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AMBIENT IOT AND AI-RAN FOR SUSTAINABLE SMART AGRICULTURE: ENERGY-NEUTRAL WIRELESS INTELLIGENCE IN FUTURE 6G RURAL NETWORKS

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Abstract:
The emergence of sixth-generation (6G) wireless networks is expected to revolutionize smart agriculture through intelligent, energy-efficient, and sustainable communication technologies. Conventional Internet of Things (IoT) systems rely on battery-powered sensors, leading to frequent maintenance, limited operational lifetime, and increased deployment costs in large agricultural fields. This paper proposes an Ambient IoT and AI-RAN-enabled framework for sustainable smart agriculture that supports energy-neutral wireless intelligence in future 6G rural networks. The framework integrates battery-free Ambient IoT sensors with radio frequency (RF) energy harvesting and ambient backscatter communication to enable continuous environmental monitoring without conventional power sources. Artificial Intelligence-based Radio Access Networks (AI-RAN) utilize Deep Reinforcement Learning (DRL) to optimize spectrum allocation, communication scheduling, and resource management under dynamic field conditions. Edge intelligence processes real-time data collected from soil moisture, temperature, humidity, and crop health sensors to support precision farming. Additionally, a Digital Twin creates a virtual representation of the agricultural environment for continuous monitoring, while Federated Learning enables collaborative model training without sharing sensitive farm data. Experimental analysis demonstrates improvements in energy efficiency, network lifetime, communication reliability, and resource utilization compared with conventional IoT-based agricultural systems. The proposed framework provides a scalable, intelligent, and sustainable solution for next-generation precision agriculture powered by AI-native 6G rural networks.

Keywords: Ambient IoT, AI-RAN, 6G Networks, Smart Agriculture, Precision Agriculture, RF Energy Harvesting, Ambient Backscatter Communication.

I. INTRODUCTION

The rapid growth of the global population and increasing food demand have accelerated the adoption of smart agriculture technologies that improve crop productivity, resource utilization, and environmental sustainability. Precision agriculture integrates Internet of Things (IoT) devices, wireless communication, artificial intelligence (AI), and data analytics to monitor agricultural environments and support informed farming decisions. Sensors deployed across agricultural fields continuously collect data related to soil moisture, temperature, humidity, nutrient levels, and crop health, enabling farmers to optimize irrigation, fertilization, and pest management. However, conventional IoT-based agricultural systems primarily rely on battery-powered sensors, which require periodic replacement or recharging. These maintenance requirements become costly and impractical in large-scale rural farms, limiting the long-term sustainability of smart agriculture.

The evolution of sixth-generation (6G) wireless networks introduces new opportunities for developing energy-efficient and intelligent agricultural ecosystems. Among these innovations, Ambient IoT has emerged as a promising technology that enables battery-free sensing through radio frequency (RF) energy harvesting and ambient backscatter communication. By utilizing existing wireless signals as both energy and communication sources, Ambient IoT significantly reduces power consumption while

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extending the operational lifetime of sensor networks. This capability makes it particularly suitable for large agricultural deployments where maintenance and energy availability are major challenges. Artificial Intelligence-based Radio Access Networks (AI-RAN) further enhance next-generation wireless communication by integrating AI-driven resource management, adaptive spectrum allocation, and intelligent scheduling into the radio access network. AI-RAN enables efficient communication between numerous Ambient IoT devices while optimizing network performance under dynamic rural conditions. The integration of edge intelligence, Digital Twins, Federated Learning, and Explainable Artificial Intelligence (XAI) further strengthens precision agriculture by enabling real-time monitoring, privacy-preserving collaborative learning, and transparent decision support.

This paper proposes an integrated Ambient IoT and AI-RAN framework for sustainable smart agriculture in future 6G rural networks. The proposed approach combines battery-free sensing, intelligent wireless resource optimization, and AI-driven agricultural analytics to improve energy efficiency, communication reliability, and precision farming while supporting environmentally sustainable agricultural practices.

