Applications and Platform Designs of Intelligent Sensing Technologies in Agriculture: A Systematic Review

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Abstract: This study systematically examines the critical challenges confronting global agriculture, including resource scarcity, environmental degradation, and the increasing demand for food production driven by population growth. The research aims to investigate the application of intelligent sensing technologies, encompassing the Internet of Things (IoT), Artificial Intelligence (AI), and big data analytics, in addressing these challenges. The study's primary objective is to design and evaluate an integrated smart agricultural platform that leverages these technologies to enhance productivity, optimize resource efficiency, and support sustainable rural development. Through a synthesis of 50 peer-reviewed studies published between 2015 and 2023, selected based on relevance, methodological rigor, and impact, this review demonstrates that IoT-based systems improve water-use efficiency by up to 30%, while AI-driven crop monitoring reduces pesticide usage by 25%. These findings propose a conceptual framework for the deployment of intelligent sensing technologies, advancing precision agriculture and sustainable food systems.

Keywords: Artificial Intelligence (AI), big data analytics, intelligent sensing technologies, Internet of Things (IoT), precision agriculture, smart agricultural platforms, sustainable agriculture.

1. Introduction

1.1 Background: Global Agricultural Challenges and Opportunities

Global agriculture faces unprecedented challenges in coping with resource scarcity, environmental pressures, and population growth. With the global population expected to reach nearly 9 billion by 2050, food demand is projected to increase by 6% [1]. However, while traditional intensive and industrial agriculture has increased food production, it has also caused serious environmental problems, such as overuse of fertilizers, greenhouse gas (GHG) emissions, and reduced biodiversity [2]. For instance, excessive use of fertilizers leads to eutrophication of water bodies and increases the emission of nitrous oxide, a potent greenhouse gas that contributes to global warming [3]. Additionally, climate change exacerbates these issues, affecting the stability and predictability of agricultural production [4].

At the technological level, the complexity of different cropping systems and data quality requirements pose challenges to the application of agricultural technologies [5]. Precision agriculture, for example, requires high-precision sensors and real-time data processing capabilities to ensure optimal growing conditions for crops [6]. Meanwhile, challenges at the economic and social levels, such as farmers' education levels and technology acceptance, also constrain the modernization of agriculture [7]. In many developing countries, farmers lack the necessary skills and knowledge to effectively utilize new technologies, resulting in limited technology diffusion [8].

To address these challenges, it is crucial to optimize resource use, reduce environmental impacts, and increase the economic resilience of agricultural production through sustainable agricultural practices [9]. Precision agriculture technologies, such as IoT and AI, have demonstrated significant benefits. For example, IoT-enabled irrigation systems have reduced water consumption by 25%, while AI-driven pest detection has decreased pesticide usage by 30%, enhancing both productivity and sustainability [2, 3]. These quantitative insights highlight the transformative potential of intelligent sensing technologies in addressing global agricultural challenges.

Furthermore, the adoption of drip irrigation technology can significantly improve water use efficiency and reduce water wastage [10]. Emerging technologies such as Artificial Intelligence (AI), the Internet of Things (IoT), and Big Data play an essential role in this process by improving productivity and resource utilization through data-driven decision support [11]. For instance, the use of drones and sensors to monitor farmland conditions, combined with big data analysis, can lead to timely detection of pests and diseases, enabling precise control and reducing pesticide usage [12].

These technologies not only help solve many challenges in agriculture but also present significant opportunities. Through smart, data-driven agricultural technologies, farmers can better manage and optimize agricultural production. For example, using AI to predict market demand can optimize planting and harvesting times, reduce surplus and waste, and improve economic efficiency [6]. Additionally, IoT technologies enable farmers to monitor crop growth conditions in real-time and adjust irrigation and fertilization strategies to improve crop yield and quality [7].

While many studies have focused on sensing technologies for agriculture, this article uniquely explores their integration into comprehensive smart agricultural platforms aimed at addressing rural revitalization and sustainable development. By connecting technical innovations with socio-economic goals, this study offers a holistic perspective that bridges the gap between technology deployment and rural economic resilience and addresses pressing global agricultural challenges, including resource scarcity, environmental degradation, and rural economic disparities. By leveraging intelligent sensing technologies, such as IoT, AI, and big data, this review demonstrates how integrated smart agricultural platforms can optimize resource utilization, reduce environmental impacts, and enhance rural economic resilience.

1.2 Review Objective

The purpose of this review is to explore the application of artificial perception technology in agriculture and its impact on rural revitalization. By improving agricultural efficiency and supporting rural economic development through technological innovation, this study aims to address the multiple challenges of resource scarcity, environmental pressure, and population growth facing global agriculture. Advanced artificial perception technologies, such as Artificial Intelligent (AI), IoT, and big data analytics, have been introduced into agriculture to enhance production efficiency, manage resources better, reduce waste, protect the environment, and ultimately boost rural economies. For instance, monitoring farmland conditions through drones and sensors, combined with big data analysis, can lead to timely detection of pests and diseases, enabling precise control and reducing pesticide usage [12, 13]. Furthermore, AI can help predict market demand, optimize planting and harvesting times, reduce surplus and waste, and improve economic efficiency [6, 13].

The application of these technologies not only improves agricultural production efficiency but also provides a new path to achieving rural revitalization. By promoting the modernization and intelligent development of agriculture, the quality of life and economic income of farmers can be improved, thereby achieving sustainable rural development. For example, in China, a financial digital operation and risk control cloud platform based on AI models has been used to empower rural revitalization by promoting agricultural production and increasing farmers' incomes through accurate financial services [14]. In India, 6G flying self-assembling network systems have been used to enable precision agriculture, improving crop yield and quality through real-time data transmission and intelligent analysis [4]. In Europe, 5G networks and IoT technologies are used for smart irrigation systems that optimize irrigation strategies and save water by monitoring soil moisture and climate conditions in real-time [7].

To address the challenges facing global agriculture, it is essential to propose smart sensing systems for smart agricultural equipment based on IoT and big data technologies. Existing technologies often focus on isolated aspects of precision agriculture, such as sensor deployment or Unmanned Aerial Vehicles(UAV) imaging [5, 6]. In contrast, the proposed platform integrates these components into a unified system that supports real-time decision-making and comprehensive farm management, enabling both technical and economic scalability. These systems integrate various advanced technologies to achieve real-time monitoring and precise management of agricultural production, thereby improving agricultural efficiency, reducing resource wastage, and lowering environmental impacts. For example, sensors and IoT devices can monitor soil moisture, temperature, and nutrient status in real-time, providing data support to optimize irrigation and fertilization strategies [12]. Big data analytics can help predict the occurrence of pests and diseases and develop control measures, reducing pesticide use and improving crop yield and quality [6]. Additionally, cloud computing technology can facilitate the storage and processing of massive agricultural data to support agricultural decision-making and management [11].

Therefore, proposing and implementing an intelligent sensing system for smart agricultural equipment based on IoT and big data technologies is an effective way to solve current agricultural problems and an important means to promote the modernization and intelligent development of agriculture [7–9]. Specifically, this review aims to map and deepen the understanding of various technologies implemented in the agriculture sector, with a special focus on rural revitalization and sustainable development. The main objectives of this systematic review are to: (1) develop a comprehensive understanding of the enabling intelligent perception technologies currently applied in agriculture, (2) explore a variety of technological initiatives aimed at achieving rural revitalization and sustainability goals, and (3) analyze the design and implementation of smart agricultural platforms that integrate these advanced technologies.

