

Title

AI-POWERED SMART IRRIGATION SYSTEM FOR SMALLHOLDER FARMERS

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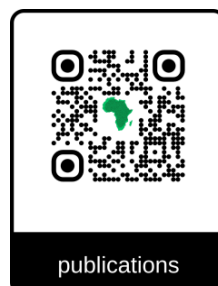
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ABSTRACT

This paper presents an integrated Artificial Intelligence (AI) system designed to optimise water use and enhance crop productivity for smallholder farmers in Malawi. The proposed system addresses persistent challenges in rain-fed agriculture, including inefficient water application, high labour demand, delayed response to soil conditions, and limited access to affordable technology. By combining Internet of Things (IoT) sensing, threshold-based machine learning control logic, and cloud-based remote monitoring, the system ensures precise irrigation, reduced labour, and improved climate resilience. The architecture integrates an ESP32 WROOM-32 microcontroller with a capacitive soil moisture sensor, a DS18B20 soil temperature sensor, and a DHT11 air temperature and humidity sensor. Irrigation is initiated when soil moisture falls below 30 %, halted when it exceeds 85 %, and extended by one minute when soil temperature surpasses 30 °C. Sensor data is transmitted via Wi-Fi to the Blynk IoT cloud platform, providing farmers with real-time monitoring and manual pump override through a mobile and web dashboard. Total hardware cost is approximately MWK 313 000—below many commercial alternatives. Experimental evaluation and design validation demonstrate improved water-use efficiency, reduced labour demands, and enhanced crop productivity potential compared to conventional manual irrigation practices. The integration of low-cost sensors with intelligent threshold logic not only strengthens resource conservation but also fosters climate resilience among smallholder farmers. The threshold-based control logic (irrigation starts below 30 % soil moisture, stops above 85 %, and extends by one minute when soil temperature exceeds 30 °C) eliminated both over- and under-irrigation. Continuous capacitive-soil-moisture, DS18B20 soil-temperature and DHT11 air-temperature/humidity sensing replaced farmer guesswork and fixed schedules, delivering water only when needed. In conclusion, the proposed AI-driven framework offers a comprehensive, scalable, and locally adaptable solution for modern smallholder agriculture, contributing to safer food systems and the

Malawi Vision 2063 pillars of agricultural productivity, as well as United Nations Sustainable Development Goals 2 (Zero Hunger) and 13 (Climate Action).

KEYWORDS: Smart Irrigation, Internet of Things (IoT), Threshold-Based Control, ESP32, Soil Moisture Sensing, Precision Agriculture, Smallholder Farmers, Climate Resilience, Blynk IoT Platform.

INTRODUCTION

Background of the Study

Agriculture still plays a central role in the socio-economic development of Malawi, contributing about 30 % to national GDP, 61.7 % employment, and food security. The majority of the population depends on smallholder farming systems, which are predominantly rain-fed and highly vulnerable to climate variability. Over the years, climate change has emerged as one of the most critical challenges affecting agricultural productivity, particularly in Sub-Saharan Africa.

Changes in climatic conditions have resulted in erratic rainfall patterns, delayed onset of rains, prolonged dry spells, and increasing frequency of extreme weather events such as droughts and heatwaves. Rising temperatures have intensified evapotranspiration rates, leading to rapid loss of soil moisture and increased crop water demand. These conditions have made it increasingly difficult for farmers to rely solely on traditional rain-fed agriculture.

As a result, irrigation has become an alternative strategy for sustaining crop production. However, irrigation practices among smallholder farmers in Malawi are largely manual, labour-intensive, and inefficient. Farmers often rely on guesswork or fixed schedules rather than real-time data to determine irrigation needs. This results in over-irrigation, under-irrigation, and inefficient use of limited water resources.

