual representation*

It creates a virtual representation of a physical object or process, enabling real-time monitoring, analysis, and optimisation. The digital twin is a high-fidelity model of the system that can be used to emulate the actual system, capturing its behaviour, characteristics, and interactions (Soori et al., 2023).

#### *2.3.1.2 Real-time data*

It uses real-time data from sensors, IoT devices, and other sources to update the virtual model. This real-time data provides an accurate reflection of the physical system's current state, allowing for timely decision making and optimisation (IBM, 2023b; PTC, 2023).

### *2.3.1.3 Simulation and analytics*

Using simulation and analytics it predicts the behaviour of the physical system and optimise its performance. Through simulation, the digital twin can simulate different scenarios and assess the impact of changes, enabling proactive maintenance and performance optimisation (Botín-Sanabria et al., 2022).

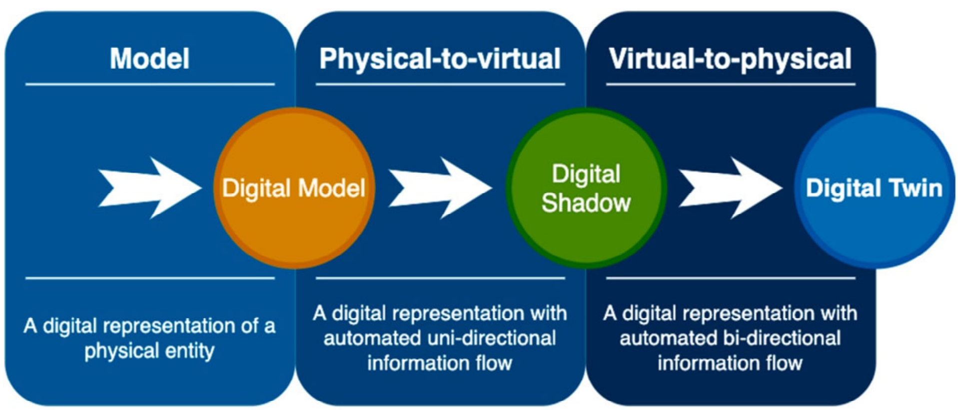
### *2.3.1.4 Machine learning*

By incorporating machine learning algorithms it analyses data and identify patterns, enabling predictive maintenance and optimisation. By learning from historical data and real-time inputs, the digital twin can continuously improve its performance and provide actionable insights (Botín-Sanabria et al., 2022).

### *2.3.1.5 Lifecycle management*

It covers the entire lifecycle of the physical system, from design and development to operation and maintenance. It enables closed-loop design processes, where engineering organisations optimise product form, fit, and function based on real-world data, leading to continuous improvement (IBM, 2023b; PTC, 2023).

**Figure 5** Digital twins: architecture (see online version for colours)




## *2.3.2 Types of digital twins*

### *2.3.2.1 Fully integrated twin*

A fully integrated twin enables bidirectional interaction between the virtual and physical worlds. This means that information flows automatically between the digital twin and the physical system. In this case, information flowing from the virtual world will be useful to perform changes in the physical model or to instruct actuators to operate (Botín-Sanabria et al., 2022).

#### 2.3.2.2 Digital thread twin

A digital thread twin is a digital representation of the physical system that spans its entire lifecycle, from design and development to operation and maintenance. This approach enables closed-loop design processes, where engineering organisations optimise product form, fit, and function based on real-world data (PTC, 2023).

#### 2.3.2.3 Digital shadow twin

A digital shadow twin is a digital representation of the physical system that is used for monitoring and analysis. This approach enables real-time monitoring and predictive maintenance, reducing downtime and improving overall operational efficiency (Soori et al., 2023).

### 2.3.3 Applications of digital twins in smart farming

#### 2.3.3.1 Predictive maintenance

Digital twin technology can be used to predict equipment failures and schedule maintenance proactively by analysing real-time data from sensors and IoT devices. For example, sensors on machines can detect when a machine is about to fail. Since data will be processed locally and network edge, the system will be able to predict if the machine may fail and even schedule maintenance whenever needed, which will potentially minimise downtime and result in saving money (Wikipedia, 2023).

#### 2.3.3.2 Resource optimisation

Digital twin technology can be used to optimise resource utilisation in smart farming. For example, sensors can monitor soil moisture levels and other environmental factors. By processing that data locally, farmers can make real-time decisions about irrigation and fertiliser application, which can improve crop yields and reduce water waste (Wikipedia, 2023).