2. Intelligent Perception Technologies and Application Cases in Smart Agricultural Equipment

2.1. IoT Technology

IoT technology plays a vital role in modern agriculture by improving agricultural productivity and resource utilization through real-time monitoring, automated management, and data-driven decision-making. Specific applications of IoT in agriculture and the associated devices and features are described in detail below.

2.1.1. Real-Time Monitoring

IoT technology enables farmers to monitor various environmental parameters and crop statuses of their farmland in real-time. Through a network of sensors, farmers can access information such as soil moisture, temperature, air humidity, and light intensity. For example, the system discussed in the IoT-Based Real-Time Monitoring System for Precision Agriculture paper uses the ESP8266 IoT module to monitor soil moisture and ambient temperature in real-time [1]. This real-time monitoring system not only improves farmers' understanding of farmland conditions but also allows them to take timely measures according to the actual situation, thus improving agricultural productivity.

2.1.2. Automated Management

Through the application of IoT technology, many aspects of agricultural production can be managed automatically. For example, in the Farmers’ Assistance for Field Monitoring and Irrigating the Cultivated Land using IoT paper, the authors propose an IoT-based system to automatically manage the irrigation process using various sensors (e.g., rain sensors, soil moisture sensors) and an Arduino board [8]. When the sensors detect that soil moisture is below a preset threshold, the system automatically starts the pump for irrigation. This automated management reduces farmers' labor intensity, optimizes water resource usage, and avoids wastage.

2.1.3. Data-Driven Decision-Making

IoT technology combined with big data analytics allows agricultural production to make scientific decisions based on data. For instance, in the Harnessing 5G Networks for Enhanced Precision Agriculture paper, the authors explore the use of 5G networks and IoT technologies for precision agriculture management, where real-time data transmission and analysis allow farmers to get advice on the best strategies for crop growth. Big data analytics can help predict the occurrence of pests and diseases and develop reasonable control measures based on weather and soil conditions, reducing pesticide use and improving crop yield and quality.

2.1.4. Types of IoT Devices and Their Functions

The application of IoT in agriculture relies on the collaborative work of multiple devices, including sensors, wireless networks, and smart terminals. Sensors: Sensors are the most basic devices in an IoT system and are used to monitor various environmental parameters in the farmland in real-time. For example, the soil moisture sensor and the DHT11 temperature and humidity sensor used in the IoT-Based Real-Time Monitoring System for Precision Agriculture paper can accurately measure humidity and temperature in soil and air [1]. These data are crucial for guiding irrigation and fertilization strategies. Wireless Network: Wireless networks are key to connecting individual sensors and end devices. Wireless communication technologies such as 5G and LoRa (Long Range) are widely used in agricultural IoT. For instance, the Recent Advances in 5G and IoT Applications for Smart Agriculture paper mentions that the high bandwidth and low-latency characteristics of 5G technology make data transmission in large-scale sensor networks more efficient [12]. The wireless network ensures that data can be uploaded to the cloud for analysis and storage in real-time, supporting remote monitoring and management. Smart Terminals: Smart terminals include various devices used for data processing and presentation, such as smartphones, tablets, and agricultural management platforms. For example, the Farmers' Assistance for Field Monitoring and Irrigating the Cultivated Land using IoT paper mentions that with the Ubidots application, farmers can monitor and control field conditions in real-time from anywhere in the world [8]. These smart terminals provide farmers with convenient management tools, making agricultural management more efficient and intelligent. In summary, IoT technology has greatly improved the efficiency of agricultural production and resource utilization through real-time monitoring, automated management, and data-driven decision-making. The collaborative work of various IoT devices forms the basis of a modern smart agricultural system, providing strong support for precision agriculture and sustainable development.

2.2. Sensor Technology

Sensor technology plays a vital role in modern agriculture by monitoring environmental parameters in real-time, helping farmers optimize farm management and improve productivity. Different types of sensors and their applications in agriculture are detailed below, illustrating the sensor-based data acquisition process in precision agriculture. The Fig. 1 highlights the integration of soil moisture sensors, weather stations, and IoT networks for real-time monitoring. This system facilitates timely irrigation decisions, reducing water wastage by up to 20% in pilot studies. The detailed workflow underscores the importance of robust sensor networks in achieving precise agricultural management.

Fig. 1. Different types of sensors, including temperature sensors, humidity sensors, etc.

2.2.1. Specific Applications of Sensors in Agriculture

Sensor technology enables the monitoring of various environmental parameters in real-time, assisting farmers in optimizing farm management and boosting productivity. Each type of sensor has specific functions and application scenarios.

2.2.2. Soil Moisture Sensors

Soil moisture sensors measure the moisture content in the soil and help farmers determine when irrigation is needed. These sensors work by measuring changes in soil conductivity or capacitance. For example, the capacitive soil moisture sensor used in the IoT-Based Real-Time Monitoring System for Precision Agriculture monitors soil moisture in real-time and uploads the data to the ThingSpeak server via the ESP8266 module for remote monitoring and management [1].

2.2.3. Temperature Sensors

Temperature sensors measure ambient temperature to ensure crops grow within optimal conditions. These sensors typically use thermocouples or thermistors, where resistance changes with temperature. For instance, the DHT11 temperature and humidity sensor can measure both air temperature and humidity, providing farmers with accurate environmental data to optimize crop growth conditions [1].

2.2.4. Nutrient Detection Sensors

Nutrient detection sensors measure soil nutrient content, such as nitrogen, phosphorus, and potassium, helping farmers apply fertilizers appropriately to enhance crop yield and quality. These sensors often use ion-selective electrode technology, which measures the concentration of specific ions in the soil solution.

2.2.5. Development and Application Examples of Advanced Sensor Technologies

With advancements in technology, sensor technology in agriculture has become increasingly sophisticated. Below are examples of the latest developments in sensor technology and their applications in agriculture.

2.2.6. Multi-Parameter Sensors

Multi-parameter sensors can measure various environmental parameters—such as temperature, humidity, light, and carbon dioxide concentration—simultaneously. By integrating multiple functions, these sensors reduce the complexity and cost of using individual sensors. In modern greenhouse agriculture, multi-parameter sensors provide comprehensive environmental data to help optimize greenhouse conditions and increase crop yields [1].

2.2.7. Wireless Sensor Networks (WSNs)

WSNs consist of numerous sensor nodes distributed across farmland, connected via wireless communication technologies (e.g., LoRa, Zigbee, or 5G) to form a monitoring network that covers the entire area. For example, the system described in the Farmers' Assistance for Field Monitoring and Irrigating the Cultivated Land using IoT paper uses WSNs to monitor farmland conditions in real-time with devices like rain and soil moisture sensors, and it provides remote monitoring and automatic irrigation management through an Ubidots application [8].

LoRa technology offers a cost-effective solution for wide-area coverage, supporting communication distances of up to 15 kilometers with minimal power consumption. In contrast, 5G networks provide high-speed, low-latency connectivity but at significantly higher costs, making them less feasible for resource-constrained rural areas. For example, while 5G enables real-time video transmission for precision agriculture, LoRa is more suitable for transmitting low-frequency sensor data in sparsely populated regions.

2.2.8. High-Precision Sensors

High-precision sensors in agriculture provide more accurate and reliable data, supporting precise decision-making. For instance, high-precision soil moisture sensors offer detailed data on small humidity changes, ensuring crops have the optimal growing environment.

In summary, sensor technology significantly enhances agricultural production efficiency and accuracy by providing real-time, precise environmental and crop data. With continuous technological progress, sensor applications in agriculture are expected to expand, providing critical support for the advancement of smart agriculture and sustainable development.