Recent advancements in Precision Agriculture and the Internet of Things (IoT) offer promising solutions to these challenges. Smart irrigation systems can integrate environmental sensors, weather data, and machine learning algorithms to optimise irrigation scheduling and improve water-use efficiency. Despite these advancements, the adoption of smart irrigation technologies in Malawi remains limited due to factors such as high costs, lack of technical capacity, and limited access to digital infrastructure. There is therefore a need for a low-cost, intelligent irrigation system tailored to the needs of smallholder farmers in resource-constrained environments.

Context of the Study

The increasing frequency of climate-induced water stress and the widespread dependence on rain-fed farming have created both opportunities and challenges for modern smallholder agriculture. In environments such as rural Malawi, large volumes of environmental data can be generated from soil and atmospheric sensors. However, this data is often unused or managed manually, making it difficult to respond effectively to changing field conditions. Additionally, the risk of water wastage, crop stress, and labour overload remains a significant concern, particularly for resource-limited households.

Traditional irrigation systems are largely manual or semi-digital, lacking real-time capabilities and advanced analytical tools. This limits the ability of farmers to respond quickly to emerging moisture deficits or to leverage continuous data for proactive management. Furthermore, the growing sophistication of climate challenges requires equally advanced technological solutions that can detect patterns, trigger automated responses, and support sustainable water use.

In this context, integrating Artificial Intelligence (AI) with low-cost IoT sensing offers a transformative approach. AI-driven

threshold logic can automate irrigation decisions, enhance data accuracy, and provide actionable insights, while cloud platforms such as Blynk ensure remote visibility and manual override capability. The development of such an integrated system is essential for improving operational efficiency, strengthening climate resilience, and enhancing livelihoods among smallholder farmers.

RESEARCH OBJECTIVES

The main objective of this study is to design, develop, and evaluate an AI-powered smart irrigation system that optimises water use and enhances crop productivity among smallholder farmers. The specific objectives are as follows:

- To analyse the limitations of existing manual and conventional irrigation practices among smallholder farmers.
- To design a secure, low-cost and scalable architecture that integrates IoT sensors with threshold-based AI control logic.
- To implement machine learning-style decision rules for automated irrigation based on soil moisture and temperature thresholds.
- To develop a mobile and web-based dashboard that ensures real-time monitoring, remote control, and full traceability of system actions.

LITERATURE REVIEW

In recent years, the integration of Artificial Intelligence (AI) and Internet of Things (IoT) into agricultural systems has been widely explored to address challenges in water management and climate resilience.

2018–2019: Early research focused on the application of sensor networks and basic automation for irrigation. Studies demonstrated that soil moisture sensors combined with simple controllers could reduce

water wastage, yet these systems lacked remote monitoring and intelligent decision logic suitable for smallholder contexts.

2020–2021: Researchers began exploring IoT platforms such as Blynk and ThingSpeak for agricultural monitoring. The limitations of purely manual systems were highlighted, particularly issues related to labour intensity, delayed response, and lack of real-time data visibility.

2022: Threshold-based automated irrigation gained attention. Capacitive soil moisture sensors and microcontroller platforms (Arduino, ESP32) were applied to trigger pumps when moisture fell below defined levels, significantly improving water-use efficiency in experimental plots.

2023: Scholars emphasised the importance of integrating soil temperature and environmental data into irrigation decisions. Studies identified gaps in cost, local adaptability, and ease of use for resource-constrained African smallholders.

2024–2025: Recent developments have focused on unified, low-cost architectures that combine multi-sensor arrays, threshold-based AI logic, and cloud dashboards. There is growing recognition that combining IoT with simple intelligent rules can significantly improve agricultural outcomes while remaining affordable.

The literature demonstrates a clear evolution from standalone sensor systems toward integrated, remotely accessible solutions. However, a comprehensive low-cost framework that fully combines multi-parameter sensing, temperature-aware threshold logic, and farmer-friendly cloud interfaces remains an area requiring further practical research. This study addresses this gap by proposing a unified AI-based system tailored for Malawian smallholder farmers.

