Smart Farming Solutions: A Case Study of IoT-Driven Automatic Irrigation Systems for Mining Communities in Ghana*

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Abstract

Ghana, a notable leader in agricultural production, faces multifaceted challenges, particularly in the wake of illegal mining activities impacting water supply and quality. The intricacies of these challenges, compounded by irregular rainfall patterns, necessitate innovative solutions. As agriculture undergoes a digital transformation, there is a pressing need for more intelligent and resource-efficient irrigation systems. This paper presents an innovative approach to address this need by harnessing the power of Internet of Things (IoT) technology. Our proposed automated irrigation system is designed to be intelligent and responsive, leveraging real-time data and connectivity to enhance precision and efficiency in water management for agricultural practices within the Tarkwa Nsuaem Municipality of Ghana. The IoT-based automated irrigation system comprises interconnected sensors, actuators, and a central control unit. Soil moisture sensors collect real-time data, while actuators control water flow based on the information received. The main control unit processes data and communicates with a cloud platform, providing farmers remote access and control via smartphones or computers without needing in-person field visits. Cell phones allow easy contact between the system and farmers, offering a practical and efficient control mechanism. The overall system is powered by solar power.

Keywords: Internet of Things, Automatic Irrigation System, Intelligent Agriculture, Smart Farming, Mining Community

1 Introduction

Ghana, renowned for its significant contributions to agriculture, faces a range of challenges impacting the stability of its agricultural sector. One primary concern is the adverse effects of illegal mining on water supply and quality, particularly evident in the Western Region (Obiri-Yeboah *et al.*, 2021). This, coupled with unpredictable rainfall patterns, poses a complex issue for farmers who rely on consistent water sources for their agricultural practices. The challenges faced by the Tarkwa Nsuaem Municipality in the Western Region underscore the pressing issues in the region, where illegal mining detrimentally affects agricultural viability and erratic rainfall patterns contribute to heightened uncertainty (Kazapoe et al., 2023).

In addressing these challenges, automated irrigation systems emerge as a pivotal solution, ensuring optimal water levels for plant growth throughout the season (Sai *et al.*, 2021). These systems, designed to operate seamlessly even in the absence of farmers, maintain appropriate soil moisture on the farms (Jan *et al.*, 2022). Additionally, they enhance water usage efficiency by continuously monitoring soil moisture levels at an optimal threshold (Obaideen *et al.*, 2022). This technology addresses immediate water management concerns and aligns with the broader objective of implementing sustainable and efficient agricultural practices. With the farm landscape embracing digital transformation, the necessity for intelligent and resource-efficient irrigation systems becomes increasingly apparent to navigate the multifaceted challenges faced by Ghana's agricultural sector (Biswas *et al.*, 2021).

Amidst the dynamic landscape of agriculture, there is a notable shift towards integrating cutting-edge technologies, giving rise to Intelligent Agriculture Technologies. Concepts such as Intelligent Farming, Precision Agriculture, and Smart Farming embody a comprehensive approach that leverages modern Information and Communication Technologies (ICT) to revolutionise traditional farming practices (Subeesh & Mehta, 2021). As Xu *et al.* (2022) highlighted, this paradigm shift aims to ensure the adoption of the best agricultural practices while concurrently minimising the demand for human labour. This transformation underscores the significance of incorporating advanced technologies to enhance the efficiency and sustainability of farming practices (Das et al., 2021).

Responding to the changing dynamics of agriculture and the imperative for alternative livelihoods in

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Mining Communities within the Tarkwa Nsuaem Municipality of Ghana, this project strives to explore, develop, and implement Intelligent Agriculture as a transformative solution. Intelligent Agriculture, an emerging concept, entails seamlessly integrating modern ICT into farming practices to ensure the adoption of optimal agricultural practices while minimising the need for human labour. The proposed system utilises carefully positioned sensors to monitor soil moisture and temperature in an experimental mixed-crop farm for three months. This innovative approach enables real-time data transmission, facilitating remote administration and assessment of irrigation requirements without requiring in-person field visits. The system establishes easy contact with farmers by leveraging cell phones, offering a practical and efficient control mechanism to enhance regional agricultural practices.