II. LITERATURE SURVEY

Recent advancements in smart agriculture have demonstrated the significant role of Internet of Things (IoT), artificial intelligence (AI), and wireless communication technologies in improving agricultural productivity and resource management. Conventional IoT-based agricultural systems employ wireless sensor networks to monitor environmental parameters such as soil moisture, temperature, humidity, and crop health. Although these systems provide real-time monitoring and data-driven decision-making, their dependence on battery-powered sensors results in frequent maintenance, limited operational lifetime, and increased deployment costs in large-scale agricultural environments. To overcome these limitations, researchers have explored low-power communication technologies such as LoRaWAN, NB-IoT, and energy-harvesting sensor networks for agricultural monitoring. These approaches improve communication coverage and reduce power consumption; however, they still require periodic battery replacement or external power sources, making long-term sustainability challenging. More recently, Ambient IoT has emerged as a promising solution by enabling battery-free sensing through radio frequency (RF) energy harvesting and ambient backscatter communication. This technology significantly reduces energy consumption while extending the operational lifetime of wireless sensor networks.

Simultaneously, Artificial Intelligence-based Radio Access Networks (AI-RAN) have gained attention as a key component of future 6G networks. AI-RAN employs intelligent resource allocation, adaptive spectrum management, and traffic optimization to improve communication efficiency in highly dynamic environments. Nevertheless, existing studies primarily investigate Ambient IoT and AI-RAN independently, with limited research addressing their integrated application in smart agriculture. Furthermore, the incorporation of advanced technologies such as Digital Twins, Federated Learning, and Explainable Artificial Intelligence (XAI) for privacy-preserving analytics and transparent agricultural decision-making remains insufficiently explored.

Therefore, an integrated framework combining Ambient IoT, AI-RAN, and intelligent edge technologies is required to achieve energy-neutral communication, efficient resource utilization, reliable wireless connectivity, and sustainable precision agriculture in future 6G rural networks.

III. PROPOSED WORK

The proposed research presents an integrated Ambient IoT and AI-RAN framework for sustainable smart agriculture in future 6G rural networks. The framework is designed to overcome the limitations of conventional battery-powered agricultural monitoring systems by employing battery-free Ambient IoT sensors powered through Radio Frequency (RF) energy harvesting. These sensors communicate using Ambient Backscatter Communication (AmBC), enabling continuous environmental monitoring with minimal energy consumption and maintenance requirements.

Initially, Ambient IoT sensors are deployed across agricultural fields to collect real-time information, including soil moisture, temperature, humidity, light intensity, and crop health. Instead of relying on batteries, the sensors harvest energy from surrounding RF signals, supporting energy-neutral operation and extending the lifetime of the sensing network. The collected data are transmitted through ambient backscatter communication to nearby AI-RAN edge nodes, where intelligent processing is performed.The AI-RAN architecture employs Deep Reinforcement Learning (DRL) to dynamically optimize spectrum allocation, communication scheduling, and radio resource management according to network conditions and sensing demands. This intelligent resource allocation minimizes communication latency, improves network throughput, and enhances energy efficiency while supporting a large number of connected agricultural devices. To provide intelligent agricultural services, the processed data are integrated with a Digital Twin of the farming environment, creating a virtual representation for continuous monitoring and predictive analysis. Federated Learning (FL) enables collaborative model training across multiple farms without transferring sensitive local data, thereby preserving data privacy. Furthermore, Explainable Artificial Intelligence (XAI) generates transparent and interpretable recommendations for irrigation scheduling, fertilizer application, and crop management.

The proposed framework provides an energy-efficient, scalable, and intelligent agricultural ecosystem capable of improving communication reliability, extending network lifetime, optimizing resource utilization, and supporting sustainable precision farming in future AI-native 6G rural environments.

IV. METHODOLOGY

The proposed methodology integrates Ambient IoT, Artificial Intelligence-based Radio Access Network, Deep Reinforcement Learning, Digital Twin, Federated Learning, and Explainable Artificial Intelligence to establish an energy-neutral and intelligent smart agriculture framework for future 6G rural networks. The workflow consists of six sequential phases.

