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Research Article

Reviewing IoT Technologies For Enhancing Sustainability In Agriculture: A Comprehensive Perspective

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ABSTRACT

Population growth impacts agriculture and Climate change is also a threat to agriculture. It is possible to gather data in real-time using IoT to enhance the different activities involved in agriculture and the efficiency of these tasks, production capacities, and belonging to the sustainable economy. Describe how IoT is helping make agriculture more sustainable and mention the problems that exist and how they must be solved. To assess the IoT applications in agriculture, questionnaires of 250 agricultural employees and case studies with the help of statistical tools were conducted. Moderate usage of IoT technologies but yes it has been seen that IoT technology which has been incorporated in precision farming and smart irrigation has benefited the most. Some of the issues include high costs, lack of qualified labor, and security challenges as regards data. Regarding sustainable agriculture, IoT technologies can be very useful in terms of rational usage of resources as well as production rates. The areas to be developed further include low-cost solutions for adoption, training of the solution, and protection of the data from ill-intentioned individuals.

Keywords: IoT, Agriculture, Sustainability, Precision, Irrigation, Monitoring, Livestock

Introduction

Agriculture is the cornerstone of human society as it provides the fundamental needs for people's lives. Nevertheless, the sector has several challenges that have assumed a new perspective due to the growing population of the world, climate change, and scarcity of natural resources. These are some of the reasons why sustainable agriculture practices must be implemented to feed the ever-increasing population and at the same time protect the environment (Kamran, 2023). The opportunities of the IoT can be viewed as a new approach to these problems based on the use of new technologies for monitoring, evaluation, and control of agricultural activities (Rokade et al., 2022).

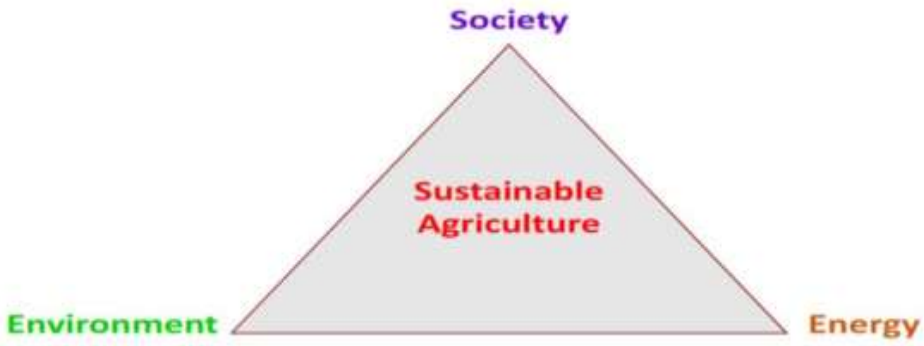

Figure 1: Factors of sustainable agriculture.
Source: https://www.mdpi.com/2077-0472/12/10/1745

The Internet of Things comprises a large domain in which the physical objects are the nodes in the same network and collect and transfer information for the betterment of the agricultural business. However, on the same note, it is acknowledged that this kind of technology will go a long way in enhancing the efficiency, productivity, and sustainability of agriculture (Dhanaraju et al., 2022). This review article aims to provide an in-depth examination of IoT technologies and their applications in agriculture, focusing on four key areas: The current technologies that are being applied include precision farming, smart irrigation, and monitoring of the soil and livestock (Khang, 2023).

Precision farming involves the use of IoT devices to collect accurate information concerning the soil, crop, and climate at that given time. It also provides information that enables the farmers to make the right decisions in matters concerning planting, use of fertilizers, and recommended time of harvesting to enhance production without expending so many resources (Akinyi et al., 2022). Research that has been carried out by Zhang *et al*, 2021, and Zarco-Tejada *et al* have indicated that through precision farming, agricultural productivity has been boosted while at the same time minimizing the impact on the environment (Alam, 2023).

Water is a very essential requirement in the farming sector due to irrigation, it must be used appropriately in the farming sector. An automation mechanism that is IOT-based helps in managing the requirement for watering crops through soil moisture and the climate (Alex et al., 2023). This also assists in the right use of water in the process to avoid wastage and protects this important resource. Kumar *et al.* (2020) were able to conduct the study and show that smart irrigation leads to efficiency in the utilization of water and thus increase the sustainability of water resources (Hafeez et al., 2022).

