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Smart Agriculture Using IoT: A Comprehensive Review Of Technologies, Applications, And Future Trends

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Abstract: The integration of the Internet of Things (IoT) in agriculture has transformed conventional farming by enabling real-time monitoring, data-driven decision-making, and automation. This research explores the implementation of IoT-based smart agriculture systems aimed at enhancing productivity, optimizing resource utilization, and addressing critical challenges such as water management, soil health monitoring, and crop protection. By utilizing sensors, wireless communication, and cloud computing, these systems offer farmers valuable insights into environmental conditions, facilitating precision farming techniques that enhance yield quality and efficiency.

This paper delves into the architecture of IoT-enabled smart agriculture, emphasizing essential components such as soil moisture sensors, water level sensors, and automated irrigation systems. Additionally, it analyzes the benefits and challenges of adopting IoT in agriculture, including cost considerations, technical barriers, and the necessity for user-friendly solutions tailored to farmers. The study concludes by identifying emerging trends in IoT-driven agriculture and highlighting its potential to promote sustainable farming through advanced technological integration.

Keywords: Automated Irrigation Systems, Environmental Monitoring, IoT in Agriculture, Precision Agriculture, Smart Farming, Sustainable Farming.

I.INTRODUCTION

Since the beginning of human civilization, agriculture has been a vital source of food, economic stability and industrial expansion. However, climate change coupled with population growth, reduced arable land and water scarcity have also contributed to increasing challenges in modern agriculture. In order to meet the projected global population of nearly 10 billion by 2050, food production must almost double. The current situation is dire. Why? Increasing demands reveal the weaknesses of conventional agriculture, which frequently involves manual labor due to unpredictability of the climate and insufficient control of resources. In order to address these challenges, it is crucial to implement intelligent, technology-based measures that increase efficiency and optimize resource utilization while also improving agricultural productivity overall. Agriculture, among other fields, has seen a significant shift towards the IoT in recent years. Why is this so? IoT enables real-time monitoring, data-driven decision-making, and automation to help farmers optimize every step of crop production. Why is this? Through the use of wireless sensors, cloud computing, and machine learning, smart agriculture powered by IoT can obtain precise information on soil moisture levels through a range of techniques, enabling optimal irrigation and reducing waste.[1] Moreover, IoT-based automation reduces the need for manual labor, improves office productivity, lowers costs, and boosts gross output. In agriculture, the use of IoT has led to significant progress in precision farming, greenhouse automation and monitoring crops. IoT-enabled solutions have been shown to reduce water usage by up to 50%, increase crop productivity, and improve soil quality.[2] Real-time soil moisture levels are used in automatic irrigation systems to regulate water supply, which can prevent overwatering and drought stress. Sensor-based pest and disease detection systems can be used as a preventive measure by farmers, which can help reduce crop losses and limit excessive use of pesticides.

In addition, IoT enables drone-based surveillance, smart greenhouses and automated machinery revolutionising traditional farming. ". IoT has its advantages, but there are several obstacles to overcome when implementing it in agriculture. Despite progress, obstacles such as costly implementation, limited rural connectivity, data security risks, and inadequate technical proficiency among farmers persist [4].

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Additionally, a complete shift from conventional farming to intelligent agriculture necessitates robust policy enforcement and infrastructure investment, as well as farmer education. The emergence of new technologies in agriculture is expected to result significantly in IoT-enabled farming, which will have a significant impact on the future of food production.[3] The integration of data analytics, automation, and real-time connectivity will enable farmers to improve efficiency, reduce environmental impact, increase food security, among other improvements.

II.LITERATURE REVIEW

The subsequent part examines significant advancements in IoT-based agriculture, including smart irrigation, soil monitoring techniques, pest control, and farm automation.