#### 2.3.3.3 Closed-loop design

Digital twin technology can be used to optimise the design of agricultural equipment and processes. By creating a digital twin of the physical system, engineers can simulate and optimise its performance, improving product form, fit, and function based on real-world data (PTC, 2023).

## 3 Applications and case studies in agriculture

### 3.1 Smart irrigation management using 5G and Metaverse technologies

Smart irrigation management is one of the important aspects of precision agriculture that aims to optimise water usage and improve crop yields (Strickland et al., 2022). By integrating 5G and Metaverse technologies, farmers can leverage real-time data, advanced analytics, and remote monitoring to enhance irrigation practices.

The study in Touil et al. (2022) discusses the integration of 5G and Metaverse technologies applied to smart irrigation management. A network of soil moisture sensors is installed across a farm, consistently gathering data on soil moisture levels. According to Liu et al. (2013), this data is transmitted in real-time via a 5G network to a Metaverse platform, utilising a four-layer framework: the physical layer, network layer, decision layer, and application layer. This structured approach ensures seamless data flow and integration, enabling efficient monitoring and analysis of agricultural conditions. Farmers can access the platform through AR-enabled smart glasses or mobile devices, allowing them to visualise the farm in augmented reality and see real-time soil moisture readings overlaid onto specific areas of the field. This enables precise irrigation decisions, ensuring optimal water usage and preventing under or over-watering.

Arsyad (2023) presents the production of cocoa in is also done through the Metaverse platform leveraging AI algorithms to provide predictive analytics on irrigation needs based on historical and real-time data. The integration of 5G and Metaverse technologies in smart irrigation management enhances water conservation, improves crop yield, and reduces operational costs.

## *3.2 Livestock monitoring and health management with augmented reality*

Livestock monitoring and health management are essential aspects of modern farming practices. With the advent of advanced technologies, such as augmented reality (AR), farmers can now access real-time data and insights to improve animal welfare and productivity. This case study explores the application of AR in livestock monitoring and health management.

Zhao et al. (2017) introduces a novel approach employing augmented reality (AR) to aid pasture-based dairy farmers in identifying and locating animals within extensive herds. The proposed method utilises GPS collars on cows, a digital camera, and on-board GPS on a mobile device to pinpoint a specific cow's location. Subsequently, the mobile application displays behavioural and pertinent key metrics through the augmentation of cow-related information onto the real-world video feed. This real-time visual overlay assists users, particularly farmers, in effectively managing their animals' welfare, health, and necessary interventions. By amalgamating GPS data with computer vision (CV) and machine learning, the mobile AR application encompasses two primary functions: firstly, the ability to locate a cow based on its distinct ID, and secondly, the presentation of cow-specific details on the device screen. Through proof-of-concept application, the potential of employing AR in precision livestock farming is demonstrated.

Caria et al. (2020) took a step further by evaluating the performance and usability of smart glasses for augmented reality in precision livestock farming operations. The researchers used smart glasses to display information about sheep, such as their identification, age, and health status, to farmworkers. The study aimed to assess the potential of AR devices in enhancing the efficiency and accuracy of livestock management tasks.

The results of the study showed that smart glasses could improve the speed and accuracy of data collection and decision making in livestock farming operations. The researchers concluded that AR technology could be a valuable and integrative tool in precision livestock farming, offering new opportunities for improving animal health management and welfare.

### 3.3 Autonomous farming operations through IoT integration

Shahu et al. (2023) explored the implementation of IoT in smart farming to increase agricultural production and the quality of the produce. The study involved the use of IoT sensors to monitor the growth and water requirements of plants with real-time data about humidity and temperature, the use of farm-based equipment with a systematic approach to increasing agricultural production and quality of the produce, the implementation of smart farming as a low-cost and low-labour method leading to an overall reduction of agricultural expenses. IoT devices, such as sensors, drones, and robotic equipment, are integrated into farming operations to collect data on soil conditions, weather, and crop health. Similarly Relf-Eckstein et al. (2019) discusses data collected by IoT devices is transmitted to a central platform, where it is processed and analysed to optimise farming operations. IoT integration enables real-time monitoring and control of farming equipment, reducing labour costs and improving efficiency.

Fastellini and Schillaci (2020) present several benefits of autonomous farming operations through IOT for instance IoT devices can automate various farming tasks, reducing labour costs and increasing efficiency, real-time data and analytics enable farmers to optimise their operations, leading to higher crop yields, and IoT integration can help farmers reduce waste and minimise their impact on the environment.

