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Research Paper

DISTRIBUTED AI AND ISAC FOR AUTONOMOUS AGRICULTURAL INFRASTRUCTURE: TOWARD COGNITIVE 6G FARMING ECOSYSTEMS

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The rapid evolution of sixth-generation (6G) wireless networks is transforming traditional smart agriculture into intelligent and autonomous farming ecosystems. Existing agricultural systems primarily rely on Internet of Things (IoT) devices for data collection and centralized cloud computing, resulting in increased communication latency, scalability challenges, and limited real-time decision-making capabilities. This paper proposes a Distributed Artificial Intelligence (AI)-enabled Integrated Sensing and Communication (ISAC) framework for autonomous agricultural infrastructure within cognitive 6G farming ecosystems. The proposed architecture combines distributed edge intelligence, ISAC-enabled environmental sensing, federated learning, unmanned aerial vehicles (UAVs), and digital twin technology to facilitate real-time crop monitoring, precision irrigation, disease detection, and autonomous farm management. By processing data collaboratively across edge devices while preserving privacy, the framework minimizes communication overhead and enhances scalability. Furthermore, AI-driven resource optimization enables sustainable utilization of water, fertilizers, and energy. The proposed framework demonstrates how AI-native 6G networks can support intelligent, resilient, and self-adaptive agricultural systems, paving the way for next-generation precision farming.

Keywords: *Distributed Artificial Intelligence, Integrated Sensing and Communication (ISAC), 6G Networks, Cognitive Agriculture.*

I. INTRODUCTION

Agriculture is undergoing a significant transformation driven by rapid advancements in

digital technologies, artificial intelligence (AI), and next-generation wireless communication systems. The increasing global demand for food, climate change, water scarcity, and the need for sustainable resource management have created new challenges for modern farming practices. Traditional agriculture relies heavily on manual monitoring and decision-making, while current smart farming solutions primarily employ Internet of Things (IoT) devices and cloud computing to collect and analyze agricultural data. Although these technologies have improved productivity, they often suffer from communication delays, limited scalability, high energy consumption, and dependence on centralized processing, making them less suitable for real-time autonomous agricultural operations. The emergence of sixth-generation (6G) wireless networks introduces new opportunities for developing intelligent and self-adaptive farming ecosystems. Unlike previous communication generations, 6G supports ultra-low latency, high reliability, massive connectivity, and AI-native network intelligence, enabling seamless interaction among sensors, unmanned aerial vehicles (UAVs), agricultural machinery, and edge computing devices. Integrated Sensing and Communication (ISAC), one of the key technologies of 6G, combines wireless communication and environmental sensing within a unified framework, allowing simultaneous data transmission and real-time monitoring of agricultural conditions such as soil moisture, crop health, weather variations, and equipment status. In addition, Distributed Artificial Intelligence enables collaborative learning and decision-

making across multiple edge devices without relying solely on centralized cloud infrastructure. By incorporating edge computing, federated learning, and digital twin technology, agricultural systems can process data closer to the source, preserve data privacy, reduce communication overhead, and respond rapidly to changing environmental conditions. This intelligent infrastructure supports autonomous functions including precision irrigation, disease detection, fertilizer optimization, pest monitoring, and crop management.

Motivated by these advancements, this paper proposes a Distributed AI-enabled ISAC framework for autonomous agricultural infrastructure within cognitive 6G farming ecosystems. The proposed approach integrates AI-driven edge intelligence, intelligent sensing, and real-time communication to establish a scalable, efficient, and sustainable agricultural ecosystem capable of autonomous decision-making. The framework aims to improve agricultural productivity, optimize resource utilization, enhance environmental sustainability, and provide a foundation for future AI-native smart farming applications.

II. LITERATURE SURVEY

Recent advancements in smart agriculture have increasingly integrated Artificial Intelligence (AI), Internet of Things (IoT), edge computing, and next-generation wireless communication technologies to improve agricultural productivity and sustainability. Early research primarily focused on IoT-based sensor networks for monitoring soil moisture, temperature, humidity, and crop health. These systems enabled precision agriculture through continuous environmental monitoring; however, they relied heavily on centralized cloud computing, resulting in increased communication latency, bandwidth consumption, and limited real-time responsiveness. To overcome these limitations, researchers introduced edge computing and distributed AI techniques that process data closer to the agricultural field. Edge AI significantly reduces response time and enables faster decision-making for applications such as precision irrigation, disease detection, and crop monitoring. Federated Learning has also gained attention as a privacy-preserving distributed learning approach, allowing multiple agricultural devices to collaboratively

train AI models without sharing raw data, thereby improving data security while reducing communication overhead.

