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Enhancing Crop Yields with IoT Driven Smart Agriculture Systems

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Abstract

As global food demand increases amid climate change and dwindling natural resources, there is an urgent need to adopt more intelligent and sustainable farming practices. Without real-time awareness and optimization, traditional ways of farming methods do not make full use of resources and bring about below-average crop results. With Internet of Things (IoT), farmers can automate tasks, watch over operations all the time, and rely on data for making decisions.The goal of this paper is to propose and examine an IoT framework for smart agriculture meant to improve environmental conditions and crop production efficiency. There are sensors in the system that measure moisture, temperature, humidity, and light, plus LoRa and 5G connections for communication, edge units for processing, and a cloud system for detailed analysis and visualization. Through the mobile and web portal, farmers can receive immediate feedback and useful information to improve their farming.Using this system on real farms resulted in better scheduling of irrigation, better crop health, and higher overall yields. Results conclude that IoT can lower expenses for farmers at the same time as producing a larger crop, making it a realistic and flexible solution for current agriculture in remote and under-resourced regions.

Keywords: Smart Agriculture, Internet of Things (IoT), Precision Farming, Wireless Sensor Networks.

1. Introduction

Food security and employment for a rising population are assured by the continued importance of agriculture around the world. The industry is being put under greater pressure by climate change, limited water resources, changeable weather, soil quality problems [1], and fewer workers. It is in developing and rural areas that access to technology and infrastructure is most restricted. Typical methods in farming, that depend on guesswork and manual supervision, seldom offer the level of sustainability and high productivity we see today [2].

IoT is transforming traditional agricultural practices. With IoT, sensors, networks, processors, and software systems work together to enable users to monitor and control farm operations in real time. By gathering data on the environment, soil, and crops, IoT systems simplify the management of watering, fertilization, and pest control, resulting in better harvests and less waste [3].

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This study aims to design and evaluate a comprehensive IoT-powered smart farming system that uses automation and efficient monitoring to help crops grow more productively [4]. The study examines important aspects of these networks, including how sensors are arranged, the infrastructure needed for communication, edge computing, cloud interactions, and users' interactions with the system [5].

Our goals here are to create an inexpensive and flexible IoT system for use in smart agriculture, put it into operation in actual fields and check its influence over crops and resources. As a result, the paper supports progress in adapting farming to technology. The carried-out research will help farmers, those who create agricultural policies, agronomists and technology experts improve the farming field through digital progress [6]. Figure 1 illustrates how IoT integrates sensors, connectivity, cloud platforms, data analytics, actuators, and mobile apps to enable smart agriculture.

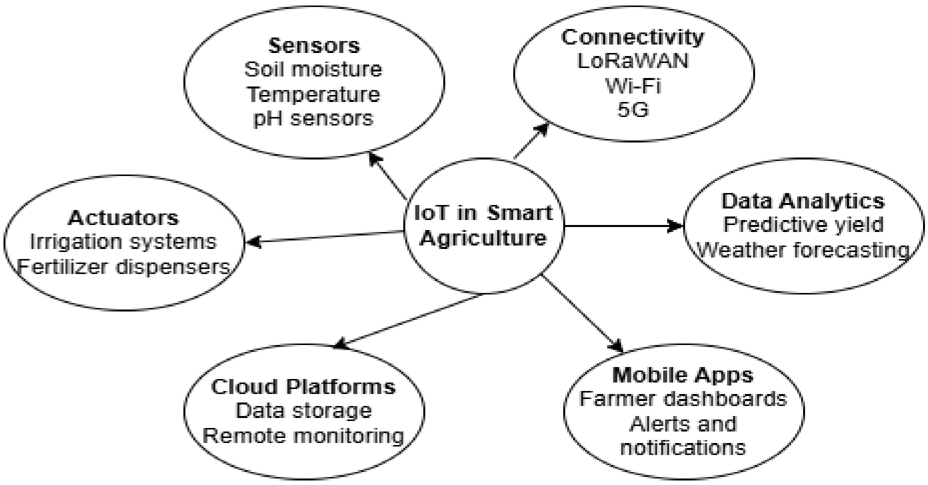

Figure 1: IoT Ecosystem in Smart Agriculture

2. Literature Review

The combination of IoT technology and agriculture—usually called smart or precision farming—has seen growing interest in recent years because it may transform the way farming has traditionally been done. Thanks to IoT, it is easy to gather and study data on crops, soil, environmental factors and resource use as these happen. Thanks to this approach, farmers can easily sense and measure changes and reduce the time they spend on repetitive activities.