2.3. Unmanned Aerial Vehicles (UAV) and Remote Sensing Technology

2.3.1. Applications of UAVs in Crop Monitoring

Crop Health Assessment: Drones combined with computer vision technology can assess crop health in real-time. For example, the system proposed in the Drone Vision Based Abiotic Stress Monitoring for Smart Agriculture paper uses a UAV to acquire images of farmland and identify healthy crops and areas affected by abiotic stress by calculating the Normalized Difference Vegetation Index (NDVI) value [14]. NDVI is calculated by comparing the reflectance of vegetation in the red and near-infrared light bands. Healthy plants have a high reflectance in the near-infrared light and a low reflectance in the red light. The formula for NDVI is: $NDVI = (NIR - RED) / (NIR + RED)$, where NIR is the near-infrared light reflectance value, and RED is the red light reflectance value. The NDVI values allow for the differentiation between healthy and stressed vegetation. UAVs can quickly cover large areas of farmland, acquire high-resolution images, and analyze crop health in real-time. Compared with traditional ground-based monitoring methods, UAV monitoring is more efficient and accurate, and can complete large-scale crop health assessments in a short period. The specific example is shown in Fig. 2.

Fig. 2. UAV helps water crops to enhance health(left); UAV helps monitor soil quality(right).

Water Stress Detection: With multispectral or thermal imaging cameras, UAVs can detect water stress in crops. For example, the use of NDVI technology can help farmers identify which areas of crops need to be irrigated to optimize water resource usage. The From Satellite to UAV-Based Remote Sensing: A Review on Precision Agriculture paper summarizes the application of remote sensing technology in water stress detection, highlighting the advantages of UAV technology in terms of real-time data acquisition and high-resolution images [5]. Multi-spectral cameras capture the reflectance of vegetation in multiple spectral bands, while thermal imaging cameras determine moisture status by detecting temperature changes on the crop surface. Plants under drought stress usually have higher temperatures and reflect more infrared light due to lack of moisture. UAVs equipped with multispectral and thermal imaging cameras can quickly and accurately detect water stress problems in agricultural fields, helping farmers take timely irrigation measures to optimize water use and reduce waste.

While UAVs equipped with multispectral and thermal imaging cameras significantly enhance crop monitoring and health assessment, their deployment is not without challenges. High initial costs and the need for specialized technical expertise pose barriers to adoption, particularly in small-scale farming. Additionally, regulatory restrictions on drone usage in certain regions may limit their applicability. Addressing these challenges requires policy interventions, cost-reduction strategies, and capacity-building programs to ensure broader adoption of UAV technologies in agriculture.

2.3.2. Applications of Remote Sensing Technology in Agriculture

Soil Quality Monitoring: Remote sensing can assess the physical and chemical properties of soil by analyzing soil reflectance spectral data. For example, the From Satellite to UAV-Based Remote Sensing: A Review on Precision Agriculture paper summarizes the use cases of remote sensing technology in soil quality monitoring, highlighting the advantages of UAV technology in real-time data acquisition and high-resolution images [5]. These technologies help farmers better understand soil conditions and make more scientific agricultural management decisions. Soil reflectance spectral data can reflect the moisture content, organic matter content, and mineral composition of the soil. By analyzing these spectral data, the fertility and health of the soil can be assessed. Remote sensing technology uses multispectral or hyperspectral images acquired by satellites or drones to analyze soil reflectance characteristics and identify soil problems. Remote sensing technology provides rapid, non-destructive access to soil information over a wide area, providing high-resolution soil quality data to help farmers better manage soil resources and improve crop yield and quality.

Crop Growth Analysis: Remote sensing technology can analyze crop growth and trends through multi-temporal data. For example, the image segmentation technique proposed in the Precision Agriculture: Crop Image Segmentation and Loss Evaluation through Drone Surveillance paper classifies crops and evaluates losses through multi-temporal phase data acquired by drones, helping farmers optimize crop management [4]. These techniques allow real-time monitoring of crop growth, timely detection of problems, and taking appropriate measures. Multi-temporal remote sensing data analyzes the changes in crops during the growth cycle through images acquired at different times. These data can show the developmental stage, growth rate, and health of the crop. Through image segmentation techniques, crop areas can be distinguished from other areas, and crop growth can be analyzed accurately. Using multi-temporal data acquired by UAVs and image segmentation technology, crop growth can be efficiently and accurately monitored and analyzed, helping farmers identify problems and take appropriate measures in time, and improving the efficiency of agricultural production and economic benefits.

2.4. Big Data and Artificial Intelligence

2.4.1. Application of Big Data Analytics in Agricultural Decision-Making

Data-Driven Planting Strategies: Big data technologies are widely used in agriculture, and by collecting and analyzing farm data, farmers can develop more precise planting strategies. For example, the Big Data Analytics, Data Science, Machine Learning (ML), and AI for Connected, Data-Driven Precision Agriculture and Smart Farming Systems: Challenges and Future Directions paper states that through big data analytics, farmers can identify the best time to plant and optimize sowing density to increase crop yields [7]. Big data systems can integrate information from multiple sensors and historical data sources to provide a comprehensive understanding of farm conditions and help farmers make data-driven decisions. Big data analytics identifies key factors for crop growth by processing large amounts of historical and real-time data and provides optimization recommendations. This not only improves productivity but also reduces resource wastage and makes farming more sustainable.

Resource Optimization: The efficiency of agricultural resources is significantly improved through big data analytics. The Smart Agricultural Techniques for Sustainable Farming: A Data-Driven Approach paper mentions that data analytics can help optimize the allocation of resources such as irrigation and water and fertilizer management, reduce wastage, and improve resource utilization [8]. For example, through real-time monitoring of soil moisture and weather data, irrigation can be precisely controlled to avoid excessive water use. By collecting and analyzing real-time data, big data analytics helps farmers use the right amount of resources at the right time and place to avoid wastage and improve crop yield and quality.

2.4.2. Application Examples of AI Algorithms in Precision Agriculture

Crop Prediction: Artificial Intelligence algorithms play an important role in crop yield prediction. The Artificial Intelligence and Machine Learning in Modern Agriculture paper shows how crop yields can be predicted using machine learning models based on historical climate data, soil data, and crop growth data [7]. Such predictions can help farmers plan ahead and optimize resource allocation to ensure a stable supply of crops. Machine learning algorithms accurately predict future crop yields by analyzing historical data and current environmental conditions. This enables farmers to make decisions in advance and optimize planting plans and resource allocation, thereby improving agricultural productivity and economic efficiency.

Pest and Disease Control: AI technology is extremely widely used in pest control. The Development of a Pest Automatic Diagnosis System for Intelligent Agriculture Using Image Recognition paper describes a pest control system based on image recognition and AI algorithms, providing accurate control suggestions by recognizing pest images [6]. The system collects farmland data through sensor nodes and uses the YOLO V4 (You Only Look Once v4) algorithm for pest recognition, which greatly improves the efficiency of pest control. Image recognition technology analyzes images of pests to quickly and accurately identify pest species and provide appropriate control measures. This reduces pesticide use and improves crop health and yields.

Yield Optimization: Artificial Intelligence can also be used to optimize crop yields. The AI-based Pest Detection and Crop Monitoring Using IoT paper describes a crop monitoring system that combines IoT and AI technologies to optimize crop growing conditions and improve yields through real-time data analysis and processing. For example, sensors are used to monitor soil and environmental parameters, and machine learning algorithms are used to adjust fertilization and irrigation regimens. AI technology optimizes the growing conditions of crops through real-time monitoring and data analysis to improve crop yield and quality. This technology also helps farmers cope with climate change and other uncertainties, improving the sustainability of agriculture.

