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Design and Implementation of an IoT-Based Smart Agriculture Automatic Irrigation System Using a Drone in Rwanda

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Abstract: An IoT-based smart agriculture automatic irrigation system is a technologically advanced solution that enhances water efficiency in farming by leveraging Internet of Things (IoT) devices. The system integrates key components, including soil moisture sensors, weather stations, automated irrigation controls, remote monitoring, and data analytics, and supports integration with other systems. Its notable benefits include water conservation, improved crop yields, labour efficiency, and enhanced sustainability. This system finds applications in various agricultural settings, including field crops, greenhouses, and urban agriculture. As IoT technology continues to advance, agriculture is undergoing a significant transformation toward greater efficiency and sustainability. This paper introduces an innovative IoT-based smart irrigation system for agriculture that optimises water use, boosts crop productivity, and minimises manual labour. The system collects real-time soil moisture, weather, and crop health data from a network of sensors throughout agricultural areas. The system analyses this data to create exact watering schedules for each crop and field area using complex algorithms. The technology automates and optimises water distribution by using IoT-controlled actuators to provide the proper amount of water to crops at the right time. Water waste is reduced, and resource efficiency is improved. Farmers can also monitor and manage the system in real time using smartphone or computer interfaces.

Keywords: Internet of Things (IoT); Smart Agriculture; Automatic Irrigation; Soil Moisture; Crop Health; Real-Time Monitoring; Water Management; Resource Management.

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1. Introduction

The design and implementation of an IoT-based smart agriculture automatic irrigation system offer a novel, technology-driven solution to the ongoing challenges farmers face in regulating water supply for their crops. One of the most important aspects of farming is managing water well. Too little or too much irrigation can hurt plant development, produce quality, and the long-term health of agricultural land. Traditional irrigation methods depend heavily on manual monitoring, decision-making based on experience, and weather that can change quickly. This can cause either too little or too much water to be given during dry spells or heavy rains. In large-scale farming, when regular human supervision isn't always possible, these problems worsen

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considerably. Automated irrigation systems that use the Internet of Things (IoT) enable continuous monitoring of environmental conditions, precise control of water distribution, and remote supervision of farm activities via smart devices. This approach is designed to solve big challenges, including ensuring there is enough water, making farming less dependent on the seasons, addressing labour shortages, and letting people check on farm conditions from afar using computers or smartphones. This skill helps farmers monitor their crops' health and soil moisture levels, and act quickly when things get bad. Agriculture remains an important social and economic activity worldwide. It provides jobs, food security, and a big boost to national economies. Tace et al. [10] noted that the use of smart technologies such as IoT, AI, and data analytics in farming heralds a new era, known as "smart farming" or "precision agriculture." However, agriculture still faces problems such as climate change, infertile soil, insufficient water, and poor irrigation methods [3]. Climate change has made rainfall less regular, prolonged droughts, and increased the frequency of extreme weather events. All of these things have a direct impact on crop productivity and soil health. Water scarcity is a global problem, especially in dry and semi-arid areas, where agriculture consumes more than 70% of available freshwater. Flood and furrow irrigation are two examples of poor irrigation practices that waste water and cause soil erosion, nutrient loss, and reduced crop response. Traditional irrigation methods rely heavily on human monitoring, intuition, and set timetables rather than on the current demands of soil and crops [1].

This leads to uneven and erroneous water distribution. To solve these problems, modern farming methods such as drip irrigation, sprinkler systems, automated pumping, and precision irrigation have been developed. Even though sprinkler and drip systems use far less water than traditional flooding methods, they can't perform as well without smart sensing and control technologies. Obaideen et al. [4] stated that almost 70% of all water used for farming is wasted due to poor irrigation practices, harming the environment and wasting resources. Because of this, modern irrigation systems need to be automated, adaptable, data-driven, and able to respond in real time to changes in soil moisture levels and weather conditions [8]. IoT-based smart irrigation systems are among the new ideas that stand out as very useful and cutting-edge. They may help farmers use less water while also making their farms more productive and environmentally friendly. IoT refers to a network of devices connected to the internet that have sensors, microcontrollers, and communication modules, enabling them to gather, transmit, and analyse data in real time [6]. In farming, IoT devices monitor key factors such as soil moisture, relative humidity, air temperature, light intensity, and reservoir water levels. These data are then sent wirelessly to cloud platforms, web dashboards, or mobile apps so farmers can analyse trends and make informed decisions about how much water to provide their crops. The proposed IoT-based smart agriculture automatic irrigation system is designed to address water scarcity, climate-related constraints in agriculture, and the inefficiencies of manual watering methods. As new engineers working with cars and electronics, researchers leveraged skills from several fields to develop and implement a solution that centred on sustainability and efficiency. Researchers identified operational gaps in existing irrigation methods, both old and new, through a thorough examination. These gaps included a heavy reliance on manual labour, unreliable soil feedback, the need to manually switch pumps, low water-use efficiency, and no remote access [10]. In response, researchers developed and implemented a more robust automated model that leverages sensing technology, cloud-based data processing, and real-time communication.