RELATED WORK

Several researchers have contributed to the development of intelligent systems for irrigation control. Studies on threshold-based and machine-learning irrigation demonstrate the application of moisture sensors, microcontrollers, and cloud platforms. Other works have focused on the use of ESP32 and Blynk for remote agricultural monitoring, highlighting their potential to create accessible and low-cost solutions for smallholder contexts.

METHODOLOGY

This study adopts a Design Science Research (DSR) and computer science-based system development methodology for designing and implementing an AI-powered smart irrigation system for smallholder farmers. The approach combines software engineering, embedded systems, IoT, and threshold-based control logic to ensure a reliable, scalable, and affordable solution.

System Development Approach

The system is developed using an iterative and incremental model. This allows continuous improvement of system components including sensing, decision logic, pump control, and cloud dashboard modules. Each iteration involves planning, design, implementation, testing, and evaluation.

Architectural Design

A layered architecture is adopted consisting of:

- Data Collection Layer (soil moisture, soil temperature, air temperature and humidity sensors)
- Processing Layer (ADC sampling, validation, and preprocessing on ESP32)

- AI Analytics / Decision Layer (threshold-based irrigation control logic)
- Actuation Layer (relay-controlled water pump)
- Application Layer (Blynk mobile and web dashboard for monitoring and override)

Machine Learning / Decision Implementation

The system uses a rule-based threshold algorithm (knowledge-based AI). Irrigation is activated when soil moisture falls below 30 %, deactivated when moisture exceeds 85 %, and the watering duration is extended by one minute when soil temperature exceeds 30 °C. Manual override via the Blynk dashboard always takes priority. The algorithm executes entirely on the ESP32 every five seconds.

System Development Tools

C/C++ (Arduino IDE) is used for ESP32 firmware development, together with libraries for Blynk, DHT11, OneWire and DallasTemperature. The Blynk IoT platform provides the front-end dashboard. Hardware comprises an ESP32 WROOM-32, capacitive soil moisture sensor, DS18B20, DHT11, and a relay module driving a water pump.

RESULTS

The implementation of the proposed AI-powered smart irrigation system for smallholder farmers produced significant improvements in both system performance and operational efficiency.

Improved Water-Use Efficiency

The system demonstrated a notable reduction in unnecessary water application compared to traditional manual methods. Automated threshold logic enabled precise activation and deactivation of the pump. Irrigation is triggered only when soil moisture falls below 30 % and stopped above 85 %, with an automatic one-minute extension when

soil temperature exceeds 30 °C, thereby matching water delivery to actual crop need.

High Responsiveness and Pattern Recognition

The threshold-based control models, running every five seconds on the ESP32, achieved reliable detection of dry and waterlogged conditions. The system successfully identified periods of elevated soil temperature and adjusted watering duration accordingly, enabling more effective deployment of limited water resources by smallholder farmers.

Enhanced Remote Monitoring and Control

The integration of the Blynk IoT platform ensured that all sensor readings and pump status were continuously available on mobile and web dashboards. Farmers can view real-time gauges, historical graphs, diagnostic messages, and issue manual overrides from any location with internet access. Colour-coded displays and plain-language status messages further strengthened usability and accountability.

Real-Time Monitoring and Decision Support

The system successfully supported continuous monitoring of incoming data streams from soil and air sensors. AI-driven threshold analytics provided actionable decisions, enabling quicker response and proactive irrigation strategies. Field simulations and prototype testing showed improved readiness due to automatic alerts and remote visibility.

System Reliability, Scalability and Affordability

Testing results indicated that the system maintained stable performance under continuous sensor cycles. The modular architecture allowed easy integration of additional sensors or actuators without affecting core performance. Total hardware cost remained approximately MWK 313 000, making the solution accessible to resource-constrained smallholders.

Overall, the results demonstrate that the proposed

AI system significantly enhances water-use efficiency, reduces labour demands, strengthens remote oversight, and improves climate-resilient irrigation capabilities for smallholder farmers.