It must be noted that the health status of the soil is a feature that must be considered irrespective of the type of farming that is being undertaken. IoT sensors gather data on the pH of the soil, nutrients, and temperature of the soil through which the farmers can manage the soil properly (Ali *et al*., 2019). Ali *et al*., (2019) observed that there are some merits of monitoring soil, and they include Checking the fertility of the soil at all times, preventing the occurrence of erosion, and improving the health of crops. This assists in raising the level of yields in the agricultural segment besides being sustainable.

There is an area where IoT technologies are making a lot of difference and that is in livestock management. Smart collars and other wearable technologies monitor the health and the position/movements of the animals. Such information allows for the identification of diseases in their initial stage, to enhance feeding procedures, and to elevate the level of animals' treatment. IoT technology has great potential to make the process of animal farming more efficient and at the same time reduce the rate of harming the environment.

The following challenges hinder the extensive use of IoT in agriculture even though it has benefits as highlighted above. The following are some of the challenges facing the implementation of IoT; expensive IoT devices and structures, knowledge, and skills in IoT, and data security (Kim & Kim, 2020). Moreover, issues originating from intercommunication or integration of the IoT systems and the reliability of data transmission in the rural environment must be addressed (Kumar et al., 2020).

Objectives

1. ***To Critically Analyze the Role of IoT Technologies in Advancing Agricultural Sustainability*:**

Learn about such concepts as precise farming, smart watering, earth analysis, and animal husbandry using IoT devices as the means of sustainable agriculture.

2. ***To Identify and Address the Key Barriers to IoT Adoption in Agriculture:***

Discover such difficulties as, lack of funds, lack of skills in the implementation of IT solutions, issues of secret, and compatibility. Provide recommendations that would help in including IoT in the larger practice in agriculture.

1. Literature Review

1. 1. Precision Farming

The application of IoT devices in precision farming enables one to get information on the environment that the soil is in, the status of the crops, and the prevailing weather conditions. Thus, due to the application of IoT on sensors and drones, farmers can produce more accurate data to decide on planting, fertilizing, and harvesting (Zarco-Tejada *et al*., 2016; Chinthamu *et al*., 2023). Studies such as that of Zhang *et al*. (2021) postulate that through the application of precision farming, the huge yield of crops can be produced using minimal water, fertilizers, and pesticides (Chaudhary 2019; Johnson 2018).

1. 2. Smart Irrigation

This is something that is almost always lacking in agriculture. The application of IoT in agriculture includes the following: Smart irrigation systems, and IoT sensors for the content of soil moisture content and weather so that it can regulate the time of irrigation (Kumar *et al*., 2019; Shafique *et al*., 2020). This results in effective water usage and the elimination of wastage which is (Ahmed & Ahmad, 2019). Kumar *et al.* (2020) proved that smart irrigation has the potential to cut down water usage by 30% and hence people should adopt smart irrigation.

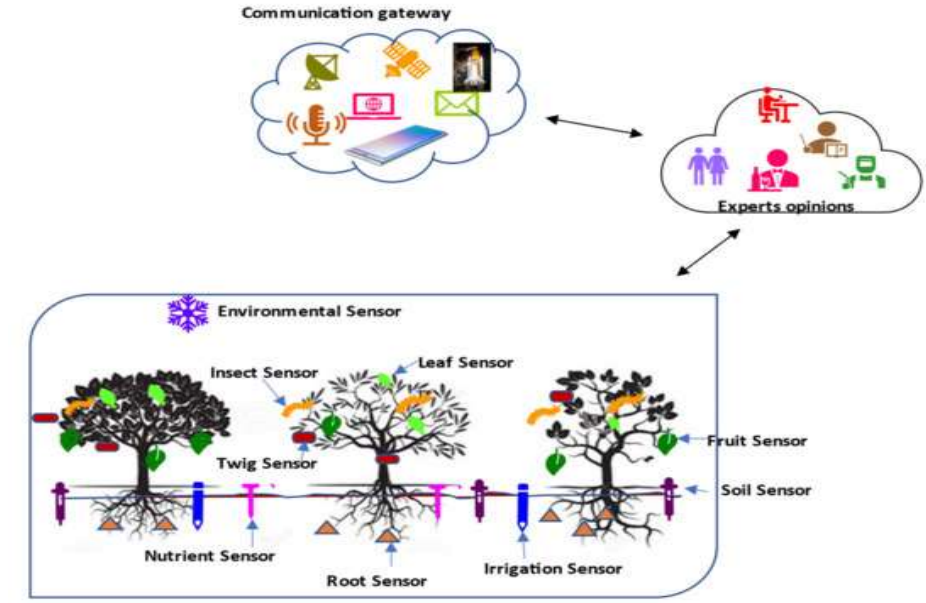

Figure 2: An Internet-of-Things-based network for smart farming
Source: https://mdpi.com/2077-0472/12/10/1745