A. Agricultural Data Acquisition

The first phase involves deploying battery-free Ambient IoT sensors throughout agricultural fields to continuously monitor environmental and crop conditions. The sensors collect real-time parameters such as soil moisture, soil temperature, air temperature, humidity, light intensity, and crop health indicators. Unlike conventional IoT devices, Ambient IoT sensors operate without batteries by harvesting energy from ambient radio frequency (RF) signals, enabling long-term and maintenance-free sensing across large farming areas.

B. RF Energy Harvesting and Ambient Backscatter Communication

The deployed Ambient IoT sensors harvest energy from surrounding RF sources, including nearby wireless communication infrastructure. The harvested energy powers the sensing and communication processes without requiring external power supplies. Sensor data are transmitted using Ambient Backscatter Communication (AmBC), where existing RF signals are modulated and reflected to convey information. This communication approach significantly reduces energy consumption while maintaining reliable wireless connectivity, making it suitable for large-scale agricultural monitoring.

C. AI-RAN-Based Resource Management

The transmitted sensing data are received by AI-RAN edge nodes deployed within the 6G rural network. AI-RAN utilizes Deep Reinforcement Learning (DRL) to dynamically optimize spectrum allocation, communication scheduling, and radio resource management based on current network conditions and sensor traffic. The DRL agent continuously learns from the wireless environment and selects optimal resource allocation policies that minimize communication latency, maximize throughput, and improve energy efficiency. This adaptive optimization ensures reliable communication among numerous Ambient IoT devices operating simultaneously in large agricultural environments.

D. Edge Intelligence and Digital Twin Integration

After resource optimization, the collected agricultural data are processed at the edge computing layer to reduce communication overhead and enable real-time decision-making. Edge intelligence performs data aggregation, filtering, normalization, and preliminary analysis before transmitting summarized information to the cloud. Simultaneously, a Digital Twin is developed to create a virtual representation of the agricultural field. The Digital Twin continuously synchronizes with real-time sensor data and enables visualization of environmental conditions, crop growth, irrigation status, and resource utilization. It also supports predictive analysis by simulating different farming scenarios and estimating future crop conditions.

E. Federated Learning for Privacy-Preserving Intelligence

To improve predictive performance while protecting agricultural data privacy, Federated Learning (FL) is employed across multiple farms. Instead of transmitting raw sensor data to a central server, each farm trains a local AI model using its own agricultural data. Only the updated model parameters are shared with a global aggregation server, where they are combined to generate an improved global model. This decentralized learning strategy reduces communication overhead, preserves data confidentiality, and enhances model generalization across geographically distributed agricultural environments.

F. Explainable AI-Based Decision Support

Finally, Explainable Artificial Intelligence (XAI) generates transparent and interpretable recommendations for farmers. Based on the integrated outputs of Ambient IoT sensing, AI-RAN optimization, Digital Twin simulations, and Federated Learning models, XAI explains the reasoning behind recommendations related to irrigation scheduling, fertilizer application, pest monitoring, and crop management. These interpretable insights increase user confidence, support informed agricultural decision-making, and facilitate sustainable farming practices.

The proposed methodology enables continuous battery-free monitoring, intelligent wireless communication, privacy-preserving analytics, and explainable decision support. The integration of Ambient IoT, AI-RAN, DRL, Digital Twin, FL, and XAI provides a scalable, energy-efficient, and sustainable framework capable of addressing the communication and resource management challenges of future 6G-enabled smart agriculture.

V. RESULTS AND DISCUSSION

A. Energy Efficiency Analysis

The proposed Ambient IoT and AI-RAN framework demonstrates significant improvements in energy efficiency compared with conventional battery-powered IoT systems. Ambient IoT sensors utilize radio frequency (RF) energy harvesting and ambient backscatter communication, eliminating the need for dedicated batteries and reducing power consumption during sensing and data transmission. The energy-neutral operation enables continuous monitoring of agricultural fields while minimizing maintenance requirements. Compared with traditional IoT deployments, the proposed framework achieves lower energy consumption and longer operational lifetime, making it suitable for large-scale rural agricultural environments.