**Table 1** Smart applications in agriculture

| *Applications* | *Technology integration* | *Domain* | *Medium* |
|---|---|---|---|
| Smart irrigation management system (Touil et al., 2022) | Drones and unmanned aerial vehicles (UAV) | Crops | Mobile phone |
| Crop information overlay (Liu et al., 2013) | Sensors (e.g., humidity, wind, temperature), network infrastructure (e.g., GPRS, Wi-Fi, etc.) | Crops | Mobile phone |
| Cocoa production (Arsyad, 2023) | Metaverse-based simulation (watering, harvesting, fermentation, drying, and storage) | Crop | Wearable: smart glasses |
| AR livestock tracker application (Zhao et al., 2017) | GPS, computer vision, machine learning (ML) | Livestock | Mobile phone |
| Livestock farming operations (Caria et al., 2020) | AR, wireless sensor networks (WSNs), cloud computing and machine learning | Livestock | Wearable: smart glasses |
| Precision farming (Shahu et al., 2023) | AR, internet of things (IoT), WSNs, cloud computing, ML | Crop and livestock | Wearable: smart glasses |
| Smart farming innovation (Relf-Eckstein et al., 2019) | Autonomous farm equipment, graphic processing, UAVs, ML | Crops | Unknown |
| Smart farming (Fastellini and Schillaci, 2020) | ML, IoT, sensors (soil moisture, temperature etc.), edge computing | Crops | Unknown |

# 4 Challenges, limitations and future developments

In this section, we will provide an overview of the challenges and limitations of our study, as well as the potential for future developments in the field. We will discuss the implications of our findings for future research and provide recommendations for future research directions.

## *4.1 Challenges and limitations*

### *4.1.1 Infrastructure requirements*

One of the primary challenges in integrating 5G and Metaverse technologies in smart farming is the need for robust infrastructure (Verma, 2023). Extensive network coverage and reliable internet connection are essential for seamless data transmission and real-time interaction between farming devices and Metaverse platforms. The deployment of 5G infrastructure, including base stations and fibre-optic networks, requires significant investment and coordination (Alahi et al., 2023). Additionally, in rural areas with limited accessibility, ensuring widespread access to 5G networks and Metaverse platforms may pose logistical and financial challenges (Tan et al., 2022).

### *4.1.2 Data security and privacy*

The integration of 5G and Metaverse technologies in agriculture presents significant security and privacy risks that must be addressed to ensure the safe and effective use of these innovations.

As agricultural systems increasingly rely on interconnected devices and platforms, the risk of data breaches and unauthorised access escalates (Adil et al., 2023). Sensitive information, such as crop yields, soil conditions, and operational data, can be targeted by cybercriminals. The reliance on digital infrastructure makes agricultural operations vulnerable to various cyber attacks, including distributed denial of service (DDoS) attacks, which can disrupt operations and lead to significant financial losses. To combat these threats, farmers and stakeholders should consider conducting frequent security assessments can help identify vulnerabilities and ensure that protective measures are effective. Developing and maintaining a comprehensive incident response plan can facilitate quick recovery from cyber incidents, minimising downtime and damage.

Cybercriminals may target agricultural entities with ransomware attacks, encrypting critical data and demanding payment for its release. Such attacks can disrupt operations and lead to substantial downtime, affecting productivity and profitability. The proliferation of IoT devices in agriculture increases the attack surface for potential cyber threats. Many IoT devices may lack adequate security features, making them susceptible to hacking and exploitation. Compromised devices can be used to gain access to larger networks, posing additional risks.

To mitigate these risks, robust security measures should be implemented, e.g., all data transmitted over networks should be encrypted to protect it from interception and unauthorised access, multi-factor authentication, and regular security audits, can help protect sensitive data from unauthorised access and breaches. Ensuring that IoT devices are equipped with adequate security features, such as secure boot, firmware updates, and network segmentation, can reduce vulnerabilities and enhance overall security. Providing training for agricultural workers on cybersecurity best practices can help build a culture of security awareness. Educating employees about phishing tactics and safe data handling practices is essential for reducing human-related vulnerabilities. Furthermore, implementing strict access controls and authentication protocols can help ensure that only authorised personnel can access sensitive data and systems.

The immaturity of 5G and Metaverse technologies may introduce unforeseen vulnerabilities that could be exploited by malicious actors. Therefore, engaging with telecommunications and technology providers to stay informed about potential vulnerabilities and patches is essential. Providing training for farmers and agricultural workers on cybersecurity best practices can help build a culture of security awareness and preparedness.