The system created solves common problems, including scheduling irrigation, reducing water waste without supervision, dealing with short growing seasons, and managing high energy and labour costs. In ancient farming techniques, people could only grow crops during the rainy season because there wasn't enough water during the dry months. IoT-based irrigation systems enable year-round crop growth by ensuring water is always available and can be controlled, regardless of the weather. The method also reduces the amount of work required because irrigation can be automated and controlled remotely. Farmers can then use the time and effort they saved to secure their crops, market them, or pursue other activities that add value. Rathika et al. [7] and Nwazor et al. [5] report that precision irrigation systems greatly improve crop yields while reducing watering frequency, water use, and operating costs. The proposed technique is just as useful on large farms, peri-urban farm clusters, smallholder farms, greenhouses, nurseries, and in urban home gardens. Users can monitor live field conditions, see how wet the soil is, track past irrigation operations, and receive automatic warnings when certain levels are reached on smartphones or personal computers. This function is especially helpful for farmers who work off-site, older people, those who run multiple farms, and people who practice rooftop farming in cities. Remote access makes things more flexible and helps quickly fix problems with irrigation systems or address changes in the weather. The system architecture includes a microcontroller unit (such as an Arduino UNO, ESP8266, or ESP32), soil moisture sensors, humidity and temperature sensors, a water pump, an electromagnetic relay, a power supply system, a water tank or reservoir, a Wi-Fi router, and optional solar power units. The main sensors that measure volumetric water content in the root zone are soil moisture sensors. The microcontroller continuously reads sensor data and compares it against thresholds set in the firmware.

The microprocessor activates the relay that powers the water pump when the measured moisture level drops below the threshold. This starts the irrigation process. The pump automatically turns off when the desired moisture level is reached, eliminating over-irrigation and waterlogging. This automatic control reduces human errors and improves irrigation accuracy. Wi-Fi or GSM-based connection modules that send sensor data to centralised cloud platforms enable IoT device connectivity. Real-time visualisations, such as moisture level graphs, pump status indicators, climatic parameter records, and alarms, can be viewed on mobile and web dashboards. Data logging lets you track environmental factors over time, enabling predictive irrigation analytics and comparing crop performance. In the future, when artificial intelligence and machine learning are used at work, the system will be able to learn about how crops use water, how water needs change with the seasons, and how irrigation needs change over time. IoT-based smart irrigation systems do more than improve productivity; they also help the environment in a big way. Optimised irrigation saves fresh water, reduces greenhouse gas emissions from electricity use for pumping, and prevents fertiliser runoff that can harm rivers and groundwater. Reduced runoff preserves soil microbiology and natural fertility, both of which are important for the long-term health of agriculture. Precision irrigation also makes plants more resistant to drought- and extreme-weather-induced stress, supporting climate-smart agriculture programs worldwide. Even with these improvements, many problems remain to be solved before IoT-based irrigation solutions can be widely used in developing countries. Some of these include the high upfront cost, the lack of internet and power access in many rural areas, the difficulty of maintaining the systems, and the fact that many farmers don't know how to use computers [2]. Also, extreme field conditions, such as heavy rain, dust, and changing temperatures, shorten sensor lifespans and reduce accuracy. To solve these problems, governments, agricultural research institutions, engineering groups, and the commercial sector must all work together.