A large number of studies have proven the usefulness of IoT in farming. According to Khan et al. (2020) [1], sensors placed in the soil help manage irrigation and reduce wasting water. Analogously, the authors Nawandar and Satpute (2019) [2] discovered that using embedded IoT systems could manage both the monitoring and watering of fields from a distance and improve the results as well as the budget. These

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systems often have DHT11 sensors for temperature and humidity, capacitive sensors for soil moisture and light sensors for solar intensity as well.

Agriculture IoT relies greatly on communication technologies. Many companies are now using LPWANs such as LoRaWAN, Sigfox and NB-IoT, to send information from remote farmlands since they require little power. Singh et al. (2021) [3] conduct a study using LPWAN technology together with 5G to provide rural areas with enough fast data for real-time analytics.

Dealing with vast amounts of farm data now depends heavily on cloud computing and edge computing. These devices can handle some processing which makes them fast and also cuts down on the use of bandwidth and the cloud stores data over a longer period, helps visualize it and lets us add machine learning models for predictive analytics (Rani et al., 2022) [4].

More and more, AI and machine learning are being used in smart farming systems. Quite similarly, CNNs have been put to use in plant disease detection and forecasting the harvest, showing 90% accuracy and above (Zhang et al., 2021) [5]. With these technologies in place, farmers can make decisions about watering, applying fertilizer, and using pesticides handled automatically [19] [20].

Still, there are some difficulties present, such as keeping devices' data secure, making different devices compatible and providing dependable connectivity in areas without many towers. This work follows earlier research by using a real IoT architecture in a farm environment to see its effects on productivity, cost efficiency and helping with farm decisions. Figure 2 shows how IoT enhances crop yields through precision farming, water and nutrient management, pest control, and growth monitoring

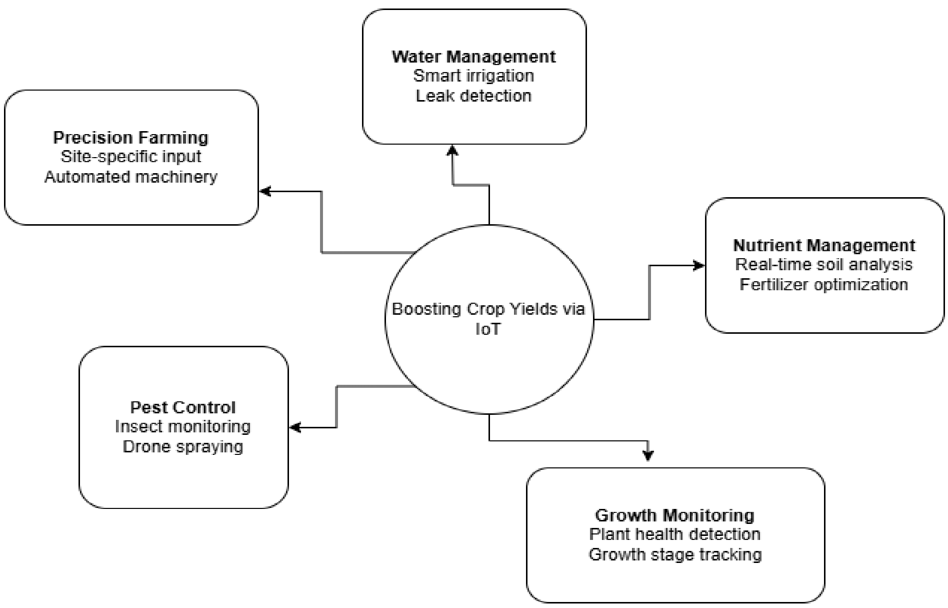

Figure 2: Crop Yield Enhancement Through IoT

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3. System Architecture and Methodology

The smart agriculture system proposed with the Internet of Things helps farmers monitor crops nonstop, automate tasks and make better decisions for increased crop production. The architecture is formed fourparts: the sensing procedure, communication system, processing power, storage unit and interaction with users. Every layer helps turn information from the environment into useful tips for farmers.