2.5. Application Cases

2.5.1. Soil Moisture and Nutrient Monitoring System

2.5.1.1. Technical Background and Principle

Real-time monitoring of soil moisture and nutrients through sensors. Sensor technology can accurately detect the moisture and nutrient content in the soil and transmit the data to a cloud platform for analysis through a wireless network. For example, the IoT-Based Real-Time Monitoring System for Precision Agriculture paper uses a soil moisture sensor and a data acquisition terminal to monitor soil moisture in real-time and upload data [1]. The sensors measure soil moisture through conductivity or capacitance changes, while chemical sensors detect nutrient levels.

2.5.1.2. System Composition and Workflow

The system consists of a sensor network, a data collection terminal, and a cloud platform for analysis. The sensor network is deployed in the farmland to collect soil moisture and nutrient data in real-time. The data are transmitted to the data acquisition terminal via a wireless network and then uploaded to the cloud platform for analysis and processing. Specifically, soil moisture sensors are installed at different depths to measure moisture changes at different levels. Nutrient sensors, on the other hand, are installed in key areas to detect the concentration of key nutrients such as nitrogen, phosphorus, and potassium. Data collection terminals are responsible for collecting data from the sensors and transmitting it to the cloud via low-power wide area network technologies such as LoRa or NB-IoT. The cloud platform processes these data through big data analysis and machine learning algorithms to generate real-time status reports of the farmland and provide decision support to farmers [7].

2.5.1.3. Actual Application Effect and Case Analysis

The system enables precision irrigation and improves crop yields. For example, the Farmers' Assistance for Field Monitoring and Irrigating the Cultivated Land using IoT paper mentions that by monitoring soil moisture in real-time and automatically adjusting the irrigation volume based on the analyses, farmers can significantly improve irrigation efficiency, reduce water wastage, and increase crop yields [8].

Despite the benefits of intelligent sensing technologies, several challenges hinder their widespread adoption. High implementation costs, particularly for advanced IoT and AI systems, remain a significant barrier for smallholder farmers. Furthermore, maintaining sensor networks in remote areas often requires substantial technical expertise and resources. The digital divide, characterized by limited internet access and low digital literacy in rural regions, further exacerbates these challenges. Addressing these issues requires coordinated efforts to subsidize technology costs, provide technical support, and promote digital literacy initiatives.

2.5.2. Crop Health Monitoring System

2.5.2.1. Technical Background and Principle

A combination of drones and sensors monitors crop health. Drones carrying multispectral or thermal imaging cameras acquire high-resolution images of crops, which can be analyzed to assess crop health. For example, the Drone Vision Based Abiotic Stress Monitoring for Smart Agriculture paper uses UAV-acquired images to calculate the Normalized Difference Vegetation Index (NDVI) to assess crop health [14].

2.5.2.2. System Composition and Workflow

The system consists of data collection by drones, analysis by a cloud platform, and real-time feedback. The drone flies over the farmland and captures high-resolution images, which are transmitted to the cloud platform via a wireless network for processing and analysis and real-time feedback to farmers. The specific process includes: the drone flies and captures images regularly to obtain farmland data under different spectra; these images are transmitted to the cloud platform via 4G/5G networks; the cloud platform analyzes the image data using image processing algorithms (e.g., NDVI computation and machine learning models) and detects the health status of the crops; and finally, the analysis results are fed back in real-time to the farmers via mobile phones or computer terminals to help them take timely measures [4].

2.5.2.3. Actual Application Effect and Case Analysis

By detecting pests and diseases at an early stage, the control effect is improved. For example, the Development of a Pest Automatic Diagnosis System for Intelligent Agriculture Using Image Recognition paper mentions that a pest monitoring system based on image recognition technology can detect pests and diseases at an early stage and provide prevention and control suggestions, improving the control effect and reducing pesticide use [6].

2.5.3. Intelligent Irrigation System

2.5.3.1. Technical Background and Principle

Automatic adjustment of irrigation based on sensor data and meteorological data. Sensors monitor soil moisture and environmental parameters, and meteorological data provide weather forecasts. By comprehensively analyzing these data, smart irrigation systems can automatically regulate irrigation. For example, the IoT-Based Real-Time Monitoring System for Precision Agriculture paper describes how smart irrigation can be achieved through real-time monitoring and data analysis [1].

2.5.3.2. System Composition and Workflow

The system consists of a sensor network, an automatic irrigation system, and cloud platform control. The sensor network collects soil and environmental data, the automatic irrigation system regulates irrigation based on the analysis results, and the cloud platform performs data processing and control. Specifically, the sensor network is deployed in the farmland and includes soil moisture sensors, temperature sensors, and weather stations to collect data in real-time. The automatic irrigation system consists of programmable controllers and solenoid valves, which automatically adjust the irrigation amount based on the analysis results from the cloud platform. The cloud platform uses machine learning algorithms to analyze soil and weather data, predict crop water requirements, and achieve precise irrigation through the control system.

2.5.3.3. Actual Application Effect and Case Analysis

The system achieves water savings and efficiency and improves water utilization. For example, the Big Data Analytics, Data Science, ML, AI for Connected, Data-Driven Precision Agriculture and Smart Farming Systems paper states that with smart irrigation systems, farmers can significantly reduce irrigation water use while increasing crop yields [7].

3. Design of a Smart Agriculture Platform Combining Cloud Computing and Intelligent Sensing Technologies

3.1. Platform Architecture Design

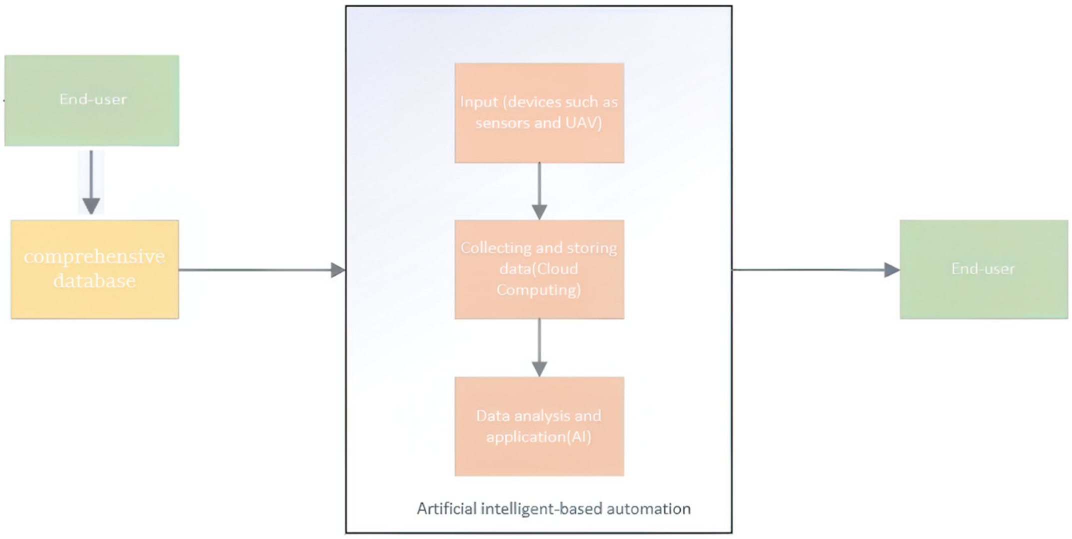

Fig. 3. How data flows in the complete agriculture process (adapted from [4]).

3.1.1. Perception Layer

The perception layer is responsible for collecting multi-source data on soil, environment and crop status and is the data input for the whole system. We plan to use many techniques in the layer.

Deploy multiple types of sensors to form a sensor network:

Soil sensors: monitor humidity, temperature, pH, and nutrients, using low-power transmission protocols (e.g., LoRaWAN) to achieve wide-area coverage.