#### *4.1.3 Training and adoption*

Integrating 5G and Metaverse technologies into smart farming requires adequate training and adoption among farmers and agricultural stakeholders. Federal Communications Commission (2020) suggests familiarising farmers with the functionalities and benefits of these technologies is crucial for their successful implementation. Training programs, workshops, and educational resources should be provided to ensure farmers are equipped with the necessary skills to operate Metaverse platforms and interpret the data provided. Furthermore, addressing the concerns and resistance to change among farmers and promoting awareness of the long-term benefits are vital to encourage widespread adoption.

#### *4.1.4 Cost implications*

The implementation of 5G and Metaverse technologies in agriculture is often hindered by high costs, which can pose significant barriers to adoption, particularly for small and medium-sized farms. The financial implications of integrating these advanced technologies must be carefully considered.

The initial investment required for deploying 5G infrastructure and Metaverse platforms can be substantial. This includes costs associated with establishing a reliable 5G network necessitates significant expenditure on hardware, such as base stations, antennas, and supporting equipment. Additionally, the deployment of IoT devices, sensors, and drones across agricultural lands further increases the financial burden. It also includes, the cost of acquiring advanced technologies, such as virtual reality (VR) and augmented reality (AR) systems for the Metaverse, adds to the overall expenses. These technologies require not only the purchase of devices but also ongoing maintenance and updates.

Beyond the initial investments, operational costs can also be high which may include continuous maintenance of the network infrastructure and devices is necessary to ensure optimal performance. Including software updates, hardware repairs, and periodic system upgrades, which can accumulate significant costs over time. Farmers and agricultural workers may require training to effectively utilise new technologies. Investing in training programs to build the necessary skills for operating and managing these advanced systems can further strain financial resources (Kang et al., 2023).

To justify the high costs associated with implementing 5G and Metaverse technologies, a comprehensive cost-benefit analysis is essential. This analysis should consider

- Long-term savings: while the upfront costs are considerable, the potential for long-term savings through improved efficiency, reduced resource waste, and enhanced productivity can offset initial investments. For example, real-time monitoring and data-driven decision making can lead to better resource management and yield optimisation.
- Government subsidies and financial support: exploring opportunities for government subsidies, grants, or low-interest loans can help alleviate the financial burden on farmers. Collaborative funding models, where multiple stakeholders share the costs, can also be beneficial.
- Shared infrastructure models: implementing shared infrastructure models, where farmers collectively invest in and utilise shared resources, can reduce individual costs while maximising technology benefits.

### *4.1.5 Technology immaturity*

The Metaverse, characterised by immersive virtual environments that facilitate interaction among users and digital representations of the physical world, is still in its developmental infancy, particularly in the agricultural sector. While the potential applications of Metaverse technologies in agriculture are promising, several specific developmental hurdles must be addressed to enable effective integration.

The Metaverse has not yet been widely tested in agricultural contexts, resulting in a scarcity of proven use cases. Most applications remain theoretical or experimental, lacking the empirical data needed to validate their effectiveness in real-world farming scenarios. The absence of standardised protocols and frameworks for Metaverse technologies creates barriers to interoperability. Different platforms may not communicate effectively, complicating the integration of various tools and systems that farmers might use. Hardware limitations: the high costs and technological requirements of VR and AR devices pose significant obstacles. Many farmers may lack access to the necessary hardware, which can hinder the widespread adoption of Metaverse applications. User adoption and acceptance: there may be resistance among farmers to adopt new technologies, particularly those that require significant changes to established practices. Concerns about usability and the learning curve associated with new tools can impede acceptance.

To advance the maturity of Metaverse technology in agriculture several key hurdles must be addressed. Improving the quality of virtual environments is essential for effective training and simulation. This includes developing realistic graphics, responsive interactions, and accurate representations of agricultural processes. Digital twins, which are virtual replicas of physical assets or processes, must be refined to ensure they accurately reflect real-world conditions. This involves integrating real-time data and advanced modelling techniques to enhance predictive capabilities. Developing intuitive and user-friendly interfaces for AR and VR applications is crucial. Farmers, particularly those less familiar with technology, need straightforward navigation and interaction methods to engage with Metaverse tools effectively. Seamless integration of Metaverse applications with existing agricultural technologies, such as IoT devices and data management systems, is necessary to create a cohesive ecosystem that supports smart farming. As data collection increases, ensuring the privacy and security of sensitive agricultural information is paramount. Establishing robust security protocols and data governance policies will help build trust among users.