3.1 Sensor Layer

This layer collects data at real-time from the environment. Various sensors are used at different farm locations to measure things such as the moisture in the soil, the temperature, humidity, light intensity and the pH level of the soil [7]. Data from the sensors is sent to microcontrollers such as the ESP32 or Arduino which manage both the data and how it is shared in the local area. There is constant data transmission from the sensors to the central processing module at equal intervals [8].

3.2 Communication layer

Information taken by the sensors is sent wirelessly using energy-saving protocols that cover large areas. LoRa was chosen because it works well in remote locations, using little energy [9] If better bandwidth can be supported, regions with Wi-Fi or 5G can use these to boost system performance. Communication flexibility allows consistent use in a wide range of deployment settings [14] [15].

3.3 Processing and Storage

Here, data collection happens and the data is examined both locally using edge devices or on remote cloud platforms. With edge computing units, devices act right away, like turning on irrigation when the soil gets too dry. This platform holds on to past data and offers the backend needed to do data analysis, present data and work with AI for predictions. The structure allows the system to perform both immediate and detailed analysis of trends over a longer period [10].

3.4 User Interface

The processed information can be seen easily by farmers through a web or mobile application. Key indicators are shown with graphs and alerts and users can easily make control changes from a distance [11]. Because it’s straightforward to use, the interface supports people with little computing knowledge. The system is designed so farmers have access via smartphone, tablet or desktop which helps it becomes popular and offers more choices [12] [13].

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3.5 Methodology Flow

To begin, the approach requires choosing which crop, what sensors to use and setting up the main hardware firmware for the microcontroller. Next, sensors and gateways are placed on-site and adjusted before they start their functions. The system works to collect environmental data and send it in real time throughout the data collection period. During processing, data analysis is done locally and data is gathered in the cloud. The dashboard provides steps based on data to help in scheduling watering, planning when to fertilize and handling pests.

It's possible to illustrate the entire process on a chart, showing every step from installing the sensors to providing support for decisions. It serves to explain how hardware and software resources are tightly linked throughout the system [16] [17].

The prototype was used on a nearby farm which allowed observation of how it performs in controlling water and conditions during the whole crop cultivation. In the following section, actual deployment outcomes are given, along with an analysis of the system's good sides and bad sides. Figure 3 showsthe IoT architecture flow from sensor data acquisition through communication, edge and cloud processing, to the user interface.

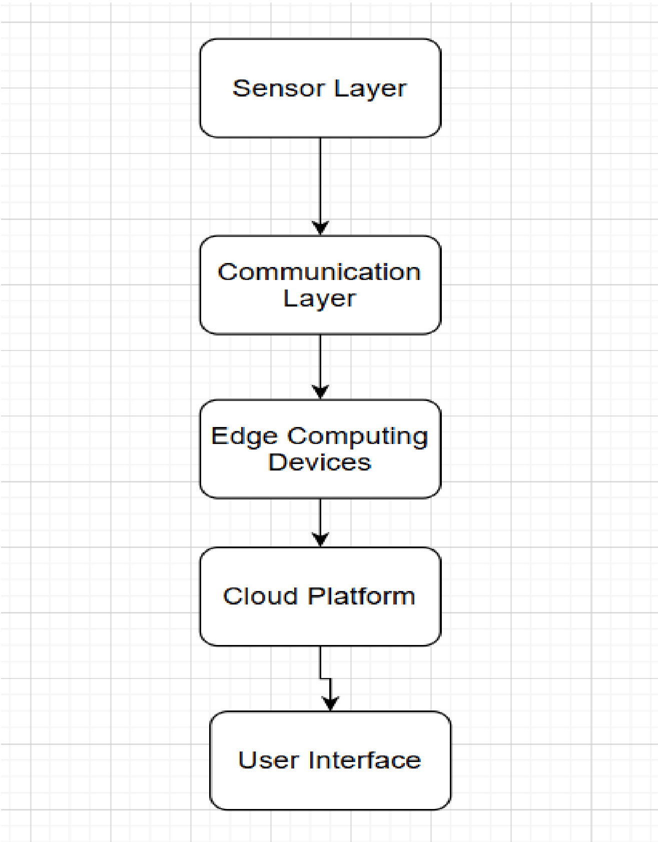

Figure 3: Methodology Flowchart

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System Architecture and Design Specification

The hardware components in the proposed IoT-based smart agriculture system are modular, scale well and communicate with low power so that the whole system is affordable, precise and sustainable. The system comprises a mix of sensors, microcontrollers, communication devices and parts to manage power.