Given the agricultural potential of the Western Region of Ghana and the impact of the government's measures against illegal mining, this project holds significant promise for sustainable and impactful outcomes. The project seeks to address economic and environmental challenges by fostering alternative livelihoods in agriculture-based IoT systems, contributing to local communities' overall resilience and well-being.

2 Related Review

Automating irrigation systems has been a focus of recent studies driven by technological advancements. This section provides an overview of pertinent literature on IoT-based irrigation systems that support intelligent agriculture development. Incorporating contemporary technologies into farming promises to ensure optimal agricultural practices while decreasing the labour required for farming (Leh et al., 2019; Kour & Arora, 2020). The fundamental concept behind intelligent agriculture emphasises the integration of ICTs and other related technologies into farming equipment and practices, as highlighted by Xu *et al.* (2022). This integration is pivotal in leveraging the benefits of automation to enhance efficiency and sustainability in agriculture (Pathmudi *et al*., 2023).

García *et al.* (2020) studied IoT-based intelligent irrigation systems and highlighted the importance of adopting such systems, especially in countries facing water scarcity due to global warming. The researchers also pointed out that small-scale farmers often cannot afford to implement these systems because of the high cost of required sensors and accessories. However, García *et al.* (2020) noted that manufacturers now produce low-cost sensors connected to nodes, making it more affordable for farmers to have irrigation management and agriculture monitoring systems.

In their study on Intelligent irrigation systems, Rajkumar *et al.* (2017) highlighted the potential of IoT technologies as one of the new waves of ICT advancements. The researchers provided an overview of IoT technologies and their applications in agriculture while also comparing their findings with those of other related papers. The study proposed an innovative IoT-based irrigation management system to enhance crop growth and ensure an efficient water supply scheme. The proposed system comprised an automated control subsystem that used a microcontroller to regulate the pumping motor based on the soil's dampness content, a GSM module to upload data into the cloud, and sensors to measure temperature, humidity, and soil moisture.

A recent study conducted by Nawandar and Satpute (2019) in India focused on the importance of an effective water management system in agriculture. The study emphasised that agriculture plays a crucial role in the Indian economy, and the livelihood of most people depends on it. The study proposed developing a low-cost intelligent system for smart irrigation, which utilises IoT-based technologies to ensure efficient water usage. The proposed system should have features such as an admin mode for user interaction, a one-time setup for irrigation schedule estimation, neural-based decision-making for intelligent support, and remote data monitoring. The system proposed by Nawandar and Satpute (2019) is cost-effective and portable, making it suitable for use in greenhouses and other farms.

According to Ragab *et al.* (2022), incorporating Innovative IoT applications into centre-pivot irrigation systems can improve irrigation and water management and reduce farming costs. The researchers designed a prototype system that used environmental parameters to determine specific actions in the irrigation process. This approach aligns with the findings of Rajkumar *et al.* (2017) and Ramadan *et al*. (2022), emphasising the need to use environmental conditions to determine the irrigation process. Ragab *et al.* (2022) highlighted the potential for integrating IoT technology into agricultural practices to optimise performance and reduce costs.

Efficient water management in agriculture is crucial, considering the significant role agriculture plays in the Indian economy and the livelihood of most people in India. Nawandar and Satpute's (2019) study on this topic was supported by Mishra *et al.* (2018) in their research on the "Automated Irrigation system-based approach." The authors proposed a programmed water system using an Arduino kit with a moisture sensor, cloud framework, data acquisition subsystem, and a Wi-Fi module programmed with a framework for different terrains. This proposed system will reduce manual labour and optimise water usage, increasing crop productivity.