Smallholder farmers can adopt technology more quickly and easily if they have access to training programs, technological subsidies, microfinance support, and user interfaces that are easy for them to use. The future of IoT-based farming looks bright and will change the way things are done. Systems will be energy-independent and able to operate in off-grid or remote locations when connected to solar-powered pumping units. Crewless aerial vehicles, thermal-imaging drones, and satellite sensing systems can all work together with IoT infrastructure to create real-time smart maps of crop health, water stress, and nutritional deficits. Blockchain technology can also be used to protect farm data and make the supply chain more transparent by enabling easier tracing of goods, verifying their quality, and ensuring fair prices. Smart contracts can handle billing for irrigation services and agreements between collaborating farmers. Also, government-led precision agricultural frameworks can include these systems in national digital agriculture missions to boost productivity at both regional and national levels. To sum up, the IoT-based smart agriculture automated irrigation system is a strong, game-changing idea that can modernise traditional farming while addressing the world's water shortages. The technology enhances irrigation efficiency, boosts agricultural productivity, and helps the environment by monitoring data in real time, applying water with greater accuracy, and automatically controlling pumps. It provides farmers with useful information, reduces the amount of work people have to do, and makes the climate more resilient. This combination of IoT technology and farming shows how new engineering ideas can solve real-world problems, ensure everyone has enough food, and create sustainable, technology-driven agricultural economies of the future.

1.1. Objective

To design and implement an IoT-based smart agriculture automatic irrigation system using a drone in Rwanda. A Case Study: Nyagatare District.

1.2. Justification of the Study

The design and implementation of an IoT-based, drone-based smart agriculture automatic irrigation system in Nyagatare District, Rwanda, is crucial for addressing the challenges faced by local farmers. Nyagatare is primarily an agricultural region, but, like many rural areas in Africa, it struggles with water scarcity, inefficient irrigation practices, and unpredictable weather patterns. Traditional irrigation systems are often inadequate, resulting in either over-irrigation, leading to water wastage, or under-irrigation, causing crop stress and reduced yields. The integration of IoT technology, particularly automated irrigation and drone surveillance, offers a solution to these issues by ensuring efficient water use, optimising crop management, and enhancing overall productivity. This study will contribute to the ongoing efforts to modernise Rwanda's agricultural sector by promoting precision farming techniques. Drones equipped with IoT sensors can monitor large agricultural areas, collecting real-time data on soil moisture, weather conditions, and crop health. This data can inform decisions on irrigation schedules and water distribution, reducing the risk of crop failure and improving water conservation. Furthermore, by implementing this system in Nyagatare, the research will highlight the potential benefits of drone-assisted smart agriculture in a local context, providing valuable insights for similar rural regions across Rwanda and East Africa. This approach aligns with Rwanda's vision of adopting innovative technologies to improve agricultural productivity, sustainability, and food security, ultimately supporting the nation's economic growth and development.

1.3. Scope of Study

This paper focused on designing and implementing an IoT-based, drone-based automatic irrigation system for smart agriculture in Rwanda's Nyagatare District. The paper used IoT technology, including sensors, weather-monitoring devices, and data analytics platforms, to monitor farm conditions and automate irrigation. The system was tested and deployed in selected farms to evaluate its performance. The paper was cost-effective, promoting sustainable water usage and environmental conservation. The paper was completed within 12 months, and its findings contributed to academic research on IoT applications in agriculture. However, the paper did not address other agricultural challenges and was not broader in scope.

1.3.1. State of the Art

The integration of IoT technology in agriculture, particularly for automatic irrigation systems, has seen significant advancements in recent years, offering solutions to critical challenges such as water scarcity, crop management, and climate variability. Smart agriculture systems leverage IoT sensors, weather-monitoring devices, and drones to provide real-time data that enables precise irrigation, reducing water waste and optimising crop yields. These systems use a combination of soil moisture and temperature sensors, along with environmental monitoring tools, to collect data, which is then analysed and transmitted to a centralised control system for decision-making [9]. This approach allows farmers to manage irrigation schedules remotely, increasing efficiency and minimising human intervention. Drone technology has become a key enabler in smart agriculture, allowing for real-time aerial monitoring of large-scale agricultural areas. Drones equipped with IoT sensors can monitor soil conditions, assess crop health, and detect irrigation needs by providing high-resolution images and geospatial data. This data can be analysed for precision agriculture, enabling targeted water application that ensures crops receive optimal moisture levels. Recent developments also focus on integrating machine learning and AI into these systems to predict weather patterns and automate irrigation systems based on data-driven insights. In regions like Nyagatare District, where agriculture is the mainstay of the local economy, these technologies can revolutionise farming practices, enhancing productivity, promoting sustainability, and ensuring food security. However, while the potential benefits of IoT-based irrigation and drone technology are clear, challenges remain in terms of cost, scalability, and integration with existing farming practices, especially in resource-constrained areas.