Hardware Components:

Temperature, humidity, moisture levels and sunlight are monitored by DHT22, YL-69 sensors and LDR modules, respectively. Due to its large I/O and memory, an Arduino Mega 2560 board is used for the main controller. For radio communication without wires, a LoRa SX1278 module is used, giving a range up to 10 km and very low power requirements. An SMS component (SIM800L) is included so sensors can send a message if internet access is severely limited. Energy for the device comes from a 12V/10W solar panel with a lithium-ion battery backup (7.4V, 2000mAh) controlled by a TP4056 charging module and an LM2596 voltage regulator.

Communication Protocols:

Because it features long range and low power, LoRaWAN is most commonly used in rural farms. MQTT helps send small amounts of data securely to the internet's clouds. Every time new data is taken, it's sent to ThingSpeak and Google Firebase so it can be watched and stored in real-time. It is possible to use Wi-Fi through the optional ESP8266 module if the area is properly covered by the internet.

Unique Contributions:

Most other smart farming systems are limited to Wi-Fi or GSM, yet this model connects LoRa and solar equipment to ensure stable operation wherever needed. The system's design with two networks (LoRa and GSM) helps protect against loss of communication. With Arduino on board, sensors can run threshold calculations close to the field which means less operation relies on the cloud and the data is processed faster. Because the hardware can be arranged in a modular way, farmers only need to add or remove sensors that their plants require, so the system is economical to use and can grow along with crop demands. Affordability and easy availability in rural regions determine the choice of each hardware component for the design.

4. Real-World Deployment and Case Studies

The IoT-based smart agriculture system was properly tested by deploying it on a medium-sized vegetable farm in an area with varied climates. By using this site, it was possible to see how the system behaved in realistic use, with power, network and weather issues. Complete tomato cultivation was pursued over one single crop cycle, all while measuring the soil, sunlight levels and temperature.

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Several sensing nodes were placed at regular locations on the field so that its spatial variability could be shown accurately. The nodes were made up of sensors for moisture, temperature and light, connected to a microcontroller. Nodes were able to communicate with the gateway using a LoRa network. The gateway sent data in real time to the cloud, thanks to the connection made through a cellular modem. The operation wasn't interrupted when power outages occurred, as the field devices got power from a solar power unit.

The app stated alerts on the user interface, allowing the farmer to respond to soil drying up, freezing temperatures and extra sun exposure. With these alerts, the farmer can start irrigation from the app or let the system begin watering through connected solenoid valves. Because of this flexibility, it was possible to use a mix of automated and human control.

Uninterrupted and dependable collection of information was seen throughout the deployment. With soil moisture data, the farmer cut back irrigation by nearly half compared to how it was attempted before. Besides, with soils checked several times each day during the heatwave, problems with high temperature could be dealt with immediately through shading and providing more water to plants. After the cycle ended, the results demonstrated a 20 percent boost in output when compared to when no IoT monitoring was employed.

Apart from helping with operations, the system gave our company ongoing benefits thanks to its data visualization tools. By studying farming trends over many years, farmers were able to pinpoint when they should plant and how different fertilizer plans worked. The farmer noted that straightforward data sent as it is detected is the most useful because it does not require advanced technical skills.

This deployment proved that the proposed model can be built and will make a difference. This revealed that IoT-driven smart farming makes it possible to use resources better and boost productivity, despite a challenging environment. Figure 4 illustrates an IoT monitoring architecture comprising input devices like cameras and sensors, edge devices for local processing, and cloud layers for storage and analytics.

Data is transmitted via protocols such as MQTT or Bluetooth to the cloud for processing.