## *4.2 Future developments and research directions*

The integration of 5G and Metaverse technologies in smart farming has laid the foundation for transformative advancements. As the agricultural landscape continues to evolve, there are several promising directions for future research and development. This chapter delves into the potential developments and research directions that hold the key to unlocking the full potential of this integration.

### *4.2.1 Autonomous systems and AI-driven precision agriculture*

The future of smart farming lies in the further enhancement of autonomous systems and AI-driven precision agriculture. Research efforts should focus on refining AI algorithms to enable autonomous decision making by farming equipment, such as drones, robotic planters, and harvesters (Federal Communications Commission, 2020). These machines can be equipped with advanced computer vision systems to identify crop health issues, optimise planting patterns, and ensure optimal harvesting conditions. AI's ability to analyse vast datasets can be harnessed to predict crop yields, optimise resource allocation, and even suggest adaptive farming strategies based on real-time environmental conditions. Collaborative research between agricultural experts, machine learning practitioners, and robotics engineers is essential to realise these advancements (Relf-Eckstein et al., 2019).

### *4.2.2 Sustainability and environmental impact*

With the increasing adoption of technology in agriculture, ensuring sustainable practices and minimising environmental impact become paramount. Future research should explore methods to quantify the environmental benefits and drawbacks of implementing 5G and Metaverse technologies (Fastellini and Schillaci, 2020). This involves assessing energy consumption, electronic waste generation, and the overall carbon footprint of technology-driven farming practices. Solutions may involve optimising sensor networks to reduce energy consumption, implementing circular economy principles for electronic components, and devising strategies for eco-friendly disposal of obsolete technology (Relf-Eckstein et al., 2019). Moreover, research could focus on developing AI-driven systems that optimise resource usage while minimising negative ecological consequences.

### *4.2.3 Data privacy and security*

As data collection and sharing become integral to smart farming, data privacy and security are critical concerns. Future research should delve into developing robust encryption mechanisms, secure data storage protocols, and anonymous data sharing frameworks, implementing robust data encryption, access controls, and secure data storage measures is essential to safeguard sensitive information (Kaur et al., 2022). Agricultural data contains sensitive information that can have significant economic implications, making it crucial to establish trust among stakeholders. Research can explore techniques such as homomorphic encryption and federated learning to enable collaborative analysis of data without compromising individual privacy (Gupta et al., 2020). Furthermore, policy recommendations and legal frameworks for data ownership, access, and sharing need to be established to ensure a fair and ethical data ecosystem.

### *4.2.4 Multi-stakeholder collaboration and policy frameworks*

The future of smart farming depends on multi-stakeholder collaboration involving farmers, technology providers, policymakers, researchers, and consumers. Research should focus on creating frameworks for effective collaboration, knowledge sharing, and problem-solving within the Metaverse (Federal Communications Commission, 2020). This could involve the development of virtual collaborative platforms tailored to the agricultural context, enabling stakeholders to engage in meaningful discussions and decision-making processes. Additionally, research on policy frameworks that address ethical concerns, data governance, and equitable technology access is crucial to ensure that the benefits of smart farming are widely distributed and sustained (Chukkapalli et al., 2021; Auer et al., 2022).

**Table 2** Challenges and proposed solution of 5G and Metaverse integration

| *Challenges* | *Proposed solution* |
|---|---|
| Infrastructure requirements and connectivity | Robust infrastructure including extensive network coverage and reliable connectivity are essential for seamless data transmission and real-time interaction between farming devices and Metaverse platforms. Deployment of 5G infrastructure, such as base stations and fibre-optic networks, is required. Exploring solutions for ensuring widespread access to 5G networks and Metaverse platforms in rural areas with limited connectivity is necessary. |
| Data security and privacy | Ensuring data security and privacy is crucial due to the collection and processing of large amounts of agricultural data. Protecting valuable agricultural data from unauthorised access, manipulation, or theft is essential. Establishing clear data governance policies, compliance with privacy regulations, and collective efforts from all stakeholders are necessary to safeguard farmers' privacy and rights. |
| Training and adoption | Adequate training and adoption among farmers and agricultural stakeholders are required for the successful integration of 5G and Metaverse technologies in smart farming. Familiarising farmers with the functionalities and benefits of these technologies through training programs, workshops, and educational resources is crucial. Addressing concerns and resistance to change, as well as promoting awareness of long-term benefits, are vital for widespread adoption. |
| Cost implications | Integrating 5G and Metaverse technologies in smart farming may involve significant upfront costs. Exploring cost-effective solutions such as public-private partnerships, government subsidies, or shared infrastructure models can help overcome financial barriers and enable broader access to the benefits of these technologies in agriculture. |

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