1.4. Materials and Methods

1.4.1. Requirement Analysis and Materials

The design and implementation of the IoT-based smart agriculture automatic irrigation system using drones in Nyagatare District required a thorough analysis of the system's functional and technical requirements. The key objectives of the system were to automate irrigation using real-time sensor data, monitor farm conditions remotely, and optimise water use while promoting sustainable agricultural practices. The following steps were taken to identify the requirements and select the appropriate materials for the system:

1.4.2. Functional Requirements

- **Real-time Monitoring:** The system should collect soil moisture, temperature, and weather data across the farm in real time.
- **Automated Irrigation:** Based on sensor data, the irrigation system should automatically activate water delivery when soil moisture falls below a predefined threshold.
- **Remote Control and Monitoring:** Farmers should be able to monitor and control the system remotely via a web application or mobile app.
- **Data Storage and Analysis:** The system should store and analyse the data to enable data-driven decisions and future planning for irrigation schedules.

1.4.3. Technical Requirements

- **IoT Sensors:** Soil moisture, temperature, and humidity sensors, as well as weather monitoring devices, were essential for accurately measuring environmental conditions.
- **Microcontroller and Communication Modules:** A microcontroller (e.g., Arduino or Raspberry Pi) was needed to process sensor data and control the irrigation system. Communication modules such as Wi-Fi or GSM were required for transmitting data to the cloud for remote monitoring.
- **Actuators:** Solenoid valves and water pumps were used to control water flow based on sensor input.
- **Drones:** Drones equipped with IoT sensors and cameras were necessary for aerial monitoring of farm conditions, including crop health and irrigation needs.
- **Power Supply:** A reliable power source (e.g., solar panels or batteries) was required to ensure continuous system operation in remote areas.
- **Cloud Platform:** A cloud-based platform, such as Adafruit IO or ThingSpeak, was selected to store sensor data and provide a user interface for remote monitoring and control.

1.4.4. Materials

- **Soil Moisture Sensors:** Used to measure the soil's water content at various points in the field.

- **Temperature and Humidity Sensors:** Monitored environmental conditions affecting crop growth and irrigation needs.
- **Microcontroller (e.g., Arduino or Raspberry Pi):** Served as the brain of the system, processing incoming data and triggering irrigation actions.
- **Wi-Fi/GSM Modules:** Enabled communication between the system and remote monitoring platforms.
- **Solenoid Valves:** Controlled the flow of water to the crops based on the processed sensor data.
- **Water Pumps:** Used to deliver water to the irrigation system as needed.
- **Drones with IoT Sensors:** Equipped to fly over the farm and capture high-resolution data for aerial monitoring.
- **Cloud Platform (Adafruit IO or ThingSpeak):** Used for data storage and providing a remote user interface for farmers to control the system.

These materials were selected to ensure the system's functionality and reliability in real-world conditions, aligning with the specific needs of Nyagatare District's agricultural landscape. The combination of IoT sensors, drones, and cloud-based platforms was expected to improve irrigation efficiency and promote sustainable farming practices in the region.