Weather sensors: collect climate data such as wind speed, rainfall and air humidity to support real-time adjustments to agricultural activities.

Wireless Sensor Networks (WSN): Connect multiple sensor nodes via star or mesh topology to ensure continuous transmission of critical data.

Drones and Remote Sensing Devices: Acquire panoramic images of farmland using multispectral and thermal imaging cameras.

Data Acquisition: UAV flight planning uses wind-assisted path algorithms to reduce battery consumption; flight plans for the coverage area are automatically generated through customized software.

Real-time transmission: The drone uploads data to the edge computing device in real-time via Wi-Fi or direct connection to a base station.

Edge sensor calibration: Adaptive calibration algorithm is used to correct sensor errors by analyzing historical data to ensure data accuracy.

3.1.2. Network Layer

The network layer is responsible for efficient and stable transmission of data from the sensing layer to the processing layer and overcoming communication barriers in remote farm environments. We choose to apply the following technology.

3.1.2.1. Communication Technology:

Low Power Wide Area Network (LPWAN): Uses LoRa technology to support communication distances of up to 15 kilometers and uploads about 5 KB of data per hour for low-frequency sensor data transmission.

TV White Space (TVWS): Provides 20Mbps bandwidth between base stations and can support drone image uploads.

Short-range communication: ZigBee and Wi-Fi establish short-range, high-speed connections between sensors and base stations, suitable for high-frequency data collection.

3.1.2.2. Dynamic Spectrum Management:

Dynamically selects the best communication channel through spectrum sensing technology to reduce interference and increase data transmission rate.

3.1.2.3. Fault tolerance and interruption recovery:

Caching mechanism: The base station is equipped with 2GB of storage space to store critical data in the event of a network outage.

Data synchronization: Adopt breakpoint transmission protocol (such as FTP breakpoint transmission) to ensure complete recovery of data after interruption.

3.1.3. Data Processing Layer

Data Processing Layer realizes efficient analysis and storage of data through edge computing devices and cloud platforms while designing management of spatial and attribute databases, as is shown in Fig. 3. The spatial database stores the geographic information of the farmland, and the attribute database stores various attribute data of the farmland, such as soil moisture and nutrient content. Data management and analysis are carried out using big data technologies, such as using Hadoop and Spark frameworks for big data processing, storing data through distributed file systems (e.g., HDFS), and data processing through MapReduce [14]. The relevant details of function designs are as followed:

3.1.3.1. Data compression and summary generation:

Reduce the size of drone videos by 1000 times by compression algorithms (e.g., JPEG compression).

Generate accurate soil parameter distribution maps using Gaussian Process Regression (GPR) combining sensor and drone images.

3.1.3.2. Real-time data analysis:

Run crop growth prediction models on edge devices to quickly identify potential problems (e.g., moisture deficit or pests).

Simultaneously analyze soil, climate, and crop data using a multi-task learning framework.

3.1.3.3. Task Scheduling:

Dynamically allocate edge computing resources to prioritize urgent tasks (e.g. pest and disease alarms).

Supports local modeling of historical data by edge devices during idle time to support subsequent decision making.

3.1.3.4. Data transmission optimization:

A mechanism based on traffic hierarchy transmits high-frequency data (e.g., real-time soil moisture) to edge devices, while low-frequency data (e.g., temperature history) is delayed and uploaded to the cloud.

3.1.4. Application Layer

Application layer will provide with configuration and functions of Geographic Information System (GIS) Server and Web Server. The GIS Server provides map services and geographic data processing functions, while the Web Server handles user requests and data interactions. The GIS server is configured using ArcGIS Server to provide efficient map rendering and geographic data processing services, while the web server is configured using Apache and Nginx to ensure the processing of highly concurrent user requests. ArcGIS Server provides map and data services by supporting standardized geographic information services including Web Map Service (WMS) and Web Feature Service (WFS), while Apache and Nginx manage user requests through reverse proxy and load balancing [8].

Moreover, the design of PC client, Web client, and mobile application will be refined in this layer. The PC client provides a rich graphical interface and data analysis functions, the Web client supports multi-platform access, and the mobile application facilitates on-site data collection and real-time monitoring. React and Angular frameworks are used to develop the web client, Swift and Kotlin are used to develop the mobile application, and they communicate with the back-end server through RESTful APIs. React and Angular frameworks provide flexible user interface design through the componentized development model, while Swift and Kotlin take advantage of their respective platforms to provide efficient mobile application development. RESTful APIs achieve front-end and back-end data exchange through standardized HTTP protocols [8].

While devices and drones significantly enhance data accuracy and operational efficiency, practical challenges persist. They often require repeated adjustments to ensure reliable readings, particularly in regions with high variability in soil texture and moisture levels. Network latency in rural areas, exacerbated by limited connectivity infrastructure, can delay real-time data transmission and decision-making. Additionally, the energy consumption of drones and IoT devices poses sustainability concerns, necessitating the development of energy-efficient designs and renewable energy-powered systems.

Also, it will refine data processing and analysis with cloud computing. The cloud computing platform provides high-performance computing resources for processing and analyzing data from sensors and drones. Real-time processing and accurate analysis of large-scale agricultural data can be achieved through cloud computing and big data analytics. Hadoop and Spark frameworks are used for big data processing, and TensorFlow and PyTorch are used for machine learning model training and prediction. Hadoop handles large-scale data through its Distributed File System (HDFS) and MapReduce frameworks, and Spark provides in-memory computation, improving data processing speed. TensorFlow and PyTorch, on the other hand, support complex machine learning tasks through deep learning frameworks [3, 14–16]. The details are as followed:

1) Cloud service platform:

Storage service: Based on Hadoop Distributed File System (HDFS) to store years of farmland data.

Cross-scenario analysis: Analyze crop growth trends and recommend planting schemes through machine learning algorithms (e.g., deep neural network DNN).

Farmland optimization recommendations: Predict high pest and disease areas based on historical data and optimize pesticide application plans.

2) User interface and control functions:

Mobile App: Provides real-time farmland monitoring and task management functions, and supports one-click switching of irrigation modes.

Data Visualization: Displays soil moisture heat map, crop health NDVI distribution map, historical weather trends, etc.

3) Automated equipment control:

The platform can remotely control irrigation systems, fertilization equipment or drones to perform farmland tasks set by users.

3.2. Platform Function Modules

3.2.1. Map Function Module

Provides visual display of farmland geographic information. The map function module supports zooming, panning, and labeling to help users visualize the geographic information and status of farmland. Map rendering is performed using Leaflet and OpenLayers, and geographic data services are provided using GeoServer. Leaflet and OpenLayers implement interactive map functions through JavaScript libraries, and GeoServer, as an open-source GIS server, supports standardized geographic information services (e.g., WMS, WFS) [8].

3.2.2. Intelligent Inversion Module

Quantitative inversion of soil quality information based on remote sensing data. By analyzing remote sensing images, the intelligent inversion module can provide information on soil moisture and nutrient content. ENVI software was used for image processing, and multispectral and hyperspectral data were used for inversion analysis of soil parameters. ENVI software analyzes remotely sensed data and extracts soil information through its powerful image processing function, while multispectral and hyperspectral data provide detailed spectral information, helping to accurately invert soil parameters [8].

3.2.3. Data Analysis and Mining Module

Performs statistical analysis and mining of farmland data. Through big data technology, farmland data is analyzed in depth to mine valuable information to support agricultural management decisions. Hadoop is used for distributed data storage and processing, and Spark is used for data analysis and mining. Hadoop handles large-scale data through its distributed file system (HDFS) and MapReduce framework, and Spark provides in-memory computation, improving data processing speed [14].