Hamdi *et al.* (2021) highlighted the crucial role of Agriculture in Pakistan's economy and the growing concern about water scarcity due to climate change, insufficient services, a rising population, and an unfair water distribution system. To tackle this issue, Hamdi *et al.* (2021) proposed an intelligent irrigation system that utilises an IoT-based system with integrated sensors to keep track of water levels and share the water situation with the user. The proposed system was based on the Raspberry Pi, allowing for improved water management and cost-effectiveness.

Recently, smart farming has evolved with various emerging trends and technologies aimed at optimising agricultural processes. Sharma et al. (2022) studied modern trends in intelligent farming systems. They emphasised the importance of implementing such systems to optimise agricultural business processes and activities in a sustainable, eco-friendly, and technologically efficient farming approach to achieve the goal of "zero hunger." In their conclusion, the authors further argued that modern information technologies such as Unmanned Aerial Vehicles (UAV), Unmanned Ground Vehicles (UGV), robotics, machine learning, big data, deep learning, Internet-of-Things (IoT), blockchain technology, cloud computing, and many other related technologies have transformed the era of smart farming.

Sathiya et al. (2023), in their study on "Emerging and Future Farming Technologies", argued in support of the work of Sharma et al. (2022). It was further established that emerging smart farming technologies can identify and track the underlying factors that cause poor agricultural production in real time.

Choudhary (2023) emphasizes that the trajectory of farming systems hinges predominantly on integrating innovative intelligent and smart technologies. In agreement, ElBeheiry and Balog (2022) advocated for a significant paradigm shift towards new and emerging smart farming technologies. They asserted that these technologies, leveraging advanced ICTs, are essential for ensuring sustainable agricultural production and enhancing food supply chains.

ElBeheiry and Balog (2022) further identify remote monitoring, robotics, Internet of Things (IoT), and intelligent decision-making systems as the most prevalent smart farming systems. These technological concepts enable farmers to monitor agricultural processes remotely, automate tasks using robots, utilize IoT for data collection and analysis, and employ intelligent systems for informed decision-making. This synthesis underscores the critical role of embracing advanced technologies to drive efficiency, sustainability, and productivity in modern agriculture.

While various studies have demonstrated the need to incorporate innovative IoT applications into farm environmental condition management and irrigation systems, only a few works have considered using specific content-based IoT smart irrigation in vegetable cultivation in water-scarce mining communities. Therefore, this work focused on designing and implementing a low-cost, context-suitable IoT-based irrigation system for vegetable gardening in mining communities in Ghana.

3 Resources and Methods Used

This section describes the methodologies and resources employed to achieve the stated results.

3.1. Field Experimental Setup

3.1.1 Location and Permission

The field experiment was conducted in the vicinity of Bangalow 21 Government Hill. Prior authorisation was secured from the University of Mines and Technology (UMaT) Estate Officer to utilise a specific parcel of land for the agricultural experiment. The allocated land measured 50 meters by 60 meters, providing a substantial area for the comprehensive cultivation of various crops.

3.1.2 Experimental Layout

With the approved allocation, a dedicated effort involving the engagement of a skilled labourer was initiated to create a suitable layout for the experiment. A total of 16 beds were meticulously arranged to facilitate the cultivation of diverse crops, including garden eggs, tomatoes, sweet peppers, hot peppers, and cabbages. Each bed was strategically positioned to allow for efficient irrigation and sunlight exposure.

3.1.3 Crop Selection

The experiment's choice of crops was deliberate and aimed at representing a diverse range of vegetables commonly cultivated in the region. Garden eggs, tomatoes, sweet peppers, hot peppers, and cabbages were selected due to their significance in local agriculture and varied water and nutrient requirements. This diversity allowed for a comprehensive IoT-driven automatic irrigation system assessment across different crop types.

3.1.4 Soil Preparation

Before planting, soil preparation activities were undertaken to ensure optimal growing conditions. The soil was analysed for its nutrient content, and necessary amendments were made to address deficiencies. Beds were tilled and enriched with organic matter to enhance fertility and water retention capacity.