2. Research Design

The study design for implementing an IoT-based, drone-based automatic irrigation system for smart agriculture in Rwanda. A Case study: Nyagatare District city is displayed in Table 1:

Table 1: Used methodology for the study

Objectives	Hypotheses	Methodology	Statistics
Design and implement an IoT-based smart irrigation system	The IoT-based smart irrigation system will improve water efficiency.	System design and development using IoT sensors, microcontrollers, and drones.	Descriptive statistics, performance metrics analysis (e.g., water usage reduction).
Monitor soil moisture and environmental conditions using IoT sensors	Real-time monitoring of soil moisture and environmental conditions is feasible and effective.	Deployment of soil moisture sensors and weather monitoring devices.	Statistical analysis of sensor data (mean, variance, correlation).
Automate irrigation based on real-time data	Automation will reduce water usage and improve crop yield.	Implement an automated irrigation system triggered by sensor data.	Comparison of water usage before and after system implementation (paired t-test).
Enable remote control and monitoring of irrigation via an app	Remote monitoring and control will enhance system management and flexibility.	Development of a mobile/web app for remote control.	Usage statistics of remote access, user feedback analysis.
Evaluate system performance in Nyagatare District.	The system will successfully increase water efficiency and crop yields in Nyagatare District.	Implementation of the system in selected farms in Nyagatare.	Comparative analysis of crop yield and water usage before and after system installation (ANOVA).
Assess the feasibility of drone integration in the irrigation system	Drones will enhance monitoring and data collection for irrigation decision-making.	Integration of drones for aerial monitoring.	Statistical analysis of drone data efficiency (e.g., area covered, accuracy).

3. Presentation of the Study Area

This research focuses on Nyagatare District in Rwanda, a major agricultural region with a rural population heavily reliant on agriculture. The district's climate and rainfall patterns make crop cultivation essential. Traditional irrigation methods are inefficient, leading to water wastage and inadequate supply. An IoT-based smart irrigation system could improve water usage efficiency, scheduling, and crop yields. The system, supported by drone technology, could be remotely controlled, conserving resources and improving productivity. Nyagatare's increasing interest in adopting modern technologies for agricultural development makes it an ideal case study for evaluating IoT-based smart agriculture solutions, benefiting farmers across the district and Rwanda.

3.1. Sampling Methods and Techniques

The study aimed to collect representative data for the design and implementation of an IoT-based smart agriculture automatic irrigation system in Nyagatare District. The sampling strategy involved selecting farms with diverse crop types, irrigation needs, and geographical locations to provide comprehensive insights. Targeted sampling was used to select farms that would benefit from the system, while random sampling was employed to avoid bias. Cluster sampling was used to manage data collection logistics, and convenience sampling was used for practical reasons. The sample size was determined based on the study's objectives and the need for statistically significant results. Data were collected through field surveys, sensor data, drone imagery, and remote monitoring. The mixed-method approach ensured the data were representative of the diverse farming conditions across Nyagatare District. It enhanced the reliability and validity of the findings, making them applicable for future large-scale implementations of IoT-based irrigation systems in similar regions.

3.2. Population of the Study

The study aimed to evaluate the impact of an IoT-based smart irrigation system on farmers and agricultural enterprises in Nyagatare District, Rwanda. The core population consisted of small- and medium-scale farmers who practised crop cultivation and were interested in adopting modern irrigation technologies. The study selected a more focused sample of farms based on factors such as irrigation practices, water access, and willingness to participate in the implementation and testing of the system. The population included agricultural cooperatives and institutions, as well as other stakeholders in the agriculture and technology sectors. The ideal participants to assess the impact and feasibility of adopting powered weeding machines and to evaluate the program are the population (100) listed in Table 2:

Table 2: Research population

Farmers	Agricultural Institutions	Agricultural Cooperatives	Relevant Stakeholders	Total
20	40	20	20	100

3.2.1. Sampling Techniques

The sample size was calculated based on the total population of technicians in Kigali, with a 95% confidence level and a 5% margin of error. This combination of methods captured various perspectives and experiences, providing actionable insights into the design of an IoT-based smart irrigation system (Table 3).

Table 3: Sample of study

Farmers	Agricultural Institutions	Agricultural Cooperatives	Relevant Stakeholders	Total
10	20	10	10	50

3.3. Sample Size

The sample size will be determined based on the overall population of technicians in the Nyagatare District. A minimum sample size of 50 participants will be targeted to provide a statistically significant basis for analysis. This sample was included approximately:

- 10 Farmers
- 20 Agricultural Institutions
- 10 Agricultural Cooperatives
- 10 Relevant Stakeholders

3.4. Criteria of Participants' Selection

The study aimed to represent the diverse agricultural conditions in Nyagatare District by selecting participants based on factors such as farm type, irrigation practices, geographical location, willingness to participate, and crop type. Smallholder, medium-scale, and commercial farms were selected based on their size, irrigation practices, geographic location, and willingness to participate and collaborate with researchers. Farmers who are open to adopting new technologies and cultivating crops with consistent moisture levels could benefit from automated irrigation systems.