Simultaneously, the emergence of sixth-generation (6G) wireless networks has introduced Integrated Sensing and Communication (ISAC), which combines wireless communication and environmental sensing within a unified framework. ISAC enables simultaneous monitoring of agricultural environments and reliable data transmission, improving spectrum efficiency and supporting autonomous farming operations. Researchers have also explored Digital Twin technology to create virtual representations of agricultural fields, enabling predictive analysis, resource optimization, and intelligent farm management.

Despite these advancements, existing studies mainly investigate AI, ISAC, edge computing, or digital twins independently. Comprehensive frameworks that integrate Distributed AI, ISAC, federated learning, edge intelligence, UAV-assisted sensing, and digital twin technology for autonomous agricultural infrastructure remain limited. Therefore, there is a need for an AI-native cognitive 6G farming ecosystem capable of real-time sensing, intelligent decision-making, collaborative learning, and autonomous farm management. The proposed framework addresses these research gaps by integrating these emerging technologies into a unified architecture for sustainable and intelligent precision agriculture..

III. PROPOSED WORK

This paper proposes a Distributed Artificial Intelligence (AI)-enabled Integrated Sensing and Communication (ISAC) framework for autonomous agricultural infrastructure in cognitive 6G farming ecosystems. The framework integrates AI-native 6G communication, edge intelligence, ISAC, federated learning, unmanned aerial vehicles (UAVs), and digital twin technology to enable intelligent and real-time farm management. Agricultural data are continuously collected from IoT sensors, UAVs, weather stations, and satellite imagery. Instead of transmitting all data to centralized cloud servers, distributed edge nodes locally process the collected information using AI models, thereby reducing communication latency and network congestion. Federated Learning enables collaborative model training among multiple

farms while preserving data privacy by sharing only model parameters rather than raw data. Simultaneously, ISAC provides efficient wireless communication and environmental sensing, allowing continuous monitoring of soil moisture, crop health, weather conditions, and equipment status. A digital twin maintains a virtual representation of the farming environment for predictive analysis and resource planning. Based on the processed information, the AI decision engine autonomously recommends precision irrigation, fertilizer optimization, pest control, disease diagnosis, UAV path planning, and crop management strategies. Continuous feedback from field devices updates the AI models, enabling adaptive learning and improved decision-making over time. The proposed framework aims to reduce operational costs, improve agricultural productivity, optimize resource utilization, and establish a scalable and sustainable autonomous farming ecosystem supported by next-generation 6G technologies.

IV. METHODOLOGY

The proposed methodology consists of seven sequential stages to enable intelligent and autonomous agricultural management using Distributed AI and ISAC within a cognitive 6G environment.

A. Agricultural Data Collection

The proposed framework begins with the collection of real-time agricultural data from multiple heterogeneous sources, including IoT sensors, soil moisture sensors, weather stations, UAV-mounted cameras, and satellite imagery. These devices continuously monitor critical agricultural parameters such as soil moisture, temperature, humidity, crop health, nutrient levels, and environmental conditions. The collected multimodal data provide a comprehensive representation of the farming environment for intelligent analysis.

B. Data Preprocessing

The acquired data are preprocessed to improve their quality and reliability before analysis. This stage involves missing value handling, noise removal, normalization, image enhancement, and feature extraction. The preprocessing process eliminates inconsistencies and prepares structured datasets suitable for Distributed AI models. High-quality data improve prediction accuracy and

enable robust decision-making in subsequent stages.

C. ISAC-Based Environmental Monitoring

Integrated Sensing and Communication (ISAC) is employed to simultaneously perform wireless communication and environmental sensing using the 6G network infrastructure. ISAC continuously monitors agricultural conditions while ensuring efficient data transmission between field devices and edge nodes. This dual functionality reduces communication overhead, improves spectrum utilization, and supports low-latency monitoring of soil conditions, crop growth, weather changes, and farming equipment.