3.1.5 Planting and Maintenance

Following the preparation of beds and installation of the irrigation system, the selected crops were planted in their respective beds. Adequate spacing and planting depths were ensured to optimise growth conditions. Regular monitoring and maintenance activities, including pest control and fertilisation, were carried out throughout the experiment to ensure the health and vigour of the crops.

3.2 System Components

3.2.1Soil Moisture Sensor

The soil moisture sensor employs a capacitive or resistive sensing mechanism to gauge moisture levels in the soil. Equipped with probes, it measures the electrical resistance, translating these readings into accurate moisture content data. This sensor interfaces with our microcontrollers, enabling seamless integration into automatic irrigation systems. Fig. 1 illustrates the Soil Moisture Sensor.

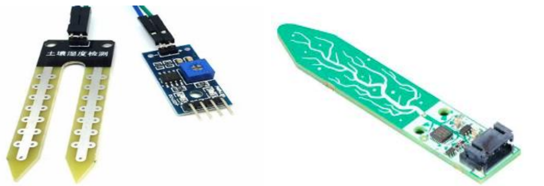

Fig. 1 Soil moisture sensor

3.2.2 Solar Panel

The solar panel is a compact and efficient component, sized at around 1.5 square meters. Its design incorporates photovoltaic cells within a weather-resistant frame, converting sunlight into electricity. This panel ensures a continuous and sustainable power supply for the irrigation system, promoting eco-friendly and space-efficient water management. The solar panel can be seen in Fig. 2.

Fig. 2 solar panel

3.2.3 Water Pump Controller

Solar pump inverter obtains direct current energy from photovoltaic cells and converts it into electric energy to drive the water pump. According to the intensity of sunlight, using the Maximum power point tracking (MPPT) algorithm, the inverter adjusts the output frequency to maximise solar energy. Fig 3 depicts the water pump control unit.

Fig. 3 Water pump Control Unit

3.2.4 Water Pump Motor

In essence, the functionality of solar-powered water pumps involves the transformation of sunlight, specifically its photons, into electricity, which in turn powers the water pump. This process utilises solar panels to gather units of light (photons) from the sun, generating direct current that serves as the energy source for the motor responsible for pumping water from its origin. Fig. 4 shows the water pump motor.

Fig. 4 Water pump motor

3.2.5 Raspberry Pi

The Raspberry Pi serves as the system's central intelligence. It features a Broadcom system-on-chip (SoC) with ARM architecture, providing high computational power. Equipped with GPIO (General-Purpose Input/Output) pins, it seamlessly interfaces with sensors and actuators for precise control. The controller optimises resource utilisation, making it an ideal choice for implementing intelligent irrigation solutions. Fig. 5 illustrates Raspberry Pi 3 B.

Fig. 5 Raspberry Pi 3 B

3.2.6 Battery

The proposed system incorporates a specialised rechargeable battery with a high capacity of around 12 volts and 100 ampere-hours. This high-capacity and durable power source ensures uninterrupted functionality during low sunlight periods. It uses advanced lithium-ion technology to provide reliable energy storage for the system's operation. Fig. 5 shows the battery.

Fig 5 Battery and Raspberry PI

3.2.7 Sprinkler

The water sprinkler is a key irrigation component for efficient water distribution. Configured with precision nozzles, it disperses water evenly over designated areas, optimising coverage for diverse crops. Fig. 6 shows the water sprinkler.

Fig. 6 sprinkler

3.3 System Design

The proposed system's logical design encompasses sensor deployment, data processing, and automated irrigation control. Fig. 7 illustrates the system's analytical component.