A. Evolution of Smart Agriculture

Human labor, past weather patterns, and conventional farming practices are crucial to the efficiency of conventional agricultural practices. Although mechanized farming in the 20th century improved productivity, it was unable to achieve the same level of success. Fig 1. Irrigation with variable rates in Valparaiso, Indiana West Central, IN. Address water loss, soil erosion, and excessive use of fertilizers & pesticides. IoT-based smart agriculture has paved the way for remote sensing, geographic information systems (GIS), and automation to become the foundation of modern agriculture. IoT enabled agriculture to function as a response to real-time monitoring and data-driven decision-making. In their research, Ayaz et al. (2019) highlights the potential of IoT sensors and communication networks to provide farmers with real-time information on soil moisture, temperature, humidity, and pest infestation, resulting in more targeted actions[8]. According to Nayyer & Puri (2016), IoT in smart agriculture can result in reduced manual labor, improved irrigation, and better crop health through predictive analytics[9].

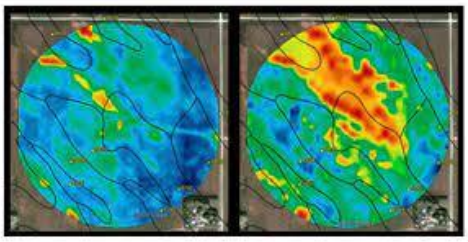

Fig 1 Variable Rate Irrigation Valparaiso Indiana West Central, IN

B. IoT-Based Smart Irrigation

Water shortages are still a major concern for agriculture, with farming being responsible for approximately 70% of global freshwater consumption. The impact of inefficient irrigation systems on crop yields is due to overwatering, water runoff, and soil salinity. This is supported by research. By utilizing IoT technology, smart irrigation systems can manage water distribution by integrating soil moisture sensors, weather data, and automated valves. This is one way to address this issue. Using IoT sensors and AI-based predictive models, smart irrigation systems were found to reduce water consumption by up to 50% while maintaining optimal crop yield in research conducted by Zhang et al. (2018)[10]. In the same way, topography-based water distribution is employed by variable rate irrigation (VRI) systems to ensure efficient irrigation on large farms.

C. Precision Agriculture and Soil Monitoring

The focus of precision agriculture is on site-specific crop management, which involves the collection of precise soil and crop data through sensor networks to optimize fertilizer application, irrigation, and pest control. The use of electrochemical sensors, optical sensors and electromagnetic probes is common in IoT-based soil monitoring systems to monitor soil nutrient levels as well as moisture content and organic matter composition. Elijah et al. (2018) discovered that soil monitoring with IoT could increase fertilizer efficiency by 40%, reducing excessive nitrogen runoff that contributes to environmental degradation.[11] This was reported in a study. Moreover, drones with multispectrum imaging help identify soil deficiencies and nutrients imbalances to deliver targeted interventions.

D. IoT for Pest and Disease Management

strategies are enhanced by IoT. Global crop losses range from 20% to 40% per year due to pest infestations and plant diseases, which are major threats that negatively impact agricultural productivity. The excessive use of chemical pesticides in conventional pest control methods can result in soil contamination, biodiversity loss, and human health issues. The use of wireless sensors, machine learning, and remote sensing technologies enables IoT-based pest management systems to anticipate pest activity and disease outbreaks. This is the future of agriculture.

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Pest and disease detection in agriculture is being revolutionized by the use of image recognition technology in artificial intelligence in fig 2. Through the use of machine learning algorithms and computer vision, AI-enabled systems can analyze images of crops to identify early signs of infestations and diseases. Through this method, farmers can quickly implement preventative measures that minimize crop losses and reduce excessive use of pesticides. Enhanced efficiency, improved yield quality and sustainability are the primary benefits of using AI for precision farming.

Fig 2 AI in Agriculture: Enhancing Pest and Disease Detection with Image Recognition

In Smart Agriculture in 2022, a comprehensive survey on the future of IoT technologies is conducted to identify emerging IOT applications that fall under various categories such as smart monitoring, water management and irrigated systems, smart harvesting and supply chain management, among others. Additionally, the article covers topics such as supply chain management using blockchain and explores potential research challenges and future possibilities. Furthermore? IEEE Journal of Automation Science[1].