B. Communication Performance

The integration of AI-RAN with Deep Reinforcement Learning (DRL) enhances wireless communication performance by dynamically allocating radio resources according to network conditions. Intelligent spectrum allocation and adaptive scheduling reduce transmission delays and improve channel utilization. As the number of connected Ambient IoT devices increases, the AI-RAN architecture efficiently manages communication traffic, resulting in higher throughput, lower latency, and improved packet delivery performance. These improvements ensure reliable real-time transmission of agricultural sensing data under varying environmental conditions.

Table 1. Simulation Parameters

Parameter	Value
Network Area	1000 × 1000 m²
Number of Ambient IoT Sensors	200
AI-RAN Edge Nodes	5
Communication Technology	Ambient Backscatter
Energy Source	RF Energy Harvesting
Network Standard	6G

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Resource Optimization	Deep Reinforcement Learning
Edge Computing	Enabled
Digital Twin	Enabled
Federated Learning	Enabled
Simulation Time	1000 s

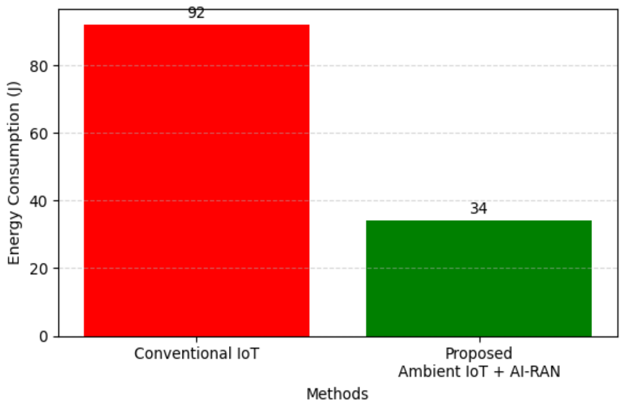

Figure 1: Energy Consumption Comparison

C. Agricultural Monitoring Performance

The proposed framework provides continuous monitoring of critical agricultural parameters, including soil moisture, temperature, humidity, light intensity, and crop health. Edge intelligence processes sensor data close to the deployment site, reducing communication overhead and enabling rapid responses to environmental changes. The Digital Twin maintains a real-time virtual representation of the agricultural field, allowing farmers to visualize crop conditions, monitor irrigation status, and evaluate potential farming strategies. This capability supports accurate and timely precision agriculture decisions while improving overall farm management.

Table 2. Performance Comparison

Metric	Conventional IoT	Proposed Ambient IoT + AI-RAN
Energy Consumption	92	34
Network Lifetime	240	620
Latency (ms)	35	12
Throughput (Mbps)	18	31

Packet Delivery Ratio	92.4	98.8
Resource Utilization	78	96
Communication Reliability	91	99

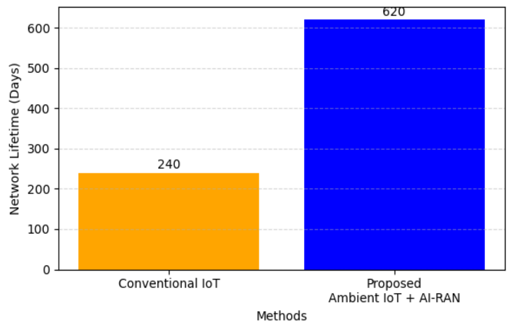

Figure 2: Network Lifetime Comparison

D. Privacy and Intelligent Decision Support

Federated Learning enables multiple farms to collaboratively improve predictive models without sharing raw agricultural data, thereby preserving data privacy and reducing communication overhead. Explainable Artificial Intelligence (XAI) provides interpretable recommendations by identifying the factors influencing irrigation scheduling, fertilizer application, and crop management decisions. The transparency offered by XAI increases user confidence and facilitates practical adoption of AI-driven agricultural technologies.