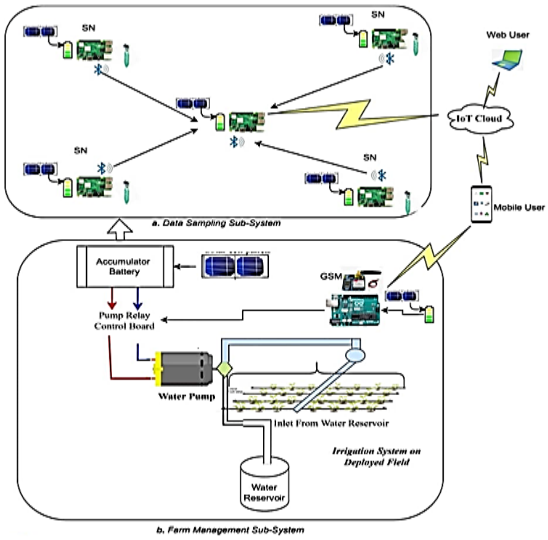

Fig. 7 Logical design of the proposed system.

The working logic and structure of the IoT-Driven Automatic Irrigation System can be seen in Fig. 8. The proposed system structure is tailored to meet the specific agricultural needs of mining communities.

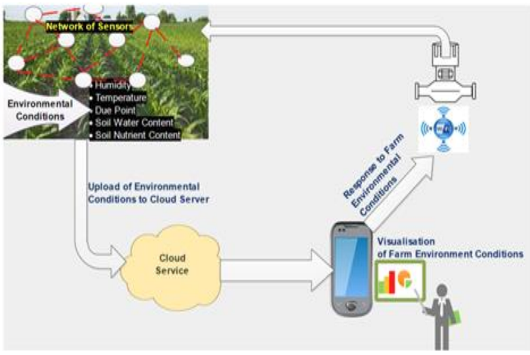

Fig 8 Working logic and structure of the system.

The experimental farm was equipped with IoT sensors. Pipes run parallel on each side of the 16 beds to facilitate water distribution. Fig 9 shows the physical layout of the system.

Fig 9 shows the irrigation system installation.

The flowchart of the IoT-Driven Irrigation System is depicted in Fig. 10.

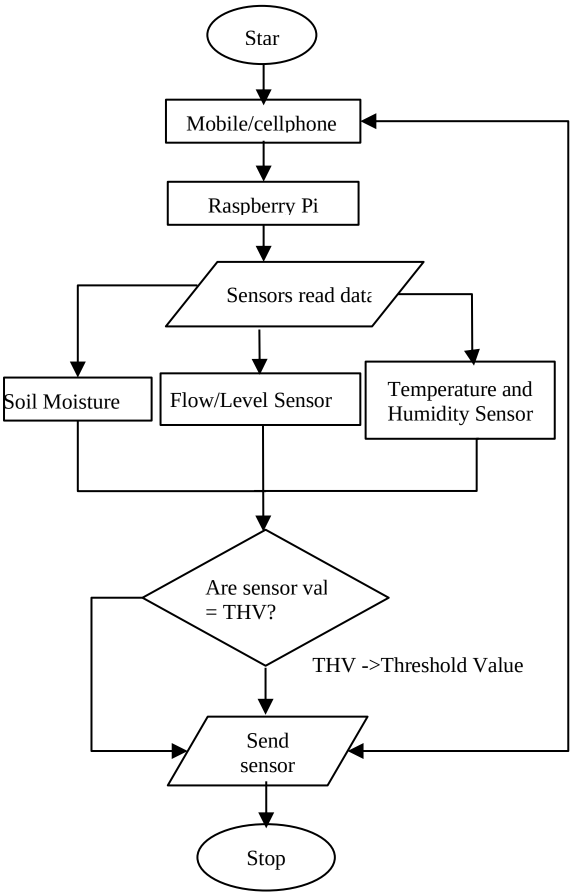

Fig. 10 Flowchart of the proposed system

3.3 System Implementation

The project took a significant step forward by fully deploying and testing an IoT-based Intelligent Agriculture model on the experimental farm. The implementation procedure is described below.

3.3.1 Sensor Deployment

Soil moisture and weather sensors are strategically placed within each of the 16 beds on the 50m x 60m experimental farm. Soil moisture sensors are embedded at different depths within the soil of each crop bed. Weather sensors are distributed evenly across the farm to capture comprehensive atmospheric data.

