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Smart Sensor Networks for Precision Agriculture: Enhancing Crop Yield and Resource Efficiency

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Abstract: Precision agriculture has emerged as a transformative approach to modern farming, enabling efficient resource utilization and enhanced crop productivity through data-driven decision-making. Smart sensor networks, integrated with Internet of Things technologies, provide real-time monitoring of environmental and soil parameters, facilitating targeted agricultural interventions. This study presents a comprehensive framework for the deployment of smart sensor networks in precision agriculture, focusing on improving crop yield and resource efficiency. The system integrates distributed sensors for monitoring soil moisture, temperature, humidity, and nutrient levels, combined with wireless communication and data analytics platforms. Machine learning algorithms are employed to analyze collected data and generate actionable insights for irrigation scheduling, fertilization, and pest management. The results demonstrate significant improvements in water-use efficiency, crop yield, and cost reduction compared to traditional farming methods. The study also addresses challenges related to scalability, energy consumption, and data reliability, highlighting the potential of smart sensor networks to revolutionize agricultural practices and support sustainable development.

Keywords: Precision Agriculture, Smart Sensors, IoT, Crop Yield, Resource Efficiency

1. Introduction

Agriculture is undergoing a paradigm shift driven by technological advancements and the need for sustainable resource management. Traditional farming practices, often characterized by uniform application of inputs such as water and fertilizers, result in inefficiencies and environmental degradation. Precision agriculture aims to address these challenges by leveraging advanced technologies to optimize agricultural practices based on spatial and temporal variability [1].

Smart sensor networks play a central role in precision agriculture by enabling real-time monitoring of environmental and soil conditions. These networks consist of interconnected sensors that collect data on parameters such as soil moisture, temperature, humidity, and nutrient levels. The collected data is transmitted to centralized or distributed processing units, where it is analyzed to support decision-making [2].

The integration of IoT technologies with sensor networks enhances data collection and communication capabilities, enabling seamless connectivity and real-time data sharing. This integration allows farmers to monitor field conditions remotely and make informed decisions, improving productivity and resource efficiency [3].

2. Background and Agricultural Context

Precision agriculture is based on the concept of managing variability within agricultural fields to optimize input use and maximize output. Variability in soil properties, weather conditions, and crop growth patterns necessitates site-specific management practices.

Smart sensor networks provide the data required to understand this variability and implement targeted interventions. For example, soil moisture sensors can identify areas requiring irrigation, while nutrient sensors can guide fertilization strategies. This targeted approach reduces waste and enhances efficiency [4].

Wireless sensor networks enable the deployment of sensors across large agricultural areas, facilitating comprehensive monitoring. These networks rely on communication protocols and energy-efficient designs to ensure reliable operation in remote environments.



3. Literature Review

The application of sensor networks in agriculture has been widely studied, with numerous systems developed for monitoring soil and environmental conditions. Early research focused on standalone sensors with limited connectivity, but advancements in IoT have enabled the development of integrated systems with real-time data transmission [2].

Machine learning techniques have been applied to analyze sensor data and improve decision-making. Algorithms such as decision trees, neural networks, and support vector machines have been used for crop yield prediction and resource optimization [5]. Studies have shown that data-driven approaches can significantly improve agricultural productivity and reduce resource consumption.

Recent research has emphasized the importance of energy efficiency and scalability in sensor networks. Energy harvesting techniques and low-power communication protocols have been developed to extend the operational lifespan of sensor nodes [6].

4. System Architecture and Design

The proposed system architecture consists of three layers: the sensing layer, the communication layer, and the application layer. The sensing layer includes sensors for measuring soil moisture, temperature, humidity, and nutrient levels. These sensors are deployed across the agricultural field to capture spatial variability.

The communication layer uses wireless technologies such as Zigbee, LoRa, and Wi-Fi to transmit data from sensors to processing units. The application layer includes data analytics platforms and user interfaces that provide insights and recommendations to farmers.

The system is designed to be scalable and adaptable, allowing it to be implemented in different agricultural settings. The use of standardized protocols ensures interoperability among different components.

5. Methodology

The methodology involves the deployment of sensor networks in an agricultural field, followed by data collection and analysis. Sensors are installed at strategic locations to capture representative data.

Machine learning models are developed to analyze the data and generate recommendations for irrigation, fertilization, and pest management. The models are trained using historical data and validated using real-time inputs.

Performance metrics such as crop yield, water-use efficiency, and cost savings are used to evaluate the effectiveness of the system.

6. Results and Analysis

The results demonstrate that the use of smart sensor networks significantly improves agricultural outcomes. Water-use efficiency increases due to targeted irrigation based on real-time soil moisture data. Crop yield improves as a result of optimized nutrient management and timely interventions [5].

The system also reduces operational costs by minimizing the use of inputs such as water and fertilizers. The integration of machine learning algorithms enhances decision-making by providing accurate and timely recommendations.

7. Discussion

The findings highlight the potential of smart sensor networks in transforming agricultural practices. The ability to monitor field conditions in real time and implement targeted interventions leads to improved efficiency and sustainability.

However, challenges such as high initial costs, data reliability, and technical complexity must be addressed. Ensuring the accuracy and reliability of sensor data is critical for effective decision-making.

8. Environmental and Economic Implications

The adoption of precision agriculture technologies can significantly reduce environmental impact by minimizing resource wastage and reducing chemical runoff. It also offers economic benefits by improving crop yield and reducing input costs.

The use of smart technologies in agriculture aligns with sustainable development goals and supports the transition to more efficient and environmentally friendly farming practices.

9. Future Scope

Future research should focus on integrating advanced technologies such as artificial intelligence, blockchain, and remote sensing into precision agriculture systems. These technologies can enhance data accuracy, security, and scalability.

The development of cost-effective solutions is essential for promoting adoption among smallholder farmers. Collaboration between researchers, policymakers, and industry stakeholders is crucial for advancing precision agriculture.

10. Conclusion

This study demonstrates the effectiveness of smart sensor networks in enhancing crop yield and resource efficiency in precision agriculture. The integration of IoT and machine learning enables data-driven decision-making, improving productivity and sustainability. The findings highlight the potential of smart technologies to revolutionize agriculture and address global food security challenges.

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