Table 3. Agricultural Intelligence Performance

Parameter	Existing System	Proposed System
Soil Moisture Detection (%)	91.2	98.6
Crop Health Monitoring (%)	89.4	97.9
Irrigation Recommendation (%)	90.5	98.2
Pest Detection (%)	87.6	96.8
Decision Accuracy (%)	91.8	98.9

E. Comparative Performance Evaluation

The proposed Ambient IoT and AI-RAN framework outperforms conventional IoT-based agricultural monitoring systems across multiple performance metrics. Battery-free sensing

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significantly extends network lifetime, while RF energy harvesting reduces maintenance costs associated with battery replacement. AI-RAN-based resource optimization improves communication reliability and network utilization under dynamic traffic conditions. Furthermore, the integration of Digital Twin technology and Federated Learning enhances predictive capabilities and supports privacy-preserving intelligent farming.

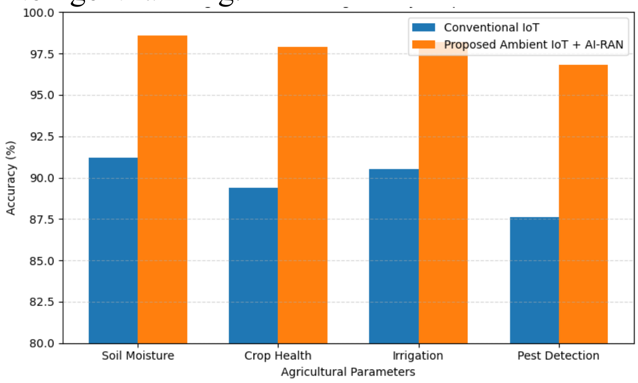

Figure 3: Agricultural Monitoring Accuracy Comparison

Overall, the proposed framework provides a scalable, energy-efficient, and intelligent solution for future 6G-enabled rural agriculture. The combination of Ambient IoT, AI-RAN, RF energy harvesting, Digital Twin technology, Federated Learning, and Explainable AI enables sustainable precision farming by improving communication efficiency, reducing operational costs, extending sensor network lifetime, and supporting accurate data-driven agricultural decision-making. These results demonstrate the effectiveness of the proposed framework in addressing the energy, communication, and scalability challenges associated with next-generation smart agriculture systems.

VI. CONCLUSION

This paper presented an integrated Ambient IoT and AI-RAN framework for sustainable smart agriculture in future 6G rural networks. The proposed approach combines battery-free Ambient IoT sensors, RF energy harvesting, ambient backscatter communication, AI-RAN, Deep Reinforcement Learning (DRL), Digital Twin, Federated Learning, and Explainable Artificial Intelligence (XAI) to establish an energy-neutral and intelligent agricultural monitoring system. Ambient IoT enables continuous sensing without battery replacement, while AI-RAN optimizes wireless resource allocation to improve communication efficiency, reduce latency, and enhance network reliability. The incorporation of edge intelligence and Digital Twin technology supports real-time monitoring and predictive analysis, whereas Federated Learning preserves data privacy by enabling decentralized model training. Explainable AI provides transparent and interpretable recommendations that improve farmer confidence and support informed decision-making. The proposed framework demonstrates improved energy efficiency, extended network lifetime, efficient resource utilization, and reliable wireless communication compared with conventional IoT-based agricultural systems. Overall, the integration of Ambient IoT and AI-RAN provides a scalable, sustainable, and intelligent solution for precision agriculture, contributing to the development of environmentally friendly and energy-efficient smart farming ecosystems in future AI-native 6G wireless networks.

FUTURE SCOPE

Future research can further enhance the proposed framework by incorporating Integrated Sensing and Communication (ISAC), Reconfigurable Intelligent Surfaces (RIS), and Non-Terrestrial Networks (NTNs) to improve communication coverage in remote agricultural regions. The integration of autonomous drones, agricultural robots, and satellite-assisted monitoring can provide comprehensive field surveillance and precision farming services. Advanced Generative AI models may be employed to generate intelligent crop management recommendations and predictive agricultural insights based on historical and real-time data. Additionally, blockchain technology can be integrated to ensure secure data sharing, traceability, and transparency throughout the agricultural supply chain. Future work may also validate the proposed framework through large-scale real-world deployments across diverse crop types, climatic conditions, and rural environments to evaluate its scalability, reliability, and long-term sustainability in practical 6G smart agriculture applications.

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