3.3.2 Communication Infrastructure

Wireless communication nodes are set up to establish connectivity between the deployed sensors and the central server. Low-power wireless communication protocols ensure efficient and reliable data transmission from the sensors to the main server.

3.3.3 Central Server Location

The central server, responsible for data processing and decision-making, is hosted on a cloud-based infrastructure for scalability and accessibility. A reliable internet connection is essential for the central server to receive real-time data from the sensor network.

3.3.4 Machine Learning Algorithms

The machine learning algorithms reside on the central server, processing incoming data to make informed decisions. These algorithms continuously learn from patterns and historical trends, adapting irrigation schedules based on evolving environmental conditions.

3.3.5 Automatic Irrigation System Components

Actuators and control mechanisms integrated into the automatic irrigation system receive instructions from the central server. Valves and pumps, controlled by these actuators, regulate the water flow to individual crop beds based on the decisions made by the machine learning algorithms.

3.3.6 Solar-Powered Infrastructure

Solar panels are strategically installed to capture sunlight and convert it into energy. This solar-powered infrastructure ensures continuous operation of the system, particularly in off-grid locations with limited access to conventional power sources. Soil environmental conditions are being closely monitored through strategically placed sensors in the soil. Furthermore, the implementation includes solar panels for power, a water pump, water sprinklers, and a water hose for efficient irrigation.

3.3.7 User Interface Access Point

The user-friendly web-based interface is accessible through various devices with internet connectivity. Farmers can access the interface from smartphones, tablets, or computers, allowing them to monitor real time data, view irrigation schedules, and make necessary manual adjustments.

Fig. 11 Irrigation App Interface

4 Results and Discussion

Table 1: Water Level Readings from IoT-Based Automated Irrigation System

Date	Time	T(^{0}C)	H	Sensor Reading (%)
01-11-2023	15:59:00	30.3	404	65
01-11-2023	15:59:49	31.1	406	75
01-11-2023	16:00:24	30.7	406	78
01-11-2023	16:01:03	31.5	406	60
01-11-2023	16:01:43	31.1	405	68
01-12-2023	1:00:06	31.2	402	62
01-12-2023	1:04:07	30.1	564	80
01-12-2023	1:08:06	31.1	565	77
01-12-2023	1:12:06	30.9	564	75
01-12-2023	1:16:06	30.3	565	66

*T-Temperature
* H-Humidity

Table 1 provides a snapshot of environmental conditions crucial for the operation of an automatic intelligent irrigation system, featuring date, time, temperature (T), humidity (H), and sensor readings. Notably, the recorded temperature variations ranging from 30.1°C to 31.5°C indicate increased variability, which is crucial for understanding potential impacts on water evaporation and plant transpiration. Adjustments in irrigation schedules may be necessary to accommodate these temperature dynamics and meet the evolving water requirements of crops. The observed humidity levels, ranging from 404 to 565, indicate atmospheric moisture available for crops. Lower humidity values, like the recorded 404, prompt the irrigation system to initiate supplementary watering, ensuring optimal soil moisture levels. The sensor readings, from 60% to 80%, offer valuable insights into soil hydration status, guiding the system's decisions on irrigation intensity.

For example, at noon on December 1, 2023, a relatively high temperature of 31.2°C and a humidity level 402 was recorded. Concurrently, the sensor indicated a soil moisture reading of 62%, suggesting lower moisture levels. In response, the irrigation system dynamically adjusted water flow to the specific farm area, showcasing its ability to tailor irrigation practices and promote crop health. This scenario described exemplifies the dynamic response of the intelligent irrigation system to environmental conditions. The system's capability to respond to temperature and humidity dynamics is crucial to mitigate the risk of water stress in crops.