This paper examines the features, protocols, technologies, security, interoperability, accessibility, and resilience of smart farming architectures that are based on IoT technology in 2022. The advantages and disadvantages of each approach are discussed, along with information on the current state of IoT architectures in the agricultural sector. ACM Digital Library.[2]

In this systematic review of 1,355 publications covering over two decades, the main barriers to IoT adoption in agriculture are cost (cost), skills (skills), and standardization (through 2022). Furthermore, it investigates connectivity and data management issues, providing practical solutions to technical and organizational problems in the field. Emerald.[3]

In 2022, a survey was conducted on the challenges and progress of IoT technology in smart agriculture, with emphasis on sensors as well as key technologies such as sensors, software, hardware. The paper addresses security and other issues, offering directions on how to tackle research challenges in smart agriculture. ScienceDirect[4].

A survey conducted in 2022 on the design of smart agriculture systems using IoT highlights the core framework for current and future agricultural development. The main components of IoT agricultural systems, such as hardware, software, and data processing components, are examined in the paper, which also explores potential problems and solutions. ScienceDirect[5].

In Smart and Sustainable Agriculture (2023), a comprehensive review of IoT technologies for agriculture is conducted to compare different sensors, controllers, communication standards, and intelligent machinery. This report highlights the importance of these technologies in smart and sustainable agriculture. Detailed analysis of data, IoT-based agricultural automation cases, and the major issues and obstacles in agriculture technology are discussed. ScienceDirect[4].

This study examines the architecture, applications, and research timeline of IoT solutions in smart agriculture. It identifies opportunities, gaps, and loopholes in the agriculture industry to enhance productivity and quality while also advocating for sustainability.' MDPI[7].

E. Automation in Agriculture

Automation in farming has progressed from mechanized ploughing and harvests to the development of autonomous tractors, robotic weeders, and AI-controlled greenhouses. Mahindra, John Deere and Case IH (Sweden's former USP) and New Holland are among the major producers of agricultural equipment that have developed autonomous tractors equipped with GPS navigation technology, LiDAR-based object detection and real-time monitoring. According to Sisinni et al. (2018), the implementation of IoT and automation in agricultural products can improve productivity, decrease operational expenses, and lessen the need for manual labor[10]. Furthermore, some of the pictured harvesting systems employ robotics has demonstrated strong promise to reduce post-return income and labour stress. "

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Fig.3 Strawberry-picking robot

Fig.4 Automatic Fruit Picker

F. Challenges in IoT-Based Smart Agriculture

Despite its numerous benefits, IoT adoption in agriculture faces several challenges[4] that hinder widespread implementation. Key barriers include:

- High Initial Costs: Setting up IoT infrastructure, including sensor networks, automated irrigation systems, and cloud storage, requires significant investment, making it less accessible for small-scale farmers[9].
- Connectivity Issues: Many agricultural regions, especially in developing countries, lack high-speed internet and robust network infrastructure, limiting the effectiveness of IoT-based solutions.
- Data Security & Privacy: With vast amounts of sensor-generated data being stored and processed, concerns regarding cybersecurity, unauthorized access, and data privacy are growing.[7]
- Farmer Education & Training: The complexity of IoT technology necessitates training programs and user-friendly interfaces to ensure farmers can effectively utilize these advanced systems.

G. Prospects of IoT in Agriculture

As 5G connectivity, edge computing, and AI-driven analytics continue to advance, the potential of IoT in agriculture is expected to expand significantly. Future developments may include:

- Blockchain-based farm management systems for secure and transparent data sharing.
- AI-powered autonomous drones for large-scale field monitoring and precision spraying.
- Smart greenhouses with AI-driven climate control systems to optimize crop growth conditions.
- Integration of IoT with renewable energy sources, such as solar-powered irrigation systems, to enhance sustainability.

As IoT technologies become more affordable, scalable, and accessible, their integration into global agriculture will play a pivotal role in enhancing food security, reducing environmental impact, and driving sustainable farming practices[1].

III.METHODOLOGY

A. Data Collection and Preprocessing

In this research, a dataset was created to simulate two farming scenarios:
1. Without IoT – Traditional farming methods with manual irrigation, fertilization, and pest control.
2. With IoT – Smart agriculture using real-time data from soil, weather, and crop health sensors for optimized decision-making.

The dataset includes parameters such as:

- Soil Properties: Moisture (%), pH level, temperature (°C).
- Weather Conditions: Humidity (%), rainfall (mm).

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- Resource Usage: Water (L), fertilizer (kg), pesticide (ml).
- Economic Factors: Labor cost ($ per hectare).