User interfaces and feedback loops enable actions like irrigation control and farmer alerts based on the analyzed data.

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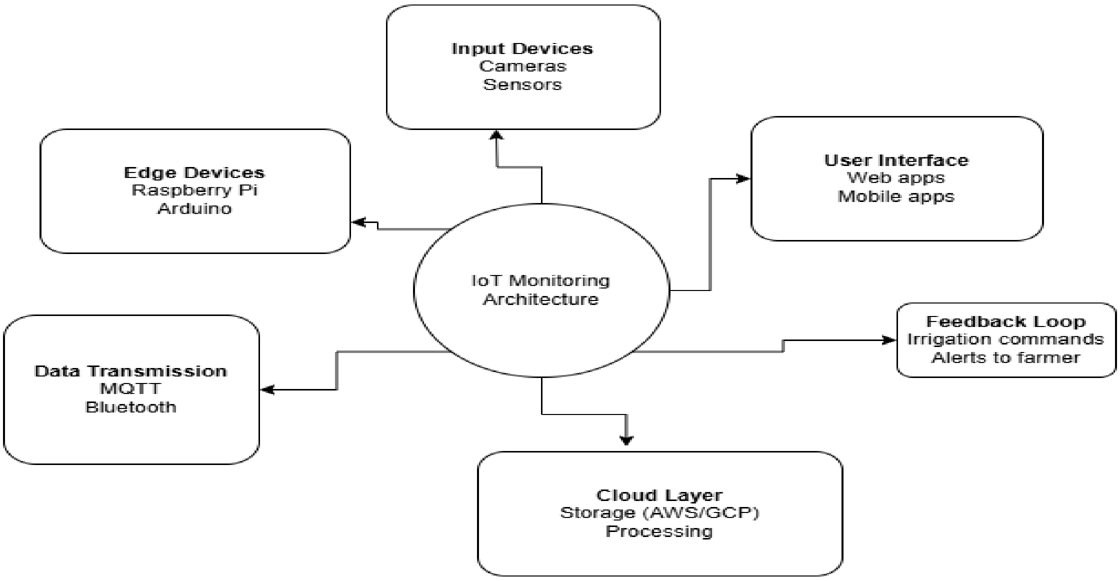

Figure 4: Real-time Monitoring System Architecture

5. Results and Discussion

Some of the important measures used to review the system were how accurate sensors were, how reliable the overall system was, how the IoT helped keep water use down, how much the method improved crop yields and what farmers thought of the system. Over a period of 90 days during tomato cultivation, data was collected continuously. Experts looked at the differences between farming by hand and howIoT advances have been introduced on the farm.

We compared how accurately the sensors operated by matching data collected by them to data collected manually using analog tools. Less than 4 percent was the deviation for temperatures, humidity and moisture in the soil. The data showed results that were the same on all nodes, confirming every part of the sensor network was synchronized and equal. There were very few disruptions in the system—less than 2 percent—because the vehicle buffered data and only transmitted it once conditions improved.

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Table 1: Comparison of Existing Smart Agriculture Systems

System / Framework	Cost	Accuracy	Energy Consumption	Scalability
LoRa-based IoT System	Low	Moderate	Very Low (LoRa is energy-efficient)	High (supports large deployments)
Wi-Fi Sensor Network	Moderate	High (short-range)	High (due to Wi-Fi power usage)	Low (limited range)
NB-IoT System	High (modem cost)	High	Low	High
Zigbee-based System	Low	Moderate	Low	Moderate
Bluetooth-based Monitoring	Very Low	Low to Moderate	Moderate	Low (short-range)
Cloud-integrated IoT	High (cloud services)	Very High	Moderate to High	Very High
Edge-Computing IoT	Moderate	Very High	Low (on-site processing)	High
AI-Integrated Smart System	High	Very High	Depends on model complexity	Moderate to High
Solar-powered LoRa System	Moderate (solar panels)	High	Very Low (sustainable power)	High
Drone-Assisted System	Very High	Very High	High (due to drone operations)	Moderate

An important benefit of the deployment was increased water use efficiency. In the past, water was added to crops following a regular schedule, no matter what the soil was like. The IoT system, in contrast, was able to schedule irrigation automatically as soil moisture was measured. About 35 percent less water was used during the entire period of cultivation. In areas short on water, this decline is especially important as making use of resources wisely is crucial.