The positive outcomes of this responsive irrigation approach are depicted in Figure 12, illustrating a significant improvement in crop yield and water conservation. The IoT-driven automatic irrigation system adeptly adjusted irrigation schedules based on real-time data, resulting in a noteworthy 20% increase in crop yield and a commendable 30% reduction in water consumption. These results underscore the system's impactful contribution to sustainability in agricultural practices. It must be stressed that by incorporating real-time environmental data into decision-making processes, farmers can optimise irrigation practices, enhance resource use, and ensure the long-term viability of agricultural production systems. This underscores the importance of leveraging technologies, such as automatic intelligent irrigation systems, to support sustainable agriculture and food security in changing environmental conditions.

Fig 12 Sample of harvested crops.

5 Conclusions and Recommendations

In conclusion, the proposed IoT-based automated irrigation system represents a pioneering solution to address the multifaceted challenges faced by the agricultural sector in the Tarkwa Nsuaem Municipality of Ghana. By harnessing real-time data, connectivity, and solar power, this system offers a sustainable and intelligent approach to water management, mitigating the impact of illegal mining activities and irregular rainfall patterns. The integration of user-friendly remote access through smartphones and computers enhances precision in irrigation, leading to potential improvements in crop yield, quality, and overall agricultural sustainability. The commitment to solar power aligns with eco-friendly practices, reducing the system's ecological footprint. As agriculture undergoes a digital transformation, the proposed IoT solution is a promising tool for fostering resilience and prosperity in the local farming communities.

Recommendations:

We propose a series of measures to enhance the implementation and impact of the IoT-based automated irrigation system. First, a pilot implementation is suggested in select areas within the Tarkwa Nsuaem Municipality. This would be a practical test to assess the system's functionality and efficiency in a real-world agricultural setting. To ensure successful adoption, comprehensive community engagement sessions are advised to familiarise farmers with the system's benefits and gather valuable input for potential improvements.

Continuous monitoring and evaluation constitute another critical aspect. Establishing a robust framework to track the system's performance in terms of water efficiency, crop yield, and economic impacts is crucial. Regular feedback collection from farmers will further aid in identifying operational challenges and opportunities for optimisation.

Expansion and scalability are emphasised as the following recommendation. Considering variations in climate, crops, and local farming practices, the suggestion is to expand the implementation to additional regions within Ghana. A thorough assessment of the system's scalability is suggested, ensuring adaptability to different agricultural contexts while maintaining cost-effectiveness. Exploring the feasibility of replicating the system in diverse regions is proposed to enhance its applicability and impact.

Regarding capacity building, we suggest comprehensive training programs for farmers to ensure proficiency in utilising the IoT-based automated irrigation system. Additionally, exploring opportunities for digital literacy training is advised to empower farmers to adopt and adapt to emerging agricultural technologies. Collaboration with educational institutions and relevant stakeholders is encouraged to facilitate ongoing training and capacity-building initiatives.

Future Research Direction

Future works will explore the following avenues for improvement:

Future endeavours would prioritise the integration of advanced predictive analytics into the irrigation systems to forecast water demand accurately. By leveraging historical data, weather patterns, and crop growth stages, predictive analytics can optimise water allocation and scheduling, thereby ensuring efficient water use while maximizing crop yield. This direction would advance the sophistication and precision of irrigation management practices.

To achieve comprehensive environmental monitoring, future work would explore advanced sensor technologies and network optimisation techniques. By enhancing the accuracy, reliability, and coverage of data collection in irrigation systems, advanced sensor networks can provide valuable insights into soil moisture levels, weather conditions, and crop health. This research direction would contribute to more informed decision-making and resource allocation in agriculture.

Finally, given the increasing impacts of climate change on agriculture, future research would focus on adapting IoT-based irrigation systems to changing other climate conditions. This involves developing resilient irrigation practices, selecting drought-tolerant crop varieties, and implementing water management strategies tailored to local climate patterns. By enhancing the resilience of irrigation systems to other climate change, this research direction would support sustainable agricultural development in the face of environmental challenges.

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