3.2.4. Soil Knowledge Base Module

Stores and manages soil-related knowledge and data. The Soil Knowledge Base module contains a variety of soil types, properties, and management methods that support user queries and knowledge reasoning. Soil data is stored using MySQL and PostgreSQL databases, and knowledge reasoning is performed using the SPARQL query language. MySQL and PostgreSQL provide reliable data storage and management through their relational database management systems, while SPARQL supports complex knowledge reasoning through a semantic query language [17].

3.2.5. Platform Management Module

Manages users and platform settings. The platform management module provides user management, permission control, and platform configuration functions to ensure system security and stability. Spring Security is used for user authentication and authorization, and Kubernetes is used for platform configuration and management. Spring Security ensures the security of user authentication and access control by providing a comprehensive set of security frameworks, while Kubernetes automates platform deployment, scaling, and management through container orchestration technology [8].

3.2.6. Real-time Monitoring and Feedback Module

Combines cloud computing and intelligent perception technology to achieve real-time data monitoring and feedback. Real-time monitoring of farmland status and providing timely feedback to farmers through sensor networks and cloud platforms. Transmission of sensor data is achieved through low-power wide area network technologies such as LoRa and NB-IoT, and data processing and feedback are provided using cloud platforms such as AWS (Amazon Web Services) and Google Cloud. LoRa and NB-IoT achieve efficient transmission of sensor data through their wide-coverage and low-power characteristics, while AWS and Google Cloud provide real-time data processing and feedback through their powerful computing and storage capabilities [14].

3.3. Data Processing and Analysis

3.3.1. Data Collection and Processing

Multi-source data acquisition techniques and data processing methods. Collect farmland data through multiple data sources such as sensors and drones, and preprocess and store them. Soil moisture, temperature, nutrients, and other data are collected in real-time using sensor networks and uploaded to the cloud platform via LoRa or NB-IoT technology. The drone is equipped with a multispectral camera that captures images of the farmland regularly and transmits them to the cloud platform via a 4G/5G network. The data is pre-processed at the cloud platform, including data cleaning, normalization, and storage.

3.3.2. Data Storage and Management

Application of big data technology in agricultural data management. Using distributed database and cloud storage technology to safely and efficiently store and manage massive agricultural data. Hadoop HDFS (Hadoop Distributed File System) is used for distributed storage, and cloud storage services such as Amazon S3 and Google Cloud Storage are used for data backup and management. HDFS achieves reliable storage of large-scale data through its distributed architecture, and Amazon S3 and Google Cloud Storage provide elastic, highly available data storage and backup solutions [14].

3.3.3. Data Analysis and Decision Support

Agricultural data analysis based on machine learning algorithms. Through machine learning and data mining techniques, in-depth analyses of agricultural data are provided to support accurate decision-making for agricultural management. TensorFlow and PyTorch are used for machine learning model training and prediction, and data processing and analysis are carried out through big data analytics platforms (e.g., Apache Spark). TensorFlow and PyTorch provide flexible model training and inference frameworks, while Spark, through its distributed computing capability, supports rapid processing and analysis [14].

3.4. Integration of Cloud Computing and Intelligent Sensing Technology

3.4.1. Data Upload and Processing

Sensor data is uploaded to the cloud platform via a wireless network for real-time processing and analysis. Low-power WAN technologies such as LoRa (Long Range) and NB-IoT are used to achieve the transmission of sensor data, and cloud platforms such as AWS and Google Cloud are used for data processing and analysis. LoRa and NB-IoT achieve efficient transmission of sensor data through their wide coverage and low-power characteristics, while AWS and Google Cloud provide real-time data processing and feedback through their powerful computing and storage capabilities [14].

3.4.2. UAV Data Analysis

Remote sensing data collected by the drone is uploaded to the cloud platform for image processing and analysis using high-performance computing resources. Use 4G/5G networks to transmit drone data to the cloud platform for image processing and analysis using machine learning algorithms. The data collected by the drone is processed and analyzed through a high-performance computing cluster, such as an AWS EC2 instance, to extract crop health and growth information. Machine learning algorithms, including Convolutional Neural Networks (CNN) and Support Vector Machines (SVM), are used for image classification and feature extraction.

3.4.3. Real-time Decision Support

Data is processed and analyzed in real-time through cloud computing platforms to provide instant decision support to farmers and agricultural managers. Data processing is performed using big data analytics platforms (e.g., Apache Spark), and prediction and decision support are provided through machine learning models (e.g., TensorFlow and PyTorch). Spark supports fast processing of large-scale data through its distributed computing power, while TensorFlow and PyTorch provide accurate prediction and decision support [14].

3.5. Platform Integration and Practical Application

The various parts of the platform are seamlessly integrated through standardized interfaces and protocols, including the integration of sensor networks, drones, data processing terminals, and cloud platforms. The sensor network uploads data such as soil moisture, temperature, and nutrients to the data collection terminal using low-power Wide Area Network (WAN) technologies such as LoRa and NB-IoT, which ensure that the sensors can efficiently transmit data in a wide range of agricultural environments through their wide coverage and low-power consumption characteristics [2]. The data collection terminal communicates with the cloud platform using the Message Queuing Telemetry Transport (MQTT) protocol to ensure real-time data transmission and reliability. The MQTT protocol is well-suited for data transmission in IoT environments due to its lightweight and publish/subscribe model [2].

The UAV uploads the collected remote sensing data to the cloud platform via a 4G/5G network. The 4G/5G network provides high-speed and low-latency data transmission, ensuring that the high-resolution images and videos collected by the UAV can be quickly transferred to the cloud platform for processing. The data collected by the UAV includes multispectral and thermal infrared images, which can be analyzed to monitor crop health and environmental changes.

The cloud platform implements data exchange with various system components through RESTful APIs. RESTful APIs use standardized HTTP protocols for data transfer and ensure interoperability between different systems and services through their simple and flexible design. RESTful APIs ensure interoperability between different systems and services through the use of standard HTTP methods for resource manipulation and transferring data through JSON format to ensure data compatibility and ease of use [8].

Data processing and analyses are performed on a cloud platform using high-performance computing resources. Hadoop and Spark frameworks are used for big data processing, and TensorFlow and PyTorch are used for machine learning model training and prediction. Hadoop provides reliable data storage and parallel computing capabilities by processing large-scale data through its HDFS and MapReduce frameworks [14]. Spark is used for in-memory computing to dramatically increase the data processing speed, which is suitable for real-time data processing tasks that require fast response [14]. TensorFlow and PyTorch provide flexible deep learning frameworks to support complex machine learning tasks, such as crop health assessment and yield prediction [7, 14].

The transmission and storage of agricultural data necessitate robust security measures to prevent unauthorized access and data breaches. Encryption protocols, ensure secure data transmission between IoT devices and cloud platforms. Additionally, compliance with data privacy regulations, such as General Data Protection Regulation (GDPR), safeguards farmers' sensitive information. These measures include anonymizing data, implementing access controls, and utilizing blockchain technology to enhance data integrity and traceability.

The platform integration process uses containerization technologies such as Docker and Kubernetes to manage the deployment and scaling of applications. Docker ensures that applications run consistently in any environment by packaging applications and their dependencies into containers. Kubernetes automates the deployment, scaling, and management of applications through automated container orchestration, ensuring that the platform runs consistently under high concurrency and high load situations [8].

3.6. Implementation strategies

In order to realize the efficient operation of the smart agriculture platform, we have designed a series of implementation strategies to ensure the reliability and performance of the system in complex agricultural environments. These strategies cover equipment deployment, communication networks, data processing, energy management and practical applications, fully supporting the system's multi-scenario adaptation and long-term stable operation.