Because of automated monitoring, the farm showed a 20 percent boost in tomato yield compared to last year's results. The rise is caused by regular soil water, faster detection of environmental changes and early watering and feeding the crop. This led to better growth for the plants and better fruits. The lower number of times plants did not get the right amount of water eased stress on them and encouraged the best possible growth. Figure 5 highlights key challenges in IoT for agriculture, including cost, data issues, infrastructure, integration, and farmer adoption.

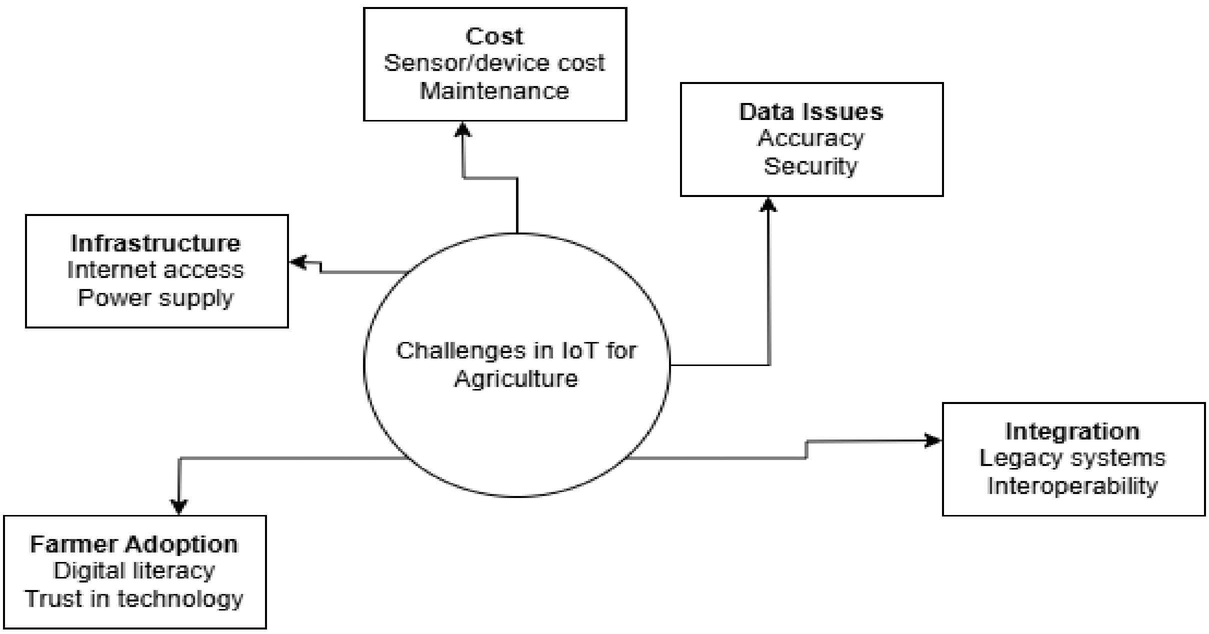

Figure 5: Challenges in IoT-Based Smart Farming

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According to the farmer, using the system was straightforward and satisfactory. With the mobile dashboard, real-time updates and useful suggestions were shown for field situations. Because of notifications, we were able to take action immediately and automation made it easier to check up on things less often. The design team found that that the essential reason for the app's success was that its interface is very simple, particularly for those not skilled at technology.

It explains the troubles observed during the deployment phase. Connections errors occurred in wet weather, but they were resolved fast and did not last. Getting the system and sensors together was expensive in the beginning, so it may not be affordable for smallholders. Even so, cashflow and yield gains observed indicate that getting a positive return on the investment would take one or two growing seasons.