A total of 100 data samples were generated, with 50 representing traditional farming and 50 using IoT-based precision farming. The dataset was split into 80% training and 20% testing for model evaluation.

B. Model Selection and Implementation

The model used is Random Forest Regressor from the scikit-learn library in python due to its ability to handle non-linear relationships well, making it suitable for complex agricultural data. It identifies key yield-influencing features through importance analysis and reduces overfitting by combining multiple decision trees. Additionally, it also performs efficiently on small to medium-sized structured datasets, ensuring stability and robustness.

1) Training the Model

- Input features: Soil, weather, resource usage, and labour cost.
- Output variable: Crop yield (kg/ha).
- Algorithm: Random Forest Regressor with 100 estimators (n_estimators = 100).
- Data split: 80% training, 20% testing.

2) Model Evaluation

- The model was tested using Mean Squared Error (MSE) and R^2 Score:
- MSE = 24,842.33
- R^2 Score = 0.86 (86% variance explained by the model).

3) Model Details

- Algorithm: Random Forest Regression
- Library: sklearn.ensemble.RandomForestRegressor
- Number of Trees (Estimators): 100
- Random State: 42 (for reproducibility)
- Train-Test Split: 80% training, 20% testing

C. Comparative Analysis: Without IoT vs. With IoT

The trained model was used to predict crop yield under both farming conditions, demonstrating improvements in yield, cost savings, and environmental sustainability.

D. Visualization and Insights

To better illustrate the impact of IoT-based farming, a comparative bar graph was generated using Matplotlib. Orange bars represent traditional farming (Without IoT) & the blue bars represent IoT-based smart farming (With IoT). Each bar is annotated with percentage improvement values. The graph clearly shows higher crop yield and lower resource consumption with IoT implementation.

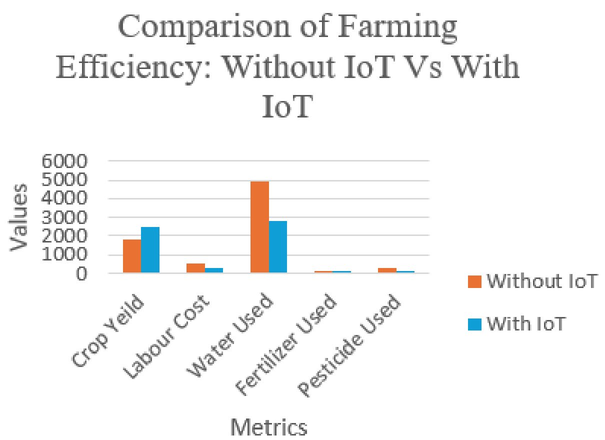

Fig 6 Comparison of Farming without IoT Vs with IoT

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IV.RESULTS

The model confirms that IoT-driven precision farming significantly enhances crop yield while reducing costs and environmental impact.

The findings demonstrate that IoT-based agriculture can:

- Increase crop yield by ~48% through optimized resource allocation.
- Reduce labour costs by ~43% via automation and precise intervention.
- Enhance environmental sustainability by minimizing water, fertilizer, and pesticide use.

These results align with global trends where IoT adoption in agriculture enhances sustainability and productivity. The reduction in resource consumption supports environmental conservation, while cost savings improve farm profitability. However, challenges remain, including high initial IoT infrastructure costs, the need for technical training among farmers, and reliable internet connectivity in rural areas.

In conclusion, IoT integration in agriculture presents a compelling case for modernizing farming practices. By improving yield, reducing costs, and promoting sustainable resource use, IoT technologies address critical challenges in food security and environmental stewardship. Policymakers and agricultural stakeholders should consider incentivizing IoT adoption to accelerate its benefits across the farming sector.

V.CONCLUSION

In conclusion, IoT integration in agriculture presents a compelling case for modernizing farming practices. By improving yield, reducing costs, and promoting sustainable resource use, IoT technologies address critical challenges in food security and environmental stewardship. However, challenges remain, including high initial IoT infrastructure costs, the need for technical training among farmers, and reliable internet connectivity in rural areas. Policymakers and agricultural stakeholders should consider incentivizing IoT adoption to accelerate its benefits across the farming sector.

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