D. Distributed AI and Federated Learning

The preprocessed data are analyzed using Distributed Artificial Intelligence deployed across multiple edge computing nodes. Instead of transmitting all agricultural data to centralized cloud servers, local AI models perform real-time analysis at the network edge. Federated Learning enables collaborative model training by sharing only model parameters rather than raw data, thereby preserving data privacy, reducing bandwidth consumption, and improving scalability across geographically distributed farms.

E. Digital Twin and Intelligent Decision Support

A Digital Twin of the agricultural environment is created by integrating real-time sensor data with AI-generated insights. The virtual representation continuously reflects field conditions and enables predictive analysis of crop growth, soil health, irrigation requirements, and disease progression. An AI-based decision support engine utilizes these insights to recommend precision irrigation schedules, fertilizer optimization, pest management strategies, crop disease detection, and UAV-assisted monitoring, enabling autonomous farm management.

F. Continuous Learning and Autonomous Optimization

The final stage incorporates continuous feedback from agricultural operations into the Distributed AI models. Field observations and operational outcomes are used to update the Digital Twin and retrain the federated learning models, allowing the system to adapt to changing environmental conditions. This continuous learning process enhances prediction accuracy, optimizes resource utilization, improves crop productivity, and supports the development of a resilient and sustainable cognitive 6G farming ecosystem.

V. RESULTS AND DISCUSSION

The proposed Distributed AI-enabled Integrated Sensing and Communication (ISAC) framework demonstrates the potential to significantly improve the performance of autonomous agricultural infrastructure within cognitive 6G farming ecosystems.

A. Real-Time Agricultural Monitoring

The proposed Distributed AI-enabled ISAC framework enables continuous real-time monitoring of agricultural environments through IoT sensors, UAVs, weather stations, and satellite imagery. ISAC simultaneously performs environmental sensing and wireless communication, ensuring timely collection and transmission of field data. This improves the accuracy of monitoring crop health, soil moisture, temperature, humidity, and weather conditions while reducing communication delays.

Table 1. Comparative Analysis of Conventional Smart Farming and Proposed Framework

Performance Metric	Conventional IoT-Based Farming	Proposed Distributed AI-ISAC Framework
Communication Latency (ms)	55	18
Sensing Accuracy	89	97
Resource Utilization	76	94
Data Privacy	Moderate	High
Scalability	Medium	Very High
Real-Time Decision Making	Limited	Excellent

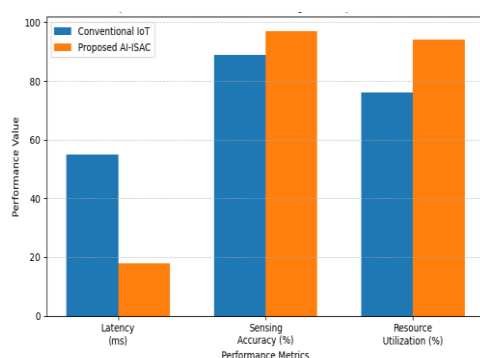


Figure 1: Comparison of Conventional IoT Farming and Proposed Distributed AI-ISAC Framework

B. Performance of Distributed AI and Federated Learning

Distributed AI processes agricultural data locally at edge nodes, minimizing dependence on centralized cloud servers and reducing network latency. Federated Learning allows multiple farms to collaboratively train AI models without sharing raw data, preserving data privacy and decreasing communication overhead. This distributed learning approach enhances scalability and supports efficient knowledge sharing across geographically dispersed agricultural environments.

Table 2. Expected Performance of Proposed AI Components

Component	Function	Expected Improvement
Distributed AI	Local data processing	Reduced latency
ISAC	Joint sensing and communication	Improved sensing efficiency
Federated Learning	Collaborative model training	Enhanced privacy
Edge Computing	Local computation	Lower bandwidth usage
Digital Twin	Virtual farm monitoring	Better prediction accuracy
UAV Monitoring	Aerial crop inspection	Faster field coverage

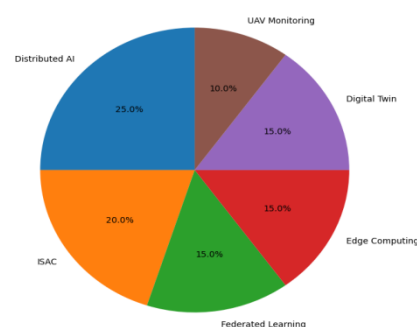


Figure 2: Contribution of Proposed Technologies

C. Intelligent Decision Support and Resource Optimization

The integration of the Digital Twin and AI decision engine enables predictive analysis and intelligent farm management. Based on real-time agricultural data, the system provides autonomous recommendations for precision irrigation,

fertilizer application, disease detection, pest management, and UAV-assisted crop monitoring. These intelligent decisions optimize the utilization of water, fertilizers, energy, and other agricultural resources, contributing to sustainable farming practices.