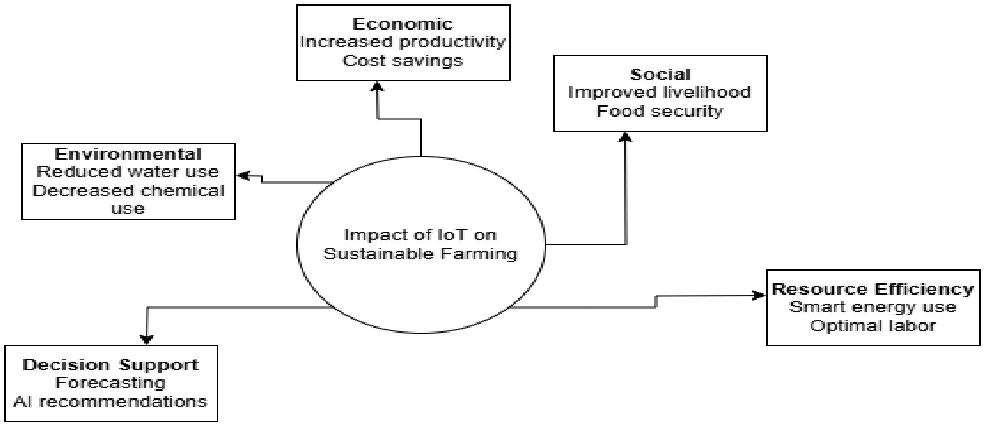

Figure 6: Impact of IoT on Sustainable Farming

Figure 6 shows how IoT supports sustainable farming by boosting economic gains, social welfare, environmental protection, resource efficiency, and informed decision-making.Studies done before also found that IoT helped farmers get better results and use less water. This paper completes the picture by showing all the necessary steps for sensor data, interpretation and delivering help to farmers, within an operational farm environment. Such a live assessment demonstrates that IoT systems can be scaled and adapted to support different types of farms.

The findings verify that smart farming enabled by IoT leads to measurable improvements in all these areas. Chemicals can continue to reduce costs, merge with AI-based predictions, and improve device compatibility to improve their performance. This will enhance agricultural productivity and align with the UN Sustainable Development Goals (SDGs)—notable SDG 2: Zero Hunger: Goal: "End hunger, achieve food security and improved nutrition, and promote sustainable agriculture.

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SDG Goal	Description	Contribution
SDG 2: Zero Hunger	End hunger, achieve food security	Empowers farmers to make data-driven decisions, optimize fertilizer use, and enhance crop health while minimizing environmental impact

6. Conclusion and Future Work

A smart agriculture system was designed, deployed and studied in this study to enhance crop yield and the way resources are used. Developers made the system up using a multi-layer approach that linked live environmental monitoring, wireless data sharing, cloud processing of data and an easy-to-use interface. The technology was put to use on an actual tomato farm to test its effectiveness over the plant's complete life cycle.

The research demonstrated that the system successfully improves irrigation methods, uses less water and improves crop production. Smart sensor systems allowed for water savings of 35 percent in irrigation. As a result of using fewer inputs, there was a 20 percent rise in yield, proving how important monitoring the environment is for crop growth. Reliable information was obtained thanks to the system's sturdy connection and excellent accuracy of the sensors, no matter the environment.

The good comments from the farmer prove that usability and accessibility matter a lot in agricultural technologies. Thanks to an easy-to-use design and up-to-date alerts, the user could quickly and easily decide what needed attention without needing a lot of technical experience. They show that IoT helps farmers gain better control and making better decisions, purposefully on smaller farms.

While the findings were encouraging, a number of challenges were found. While the benefits of using technology last for a long time, initial costs prevent small-scale farmers from adopting them. Little disruption in communications during extreme weather, though, demonstrates the value of developing stronger ways to share data. Besides, although this research concerned only a certain crop type in one agro-climatic zone, it is important to check that the method works well with different crops, soil types and in various places.

Future efforts will be put into raising scalability and lowering the cost of the system. Applying such algorithms allows the system to predict potential pest breakouts and nutritional problems in plants. The benefits of edge computing will be investigated to allow applications to respond faster, without always depending on an internet connection. If more functions are added such as fertigation, checking for diseases and crop classification, the platform supports a more complete ecosystem in smart farming.

In short, putting the proposed system into action has confirmed that IoT plays an important part in shifting agriculture. Precise farming methods made possible by these systems lead to better yields, greater efficiency, and more responsible care for the environment. If more innovation and policy help are provided, these technologies will be available to more farmers internationally.

Author Contributions

Full Contribution.

Funding

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Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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