3.5. Data Collection Techniques and Instruments

The study used various techniques to assess the impact of an IoT-based smart irrigation system on farm performance and water efficiency. Field surveys were conducted to gather baseline information on existing practices, crop types, and water usage habits. Sensor data were collected using IoT sensors to monitor soil moisture levels, weather conditions, and irrigation system performance. Drone monitoring was used to gather aerial images and video footage for crop health assessment. A remote monitoring and cloud-based platform was used to collect data on system performance and management. Focus Group Discussions (FGDs) were conducted to gather qualitative data on farmers' experiences and feedback on the system's usability and challenges.

3.6. Type of Data and Techniques of Data Collection

This study collected data on irrigation system performance, soil moisture levels, crop yield, water usage, and sensor readings. Quantitative data included soil moisture levels, irrigation data, weather data, and crop yield. Qualitative data included farmers' feedback, perceptions of system performance, and challenges encountered during the implementation of an IoT-based irrigation system. Data was collected through surveys, focus group discussions, and open-ended survey questions. Both types of data were analysed. Table 4 shows the data type and the data collection techniques.

Table 4: The type of data and techniques of data collection

Activities	Techniques	Instruments
Survey	Questionnaires	Online surveys using Google Forms
	Interviews	Structured interviews
	Focus groups	Group discussions with predefined questions
Observation	Direct observation	Observing participants' interactions with the system
	Video recording	Recording driving sessions to analyse behaviour
	Field notes	Written notes on observed behaviours and system usage
Data Analytics	Data mining	Analysing large datasets to identify patterns and trends
	Statistical analysis	Applying statistical tests to quantify system performance
	Machine learning algorithms	Developing predictive models based on historical data
Interviews with Experts	Expert consultation	Interviewing engineers, designers, or policymakers
	Stakeholder interviews	Engaging with stakeholders to gather insights

3.7. Field Survey

The field survey was a crucial part of a study aimed at understanding the current state of agriculture in Nyagatare District and how the introduction of an automated irrigation system could improve farm productivity, water conservation, and overall agricultural efficiency. The survey assessed existing irrigation practices, water usage patterns, farm characteristics, and farmers' knowledge and attitudes towards IoT-based irrigation technologies. A structured questionnaire was used to capture both quantitative and qualitative data. The survey was administered by trained enumerators who visited farms in person, focusing on farm size, crop types, irrigation practices, water sources, water usage, water management challenges, and the use of modern technologies. The survey also revealed that a large proportion of farmers expressed interest in adopting smart irrigation technologies, particularly those that could reduce water wastage and improve crop yields. Technological barriers, such as high upfront costs and limited access to mobile technology in rural areas, were identified. The survey provided valuable data that informed the design and implementation.

3.8. Data Analysis Techniques

This study evaluated the effectiveness of an IoT-based smart agricultural irrigation system in Nyagatare District, focusing on water use, crop yields, and farmers' attitudes towards IoT technologies. Qualitative and quantitative data were collected, with thematic and content analyses used to identify patterns. The results provided insights into the system's performance, its impact on water-use efficiency, and its effectiveness in improving crop yields. The findings contribute to understanding the relationship between technological adoption and agricultural productivity.

4. Results and Discussion

The study highlights the transformative potential of Internet of Things (IoT) technology in reshaping modern agriculture. IoT systems optimise water use, reducing waste and contributing to the long-term sustainability of water resources. Automated systems, such as drones and robotic harvesters, reduce labour costs, allowing farmers to focus on strategic planning and quality control. IoT also affects the quality and quantity of agricultural products, enabling farmers to make data-driven decisions to produce healthier crops and achieve higher yields. As technology advances, IoT systems will become more integral to agricultural practices, enhancing precision and efficiency. As adoption increases, IoT could become a key driver of more sustainable agriculture, reduced environmental footprint, and increased food security (Figure 1).