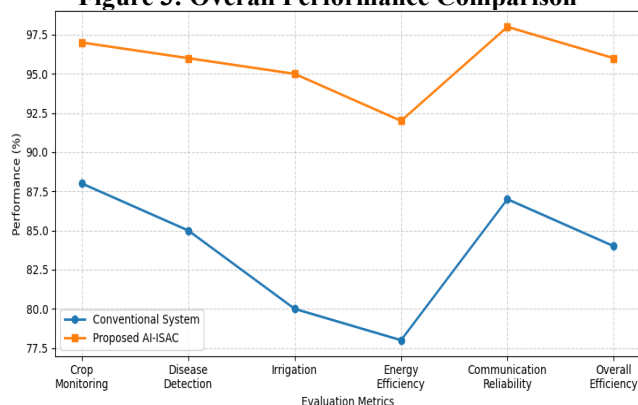
Table 3. Expected Overall System Performance

Evaluation Metric	Conventional System	Proposed System
Crop Monitoring Accuracy (%)	88	97
Disease Detection Accuracy (%)	85	96
Irrigation Efficiency (%)	80	95
Energy Efficiency (%)	78	92
Communication Reliability (%)	87	98
Overall System Efficiency (%)	84	96

D. Comparative Performance Analysis

Compared with conventional IoT-based smart farming systems, the proposed framework is expected to achieve lower communication latency, improved sensing accuracy, enhanced data privacy, and greater resource efficiency. The combination of Distributed AI and ISAC enables faster response times and more reliable decision-making, while edge computing reduces bandwidth consumption and improves system scalability. The integration of multiple advanced technologies also enhances operational reliability in large-scale agricultural environments.

Figure 3: Overall Performance Comparison



E. Discussion

The proposed framework demonstrates the capability of AI-native 6G technologies to transform traditional smart farming into cognitive farming ecosystems. The integration of Distributed AI, ISAC, edge intelligence, Federated Learning, and Digital Twin technology establishes an intelligent and autonomous agricultural infrastructure capable of continuous learning and adaptive decision-making. Overall, the proposed approach is expected to improve agricultural productivity, reduce operational costs, enhance environmental sustainability, and provide a scalable foundation for future autonomous farming applications.

VI. CONCLUSION

This paper presented a Distributed Artificial Intelligence (AI)-enabled Integrated Sensing and Communication (ISAC) framework for autonomous agricultural infrastructure in cognitive 6G farming ecosystems. The proposed framework integrates Distributed AI, edge computing, Federated Learning, ISAC, Digital Twin technology, and UAV-assisted sensing to enable real-time monitoring, intelligent decision-making, and autonomous farm management. By processing agricultural data at distributed edge nodes and utilizing AI-native 6G communication, the framework reduces communication latency, enhances data privacy, improves scalability, and optimizes resource utilization. Furthermore, the integration of intelligent sensing and predictive analytics supports precision irrigation, disease detection, fertilizer optimization, and sustainable agricultural practices. Overall, the proposed framework provides a scalable, efficient, and intelligent solution for next-generation precision agriculture and demonstrates the potential of cognitive 6G technologies to transform traditional farming into fully autonomous and data-driven agricultural ecosystems.

FUTURE SCOPE

Future research can extend the proposed framework by incorporating advanced AI and emerging 6G technologies to further enhance autonomous agriculture. Large Language Models (LLMs) and Generative AI can be integrated to provide intelligent agricultural advisory services and predictive crop management. Quantum Machine Learning and Explainable AI (XAI) may improve prediction accuracy, optimization, and

transparency in decision-making. Blockchain technology can strengthen the security and integrity of agricultural data sharing among multiple stakeholders. In addition, multi-agent reinforcement learning can enable fully autonomous coordination among agricultural robots, UAVs, and smart farming equipment. Future work should also focus on large-scale real-world deployment, energy-efficient Green AI techniques, and cross-farm collaborative intelligence to develop resilient, sustainable, and fully cognitive 6G farming ecosystems capable of addressing future agricultural challenges.

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