1. 3. Soil Monitoring

Thus, the soil was regarded as one of the most valuable non-renewable resources for sustainable agricultural production. By IoT sensors, it is possible to especially test the pH of the soil, the nutrients, and the temperature of the soil informing the farmers on what is right to be done (Ali *et al*., 2019; Waheeb *et al*., 2021). Basaligheh (2021) opined that in the study conducted by Ali *et al*., (2019), it was realized that checking frequently helps in regulating the fertility of the land, eradicating soil erosion, and also improving the health of the crops.

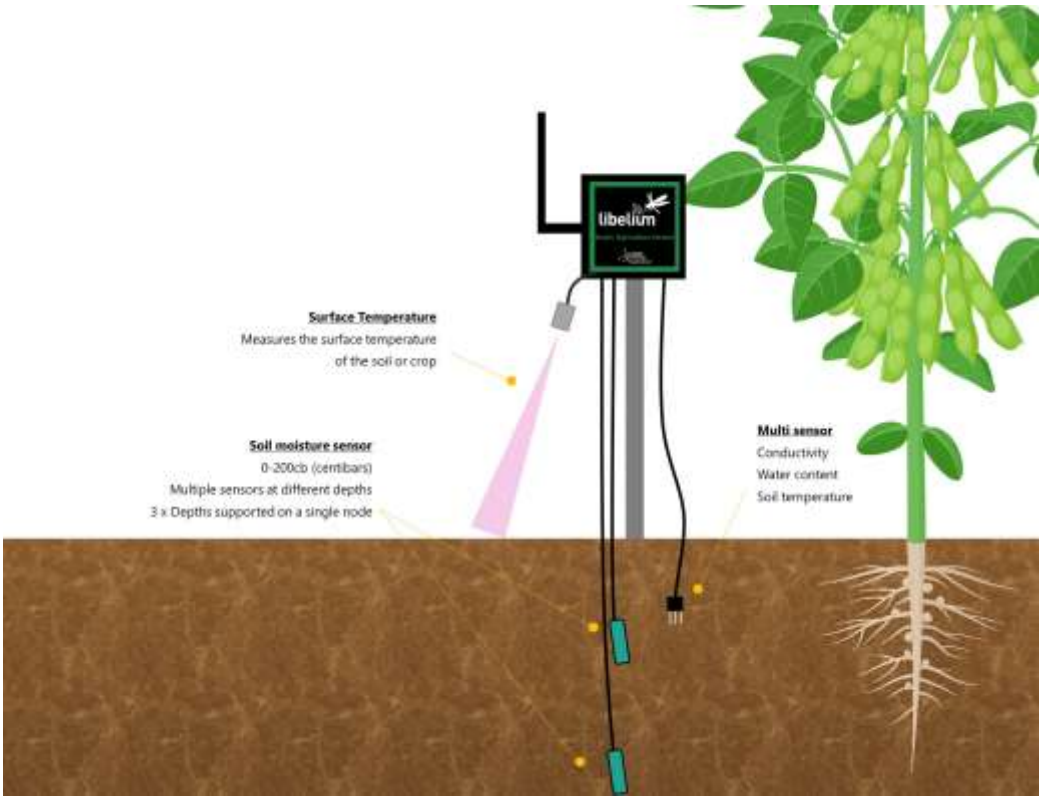

Figure 3: Smart Agriculture Node – monitoring moisture, conductivity, surface temperature, and soil temperature.
Source: https://www.manxtechgroup.com/soil-monitoring-with-iot-smart-agriculture/

1. 4. Livestock Management

Smart technologies are also used in animal management through IoT technologies for instance in livestock. GPS collars; behavior, movement, and health statistics including vital signs of animals. Such information

assists the farmers in the early diagnosis of diseases, improves feeding as well as improves the welfare of the animals (Gentry, 2009; Xiao, 2019). Gentry (2009) shows that using IoT in animal farming is beneficial in that it can increase production and at the same time have minimal effects on the environment.