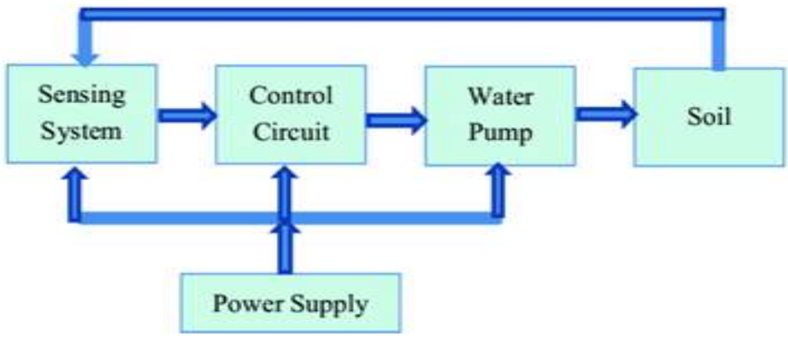

Figure 1: Block diagram of IoT in irrigation

4.1. Strength

The study leveraged a diverse range of data collection methods, including surveys, field experiments, and remote monitoring, to gather comprehensive information on the effectiveness of the IoT-based smart irrigation system. This multi-method approach ensured the collection of both qualitative and quantitative data, providing a well-rounded understanding of the system's impact on water use, crop yields, and farmers' attitudes toward technology adoption. Additionally, integrating drone technology for real-time monitoring and using IoT sensors enabled precise data collection, yielding more accurate and actionable insights.

4.2. Opportunities

The study suggests that optimising the capital structure of the IoT-based irrigation system could unlock further opportunities for scalability and adoption in other regions of Rwanda and beyond. By improving the system's cost-effectiveness, particularly through local partnerships, it could be made more accessible to a broader range of farmers. Additionally, the study highlights the potential to expand IoT applications in agriculture, such as integrating weather-forecasting tools and soil health monitoring, thereby enhancing the system's overall impact on sustainable farming practices.

4.3. Limitations

The study's limitations include its geographic focus on Nyagatare District, which may not fully represent the diverse agricultural environments across Rwanda. The results from this specific location may not be directly applicable to other regions with varying climatic conditions, soil types, and farming practices. Furthermore, the study did not account for all possible external factors that could influence irrigation efficiency, such as access to reliable internet connectivity or the availability of technical support, which could be crucial for the widespread adoption of IoT-based technologies.

5. Conclusion and Recommendations

The IoT-based smart agriculture autonomous irrigation system installed in Nyagatare District, Rwanda, has significant potential to transform how farmers operate, making them more efficient and sustainable. The system lets you control water use accurately by using sensors and real-time data to monitor weather, soil moisture, and your crops' water needs. This reduces water waste, ensures irrigation is done at the right time, and helps crops stay healthy and grow faster. Also, automation reduces the number of workers needed, allowing farmers to focus on other useful tasks and saving total costs in the long run. Even with these benefits, a few problems make it hard for the system to be used broadly. The high cost of setting up and maintaining IoT devices remains a major problem, especially for smallholder farmers. Infrastructure problems, such as poor internet and power in remote regions, also make the system work less well. Also, the fact that farmers don't know much about technology underscores the importance of providing them with sufficient training and ongoing technical support to ensure they use the system correctly. To get more people to use IoT technologies, future initiatives should focus on making them cheaper by subsidising them or manufacturing them locally. To make things run more smoothly and for more people to embrace them, farmer education programs and capacity-building projects are really important. Food security may be much better if the approach were used in other areas with similar farming conditions. Future research should investigate the system's long-term sustainability, scalability, and adaptability across various climatic conditions and soil types to assess its efficacy across diverse agricultural settings.

List of Abbreviations

- **IoT:** Internet of Things
- **AI:** Artificial Intelligence
- **ML:** Machine Learning
- **WSN:** Wireless Sensing Network
- **GPS:** Global Positioning System
- **PLC:** Programmable Logic Controller
- **ADC:** Analogue-to-Digital Converter
- **DAC:** Digital-to-Analogue Converter
- **RAB:** Rwanda Agriculture Board
- **API:** Application Programming Interface
- **WIFI:** Wireless Fidelity
- **V.E:** Volumetric Efficiency
- **T.Fr:** Theoretical Flowrate

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