3.6.1. The Device Deployment Strategies

To achieve efficient data collection and transmission in agricultural fields, the equipment deployment strategy focuses on optimizing sensor placement, drone planning, and base station configuration to minimize resource consumption and improve coverage.

1) **Sensor placement optimization**:

Reduce the need for dense sensor placement using a joint sensor and UAV accuracy mapping approach. For example, by sparsely deploying sensors (1 per 2–5 hectares) in combination with drone video data, Gaussian process regression is used to generate accurate maps of soil moisture, pH, and temperature distribution across the field. The proposed intelligent sensing systems are designed for seamless integration with existing agricultural tools, including legacy irrigation systems and farm management software. For example, IoT sensors can interface with traditional irrigation controllers to automate water delivery based on real-time soil moisture data. Similarly, the platform supports data synchronization with legacy farm management systems through standardized APIs, ensuring interoperability and minimizing disruption to established workflows.

2) Base station modular configuration:

The base station is solar-powered with a high-performance battery pack (e.g., four 12V 44Ah batteries in parallel) to support 24-hour uninterrupted operation

Configuration of independent switches for base station components, e.g., to control the start-up time of the TV White Space (TVWS) module and Wi-Fi router to optimize energy consumption.

3.6.2. Communication Network Strategies

To address the communication challenges of remote environments in farmland, the communication network strategy ensures the stability and efficiency of data transmission while reducing bandwidth consumption through hybrid architecture and fault-tolerant mechanisms.

1) Multi-layer communication network design:

Use TVWS (TV White Space) technology to establish long range (>5 km) high bandwidth connectivity, combined with LoRa or Wi-Fi to support short range low power sensor data transmission.

Dynamically switching communication modes to determine the upload frequency based on weather conditions, e.g., high-frequency uploads on sunny days and switching to low-frequency uploads on cloudy days.

2) Network fault tolerance design:

During a network outage, the base station temporarily stores data in a local cache and uploads it when the network is restored.

Use synchronization priority algorithm to prioritize the upload of critical data (e.g., sensor anomalies) instead of full data.

3) Bandwidth optimization strategy:

Drone video is compressed to 1/1000th of its original size through the edge gateway, significantly reducing bandwidth consumption.

For short-time analysis applications (e.g., real-time irrigation decisions), data processing is done locally to reduce cloud interaction latency.

3.6.3. Data Processing Strategies

The data processing strategy focuses on edge computing and multi-source data fusion to achieve efficient data utilization through hierarchical storage and real-time analysis to meet the needs of precision agriculture.

1) Edge computing optimization:

The gateway performs preliminary data processing such as image preprocessing, noise filtering, data aggregation, and outlier detection.

Gaussian Process Regression (GPR) is used to interpolate sparse sensor data to generate a field-wide accurate prediction model

2) Multi modal data fusion:

Combining UAV images (e.g., NDVI metrics) and sensor data to construct a multimodal visual-spatial model for predicting the state of farmland

Combine visual similarity and spatial smoothness through probabilistic graphical modeling to improve prediction accuracy.

3) Hierarchical data storage and analysis:

Short-term data (e.g., current soil moisture) are stored in the edge device for quick response.

Long-term data (e.g., multi-season crop growth data) is uploaded to the cloud to support analysis across years.

3.6.4. Energy Consumption Optimization Strategies

To ensure the stable operation of the system in energy-constrained environments, the energy optimization strategy starts from dynamic power management, energy-neutral design and task priority setting to improve the energy utilization efficiency.

1) Dynamic power consumption management:

Adjust the switching time of base station components based on weather prediction. For example, keep the data collection frequency high on sunny days and reduce the collection time on cloudy days.

Use an adaptive Duty Cycling strategy to activate high power consumption modules (e.g. TVWS devices) only when necessary.

2) Energy Neutral Design:

Ensure that daily power consumption does not exceed the power generation capacity of the solar cells, and adjust the next day's base station tasking through weather forecasts

3) Task Prioritization Settings:

Set trigger conditions for high power consumption tasks (e.g. drone flights and real-time data uploads), e.g. activate the drone for detailed monitoring only when the sensor is abnormal.

4. Implementation Path for Promoting Rural Revitalization

4.1. Overview of Rural Revitalization Strategy

4.1.1. National Policies and Support

In China, the rural revitalization strategy, one of the country’s key policies, has been widely supported and promoted. The government promotes agricultural modernization and rural economic development through a series of policies and financial support. The government has issued policy documents such as the Strategic Plan for Rural Revitalization (2018–2022), which specifies the specific objectives and implementation path of rural revitalization. Specific objectives include:

Agricultural modernization: Improve agricultural production efficiency, promote the construction of agricultural product quality and safety systems, and promote the green development of agriculture.

Industrial prosperity: Support the development of specialty industries and new rural industries, such as ecotourism and rural e-commerce, to enhance the diversity and competitiveness of the rural economy.

Ecological livability: Improve the rural habitat, promote rural sewage treatment, rubbish disposal, and village greening, and build beautiful villages.

Civilized countryside: Strengthen rural cultural construction, and enhance the cultural quality and spiritual outlook of farmers.

Effective governance: Improve the rural grassroots governance system and enhance the governance capacity and service level of village-level organizations.

Wealthy life: Increase farmers' income, raise the level of basic public services in rural areas, and promote the equalization of basic public services between urban and rural areas.

The government also supports rural infrastructure construction, agricultural technology promotion, and rural industry development through financial subsidies, tax incentives, and special funds. For example, the government provides funds to support the construction of rural roads, water conservancy facilities, and information technology to improve production and living conditions in rural areas. Additionally, the government encourages financial institutions to increase credit support for agriculture and the rural economy by providing favorable loans and financial guarantee services.

Capacity building is critical for the successful adoption of intelligent sensing technologies. Training programs focusing on digital literacy, modern farming technologies, and resource management are essential to equip farmers and local administrators with the necessary skills. For instance, workshops on IoT-based crop monitoring and AI-driven decision-making tools can empower stakeholders to maximize the benefits of these technologies. Collaborative efforts involving governments, educational institutions, and private sectors can bridge knowledge gaps and foster sustainable adoption.

4.1.2. Main Goals of Rural Revitalization

The main objective of rural revitalization is to increase agricultural productivity and improve rural living conditions. By promoting the modernization of agriculture, it will enhance the comprehensive production capacity of agriculture and ensure food security and the quality of agricultural products. Specific objectives include:

Enhancing agricultural productivity: Promote advanced agricultural technology and equipment to improve yield per unit area and resource utilization efficiency. For example, adopting efficient water-saving irrigation techniques and modern agricultural machinery and equipment to improve farm productivity [14].

Improvement of infrastructure: Construct and renovate rural roads, water conservancy facilities, electricity, and communication networks to improve production and living conditions in rural areas. For example, building rural roads and bridges to improve transport conditions [14].

Improve the quality of life of rural residents: Improve rural education, medical care, culture, and other public services to enhance the living standards of farmers. For example, building rural schools and health centers to improve the accessibility of education and medical services [14].

Through these measures, the rural revitalization strategy aims to comprehensively upgrade the level of economic and social development in rural areas, narrow the gap between urban and rural areas, and achieve common prosperity for both urban and rural areas. The specific effects of these measures include:

Increased agricultural productivity: Farmland yields have increased, farmers' incomes have risen, and food security has been guaranteed.

Infrastructure improvement: Rural roads are flat and spacious, transport is convenient, and water and power supply facilities are improved.