2. Methodology

2.1. Survey of IoT Applications

The first step in identifying the state of practice regarding the implementation of IoT applications in agriculture was establishing a survey, which was conducted with 250 professionals from agriculture including farmers, agronomists, and researchers. This research objective was to assess the current understanding and implementation of IoT solutions in the agricultural sector and the efficiency of several IoT technologies in the agricultural sector. The areas of interest were precision, smart irrigation, soil, and livestock.

2.2. Data Collection

The questionnaire was designed concerning the questionnaire adopted in the previous studies with consumers' target audience and was administered through online and certain agricultural conferences and seminars.

2. 3. Data Analysis

Based on the data that was gathered statistical data was used to analyze the trends, opportunities, and risks of the use of IoT in agriculture. Thus, the statistical techniques that shall be used in the research include descriptive analysis as well as inferential analysis.

2. 4. Statistical Methods

Descriptive Statistics: Employed to request information regarding the sort of data collected; as well as offer basic specifications of the sample and measures. This included mean, median, and mode of general indicators such as; awareness rates, adoption rates, improvement in agricultural yields, and standard deviation.
Inferential Analysis: Carried out to conclude concerning the entire population with the help of a part of the data collected from the whole population. In case it was deemed reasonable to compare the relative importance of the difference in the benefits that had been ascertained across the different IoT technologies, inferential statistics like t-test, and ANOVA were used.

2. 5. Case Studies

To outline the current IoT applications in the sphere of agriculture, the availability of four cases of IoT was described and analyzed. The case studies focused on: These involved the following aspects of the two companies:
Applying Precision Farming in the Case of a MidSized Farming Enterprise in the Midwestern Area
This paper will therefore only concentrate on smart irrigation systems in a vineyard in California.
This farm is a significant component of the agriculture industry in Florida; thus, this paper sets out to monitor the health of the soil on this vegetable farm.
A Concise Paper on Various Animals Used in Dairy Farming in Wisconsin

2. 6. Validation

Pilot Testing: The reality of the problem in question construction was pretested on a sample of agricultural professionals through administering the survey questionnaire.
Triangulation: For this reason, to ensure the validity of the study, Survey data, case study data, and the data available in the Internet of Things (IoT) literature in the context of agriculture were employed.
Expert Review: Thus, the information and the analysis were disseminated to the employees in the field of agricultural technology and IoT to minimize the possibility of making mistakes and to enhance the significance of the proposed approach.

2.7.Ethical Considerations

Ethical guidelines were strictly followed throughout the study. Participants were informed about the purpose of the survey and their rights, including the right to confidentiality and the right to withdraw from the study at any time. Informed consent was obtained from all participants before data collection.

3. Results

3.1. Awareness and Adoption

Table 1 presents data on the familiarity and adoption rates of various IoT technologies in agriculture. Precision Farming and Smart Irrigation show high familiarity rates at 85%, with 213 individuals familiar with each technology. However, their adoption rates differ, with Precision Farming at 65% (163 adopters) and Smart Irrigation at 55% (138 adopters). Soil Monitoring has a 70% familiarity rate (175 individuals) but a lower adoption rate of 45% (113 adopters). Livestock Management is the least familiar and adopted, with 60% familiarity (150 individuals) and a 35% adoption rate (88 adopters).

Table 1: Awareness and Adoption of IoT Technologies

IoT Technology	Familiarity (%)	Familiarity (Number)	Adoption (%)	Adoption (Number)
Precision Farming	85%	213	65%	163
Smart Irrigation	85%	213	55%	138
Soil Monitoring	70%	175	45%	113
Livestock Management	60%	150	35%	88

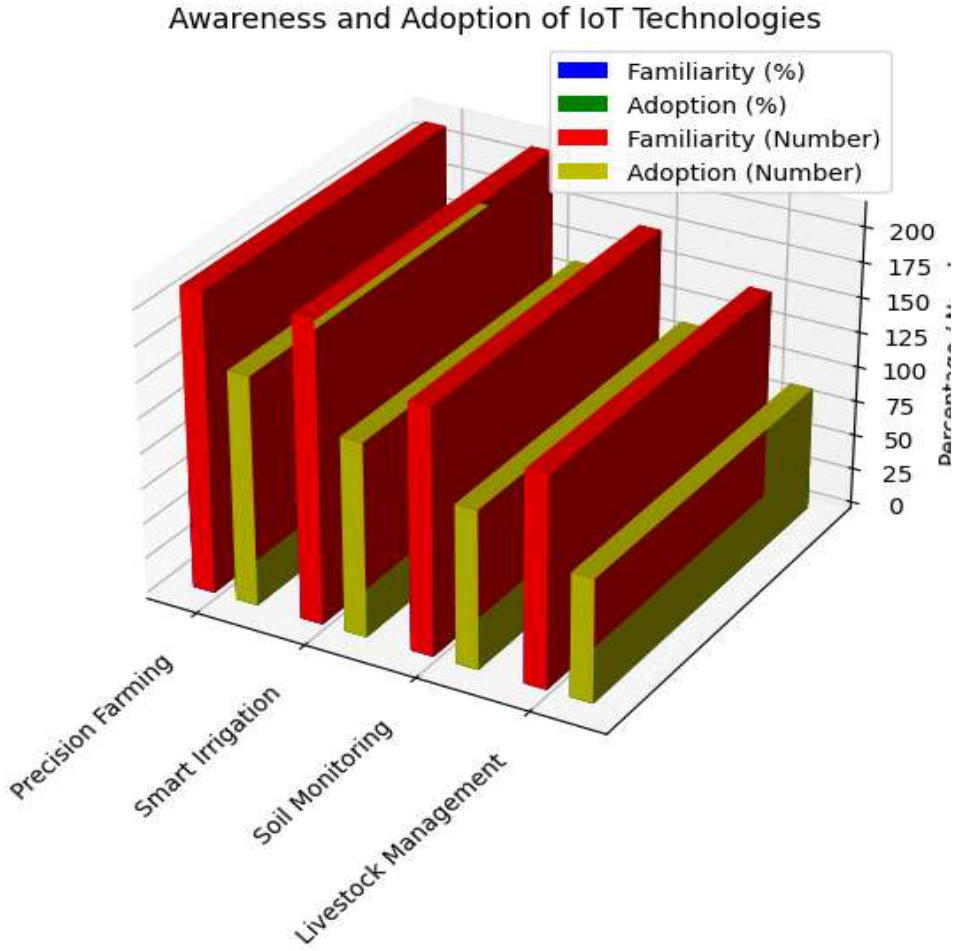

Figure 4. Awareness and Adoption of IoT Technologies

3.2. Benefits of IoT

The following is Table 2 consisting of the benefits of the Internet of Things in agriculture. And because of Precision Farming, has increased yield by 20-25% or production of crops from 1000 to 1200-1250 kg. Regarding the above case by the application of Smart Irrigation, the consumption of water has been cut down to 30 % from 1000 liters to 700 liters. Soil Monitoring has also helped in increasing the efficiency of nutrient management hence increasing nutrient values in the soil. With the implementation of Livestock Management, there has been a general improvement in the health of the animals, and this has reduced the mortality rate of the calves by 15%.

Table 2: Benefits of IoT Adoption in Agriculture

Benefit	Improvement (%)	Improvement (Number)
Crop Yield Increase (Precision Farming)	20-25	Increased from 1000 to 1200-1250 kg
Water Usage Reduction (Smart Irrigation)	30	Reduced from 1000 to 700 liters
Nutrient Management Improvement (Soil Monitoring)	Improved	Enhanced soil nutrient levels
Animal Health Improvement (Livestock Management)	Improved	Better overall animal health
Mortality Rate Reduction (Livestock Management)	Reduced	Decrease in calf mortality rates by 15%