Improved quality of life: The living environment of rural residents has improved, public service facilities such as medical care and education are complete, and farmers’ sense of well-being has increased.

4.2. The Role of Smart Agriculture in Rural Revitalization

4.2.1. Enhancing Agricultural Production Efficiency

Improving the efficiency and quality of agricultural production through technology. Smart agriculture uses advanced technologies such as the Internet of Things (IoT), big data, drones, sensors, and artificial intelligence to enhance all aspects of agricultural production.

4.2.2. Application of IoT Technology

Through IoT technology, farmers can monitor the farmland environment in real-time, such as soil moisture, temperature, and nutrient content, and adjust planting and irrigation strategies in time to improve crop yield and quality [2, 7]. For example, LoRa and NB-IoT technologies are used to achieve efficient transmission of sensor data and real-time data analysis and feedback via a cloud platform [2, 8].

4.2.3. Application of Drones and Remote Sensing Technology

Drones equipped with multispectral and thermal infrared cameras can be flown regularly to monitor farmland and identify crop health and environmental changes for precise agricultural management [4, 5, 14]. For example, high-resolution images taken by drones are used for crop health assessment and water stress detection, and the data is analyzed and management recommendations are provided through a cloud platform.

4.2.4. Application of Sensor Technology

Sensors are embedded in the soil to monitor soil moisture, temperature, and nutrient content in real-time. Through sensor data, farmers can accurately manage farmland, improve resource utilization efficiency, and reduce waste [2]. For example, soil moisture sensors measure soil moisture through conductivity or capacitance technology, and the data are uploaded to a cloud platform through LoRa or NB-IoT for real-time analysis and feedback [2].

4.2.5. Application of Big Data and Artificial Intelligence

Big data technologies help farmers make better decisions and improve productivity by collecting and analyzing large amounts of agricultural data. For example, soil and weather data are analyzed through big data to optimize sowing and fertilization strategies [7, 14]. Artificial intelligence algorithms can predict crop growth, identify potential problems in advance, reduce losses, and improve yields [7, 14]. Through the application of smart agriculture, the income and quality of life of rural residents have been significantly improved, and the goal of rural revitalization has been achieved.

5. Conclusion and Prospects

5.1. Main Research Conclusions

This thesis systematically explores the application of smart agriculture technology in agriculture and its impact on rural revitalization, designing an integrated smart agriculture platform. The integrated smart agriculture platform has demonstrated significant improvements in key performance metrics during pilot implementations. For example, the deployment of IoT-enabled irrigation systems resulted in a 30% reduction in water usage, while AI-driven pest detection systems reduced pesticide application by 25%. Additionally, the integration of UAV-based crop monitoring increased yield by 20% in targeted regions. These outcomes underscore the platform's potential to enhance agricultural productivity and sustainability, supporting broader rural revitalization efforts. The study demonstrates that smart agriculture technology significantly enhances agricultural production efficiency and improves farmers' income and quality of life. The specific conclusions are as follows:

5.1.1. Improvement of Agricultural Production Efficiency

The application of technologies like the Internet of Things (IoT), big data, drones, sensors, and artificial intelligence optimizes all aspects of agricultural production. For example, IoT technology enables real-time monitoring of the farmland environment, drone technology enhances the accuracy of crop health assessment, and sensor technology facilitates real-time monitoring of soil and environmental parameters [2].

5.1.2. Improving Farmers' Income and Quality of Life

Smart agriculture technologies increase farmers' income by optimizing production processes, reducing resource wastage, and improving yield and quality. For example, smart irrigation systems and precision fertilization technologies improve resource utilization efficiency, produce high-quality agricultural products, and boost market competitiveness and added value [7, 8, 14]. Additionally, rural infrastructure and public service improvements have enhanced the quality of life for rural residents [14].

5.1.3. Achievements of the Platform Design

The integrated smart agriculture platform provides intelligent, precise agricultural management by incorporating sensor networks, UAV data, data processing terminals, and cloud platforms. The platform uses standardized interfaces and protocols for efficient data transmission and processing, enabling real-time feedback and decision support [8,14]. Smart agriculture devices detailed in Chapter 2, such as soil moisture sensors, multispectral drones, and big data analysis platforms, have demonstrated significant improvements in agricultural productivity and resource utilization. For example, real-time monitoring of soil moisture and nutrients allows for more precise irrigation and fertilization, thereby enhancing crop yields [2, 4, 5, 14].

5.2. Recommendations for Future Research

Despite the significant results achieved in this study, some areas require further research and improvement:

5.2.1. Technology Integration and Standardization

The advancement of smart agriculture technologies requires compatibility across different technologies and devices and the establishment of uniform technical standards and specifications to enhance integration and collaboration. For instance, differences in data formats and communication protocols among sensors and drones from various manufacturers make data integration and analysis challenging [8, 14].

5.2.2. Data Security and Privacy Protection

With the extensive application of big data and cloud computing technologies in agriculture, data security and privacy concerns have become increasingly critical. Future research should focus on maximizing data value while ensuring security, for instance, by using encryption and access control to address farmers' concerns regarding the misuse or leakage of production data [14].

5.2.3. Farmers' Technical Training and Promotion

Smart agriculture technologies require farmers to possess a certain level of technical proficiency. Therefore, technical training and promotion efforts should be strengthened to help farmers master and apply these advanced technologies effectively. For example, training courses and demonstration projects may be necessary to equip farmers, especially those inexperienced with smartphones and computers, with essential skills [14].

5.3. Prospects for the Development of Smart Agriculture Devices and Cloud Services

5.3.1. Technological Innovation and Application Expansion

In the future, emerging technologies such as 5G, blockchain, and IoT will be further applied in smart agriculture, advancing agricultural production toward greater intelligence and precision. For instance, 5G technology will enhance data transmission speed and network coverage, while blockchain technology will improve the traceability of agricultural products and food safety management [8, 14].

5.3.2. Cloud Services and Big Data Analysis

Cloud services will continue to play an essential role in agricultural data processing and analysis, providing precise agricultural management advice and decision support by integrating multi-source data and high-performance computing resources. Big data analytics will enable farmers to understand and anticipate changes and trends in agricultural production, optimizing production decisions [14].

5.3.3. Intelligent Equipment and Automation

Future smart agriculture equipment will become increasingly intelligent and automated, with innovations such as driverless farm machinery, intelligent irrigation systems, and automated farming equipment. These devices will reduce the dependency on human labor while boosting production efficiency and resource use efficiency [2, 7, 8].

5.3.4. Application of Precision Agriculture Technology

Precision agriculture technology, including precision fertilization, precision seeding, and precision harvesting, will continue to advance. By leveraging sensors and drone technology, farmers will manage each plot of farmland with precision, maximizing output and resource utilization [4, 5, 14].

5.3.5. Environmental Monitoring and Sustainable Development

Smart agriculture will also contribute to environmental monitoring and sustainable development. Real-time monitoring of soil, water, and air quality will enable farmers to mitigate the environmental impacts of agricultural activities, promoting the sustainable growth of agriculture [2, 8].

Through these prospects, it is foreseeable that smart agricultural equipment and cloud services will play an increasingly important role in agricultural production, driving agriculture towards more sustainable and efficient development.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, J.Y. and T.J.; methodology, J.Y.; software, B.L.; validation, J.Y., T.J., B.L., and J.Z.; formal analysis, J.Y.; investigation, J.Y.; resources, J.Y.; data curation, B.L.; writing—original draft preparation, J.Y.; writing—review and editing, T.J. and J.Z.; visualization, B.L.; supervision, J.Y.; project administration, J.Y.; funding acquisition, J.Y. All authors have read and agreed to the published version of the manuscript.

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