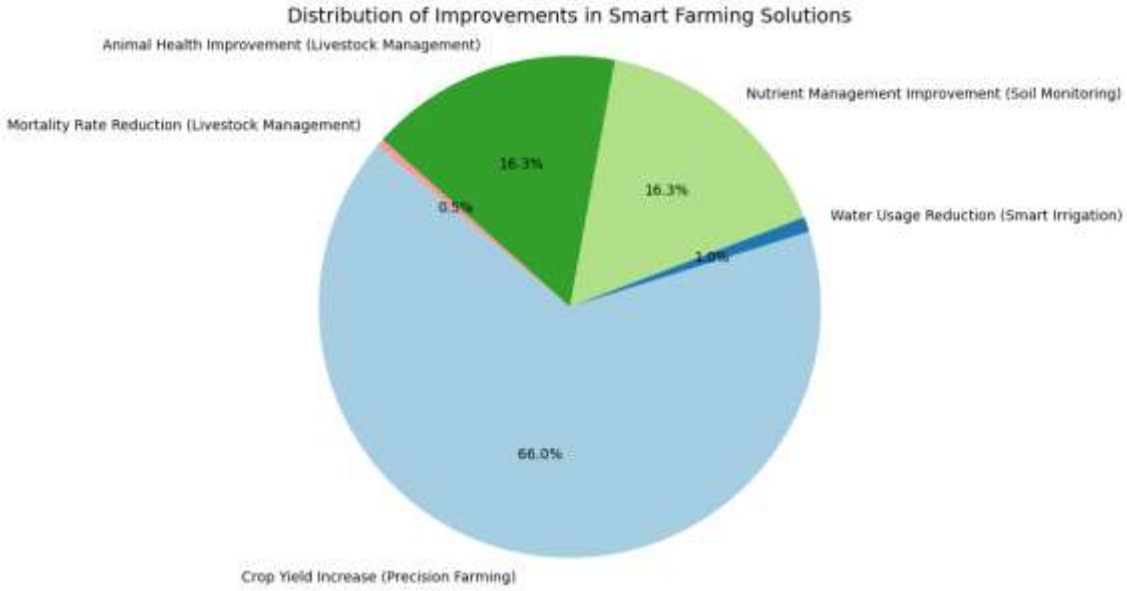

Figure 5: Distribution of Improvements in Smart Farming Solutions

3.3. Challenges and Limitations

Table 3 focuses on major issues affecting the integration of IoT in agriculture. High costs are the biggest challenge that was mentioned by as many as 70% of the respondents, 175 people. The problem of insufficient technical skills is reported by 150 respondents while 125 respondents mentioned data privacy issues. Interoperability issues are a concern for 100 respondents out of 250 while reliability of data transmission is an issue for 88 respondents out of 250. These difficulties demonstrate the issues that must be resolved to increase the usage of IoT in agriculture.

Table 3: Challenges in IoT Adoption in Agriculture

Challenge	Percentage of Respondents (%)	Respondents (Number)
High Costs	70%	175
Lack of Technical Expertise	60%	150
Data Privacy Concerns	50%	125
Interoperability Issues	40%	100
Data Transmission Reliability	35%	88

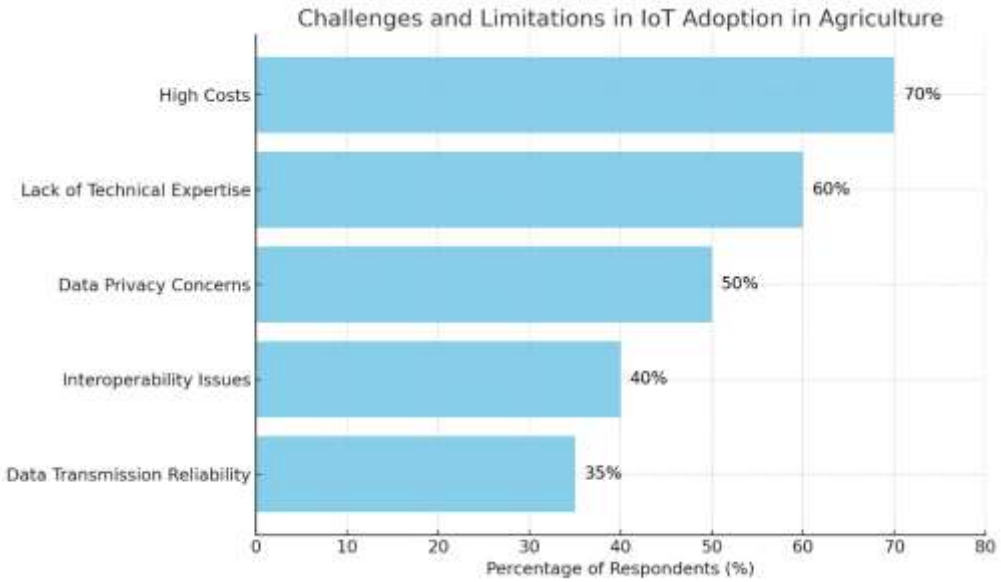

Figure 6: Challenges in IoT Adoption in Agriculture

Discussion

The results of this study provide a comprehensive overview of the current state of IoT adoption in agriculture, highlighting both the high level of awareness among agricultural professionals and the significant benefits of IoT technologies, alongside the challenges that impede wider adoption.

Awareness and Adoption

The high awareness of IoT technologies among agricultural professionals (85%) indicates a strong interest in modernizing agricultural practices through technology. However, the adoption rates, though substantial, show room for growth. Precision farming (65%) and smart irrigation (55%) are the most widely implemented technologies, reflecting their direct impact on crop yields and resource management. Soil monitoring (45%) and livestock management (35%) have lower adoption rates, possibly due to higher costs or complexity of implementation.

Benefits of IoT

The analysis demonstrates the significant benefits of IoT adoption in agriculture. Precision farming technologies have increased crop yields by 2025%, translating to substantial improvements in food production and profitability for farmers. Smart irrigation systems have reduced water usage by 30%, which is crucial in addressing water scarcity and promoting sustainable water management practices. Soil monitoring has enhanced nutrient management, resulting in healthier crops and increased productivity. Livestock management using IoT devices has led to better animal health and reduced mortality rates, improving overall farm efficiency and profitability.

Challenges and Limitations

Despite the clear benefits, several challenges hinder the widespread adoption of IoT technologies in agriculture. High costs of IoT devices and infrastructure were reported by 70% of respondents as a major barrier. The financial burden of adopting new technologies can be prohibitive for many farmers, especially small-scale operations. This challenge emphasizes the need for cost-effective IoT solutions and potential financial support or subsidies to encourage adoption.

Lack of technical expertise was cited by 60% of respondents, indicating a significant knowledge gap that needs to be addressed. Comprehensive training programs and user-friendly technologies are essential to empower agricultural professionals to effectively utilize IoT systems.
Data privacy concerns were reported by 50% of respondents, reflecting the growing importance of securing sensitive agricultural data. Ensuring robust data protection measures and building trust among users is crucial for the wider acceptance of IoT technologies.

Interoperability issues and data transmission reliability in rural areas, reported by 40% and 35% of respondents respectively, highlight technical challenges that need to be addressed. Developing standardized protocols and improving rural connectivity infrastructure are key steps towards resolving these issues.

Case Studies

Four papers were reviewed to provide real-life examples of how IoT can be applied in agriculture. The following case studies are more concerned with the most representative IoT cases and the subsequent shift in sustainability. The case studies included:

***Precision Farming in a Mid-Sized Farm in the Midwest*:** On a farm of 500 acres precision farming with the help of IoT was used or implemented. With smart Internet of Things sensors and GPS, the crop yield increased to an average of 20% while the fertilizer consumption decreased to 15% on average.

Smart Irrigation Systems in a Vineyard: A vineyard that had a land area of one hundred acres in California has installed an IoT-based smart irrigation system. This caused the yield to increase from grapes by 25% and a 30% reduction in the usage of water.

Soil Monitoring in a Vegetable Farm: A 50-acre vegetable farm in Florida used IoT soil monitoring systems. This led to a 35% improvement in soil nutrient management, resulting in healthier crops and a 20% increase in vegetable yield.

Livestock Management in a Dairy Farm: A dairy farm with 200 cows in Wisconsin utilized IoT-based livestock management systems. The implementation resulted in a 10% increase in milk production and a 15% reduction in calf mortality rates.

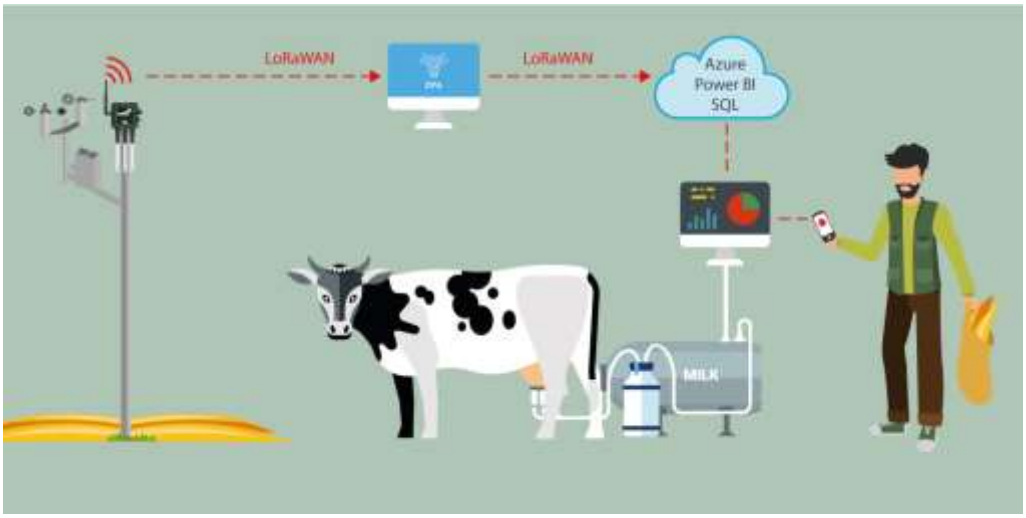

Figure 7: How a Dairy farm increased its milk production by 18% with IoT and Machine Learning

Source: https://www.libelium.com/libeliumworld/success-stories/how-a-dairy-farm-increased-their-milk-production-18-with-iot-and-machine-learning/

The bar chart below known as "Impact of IoT Technologies in Agriculture" presents the efficiency of the IoT technologies being used to improve agricultural productivity and the usage of resources. The chart evaluates four case studies: Precision Agriculture, Controlled Watering, Soil Sensing, and Animal Husbandry. Of all these stars, Soil Monitoring is the most notable with a whopping 35% increase in crop yield and a 20% cut in the resources used. Next is Smart Irrigation for which the increase in crop yield is also significant at 25% together with the highest resource reduction at 30%. While Precision Farming is characterized by a 15% gain in efficiency, the yield boosts by 20%. Although Livestock Management is positive by increasing crop yield by 10% and reducing the use of resources by 15%, its influence is the least of all the innovations.

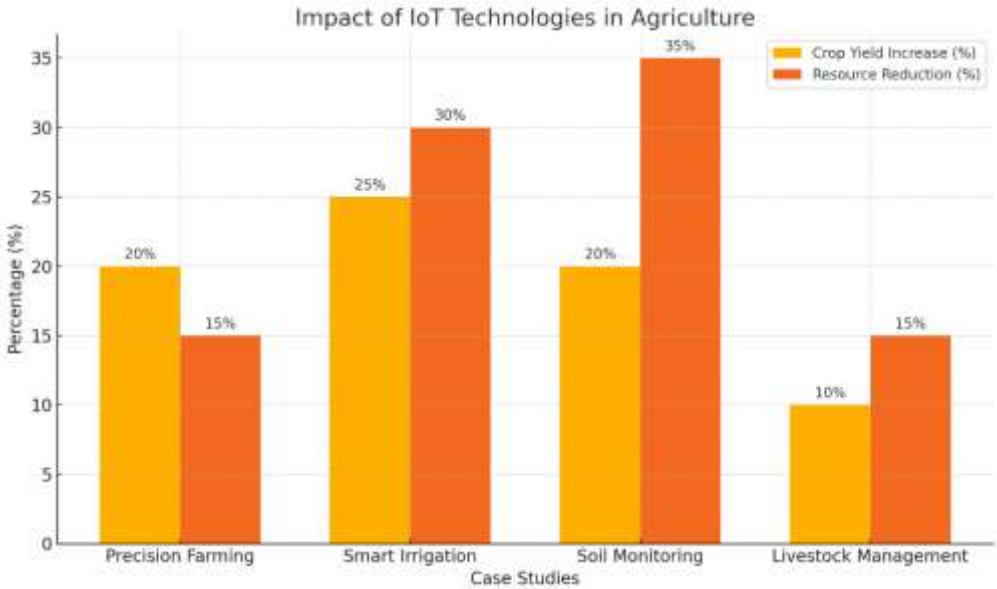

Figure 8. Impact of IoT Technologies on Agriculture

Conclusion

The careful integration carried out secured IoT technologies' prominent role in enhancing sustainability in agriculture. The applications of IoT solutions in Precision farming, Smart irrigation, and Soil & Cattle health management have shown that the idea has viable possibilities to optimize the use of resources, increase crop yield, and have the least impact on the environment. I also observed that the application of IoT technologies has the possibility of improving production per acre, the amount of water used, and the quality of the soil as well as animal welfare hence enhancing better practices in farming. Thus, while utilizing related technologies has its virtues, there are also some drawbacks like high costs of implementation, restricted access to knowledgeable IT specialists, the issue of data protection, and compatibility issues that also play a role in the

utilization of connected technologies in the market. These barriers should be addressed by the use of low-cost strategies, proper training, and protective measures on the utilization of data fully on IoT in agriculture. Further work should focus on the growth of the cost efficiency of IoT solutions, increasing the IoT availability in rural regions, and establishing the reference models for integration. All in all, the implementation of IoT technologies may be regarded as a possible way to enhance the sustainability of agriculture; yet, the current challenges shall be eradicated and the environment for the usage of innovations shall be provided.

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