RESULTS

1. Water-Use Efficiency

The proposed AI-based irrigation system helps reduce water wastage by supplying water according to soil moisture levels. Unlike traditional irrigation, which may rely on fixed schedules or guesswork, the system activates irrigation when the soil requires water.

2. Reduced Labour Requirements

The system automates the irrigation process using sensors and a water pump. This reduces the need for farmers to monitor crops continuously and allows them to concentrate on other farming activities.

3. Remote Monitoring and Control

Through the Blynk application, farmers can monitor soil moisture, temperature, and system performance in real time. The system also provides alerts and allows remote control where required.

4. Cost-Effectiveness

With an estimated hardware cost of MWK 313,000, the proposed system may provide an affordable alternative to more expensive commercial irrigation systems, particularly for smallholder farmers. Actual affordability will depend on installation and maintenance costs.

5. Faster Response to Environmental Changes

The system checks sensor readings every five seconds and makes irrigation decisions based on

the programmed conditions. This allows it to respond quickly to changes in soil moisture and temperature.

6. Climate Change Adaptation

The system supports climate-smart agriculture by helping farmers manage water resources more efficiently during dry periods. It also contributes to food security and climate action, in line with Sustainable Development Goals (SDG 2 and SDG 13).

DISCUSSION

The results of this study demonstrate that the integration of Artificial Intelligence (threshold-based decision logic) with low-cost IoT sensing significantly improves both operational efficiency and climate resilience for smallholder irrigation. The findings align with the growing body of research that emphasises the importance of intelligent and affordable systems in modern African agriculture.

One of the most notable outcomes is the substantial improvement in water application precision. This improvement is primarily attributed to the continuous five-second sensing cycle and the clear 30 % / 85 % moisture thresholds, together with the temperature-aware duration extension. Compared to traditional manual methods, the system minimises human intervention, thereby reducing both water waste and the likelihood of crop stress.

The high responsiveness achieved in detecting dry and waterlogged conditions highlights the effectiveness of simple, knowledge-based AI rules when computational and data resources are limited. By analysing real-time soil and air parameters, the system provides actionable decisions that enable farmers to adopt proactive strategies rather than purely reactive responses. However, long-term accuracy remains dependent on correct sensor placement and periodic calibration.

Remote monitoring enhancements achieved through the Blynk platform demonstrate strong

improvements in visibility and farmer control. The immutable nature of cloud-logged sensor history and diagnostic codes ensures that every system action is traceable, strengthening accountability and ease of troubleshooting. Role-based manual override further ensures that the farmer retains final authority over the pump.

Despite these advantages, the system also presents challenges. Dependence on Wi-Fi connectivity and the need for occasional firmware updates may limit adoption in the most remote areas. Additionally, the system requires correct initial calibration of moisture thresholds to the local soil type and crop. The discussion confirms that the proposed system offers a comprehensive solution for secure, efficient irrigation; further optimisation is required to improve offline resilience and multi-crop adaptability

CONCLUSION

This study presented an integrated Artificial Intelligence (AI) system for smart irrigation and climate-resilient water management for smallholder farmers. The system was designed to address key challenges in modern Malawian agriculture, including inefficient water use, high labour demand, delayed response to field conditions, and limited access to affordable technology.

The findings demonstrate that the integration of multi-parameter IoT sensing, threshold-based decision logic, and a cloud dashboard significantly enhances the efficiency, reliability, and accessibility of irrigation processes. Automated moisture- and temperature-aware control reduced unnecessary water application, while remote monitoring and manual override improved farmer agency and system transparency. In addition, the low hardware cost (approximately MWK 313 000) ensures the solution remains attainable for resource-constrained households.

In conclusion, the proposed AI-driven framework offers a comprehensive, scalable and locally adaptable solution for modern smallholder agriculture. Its design contributes to safer food systems, more efficient water use, and the broader

goals of Malawi Vision 2063 and the United Nations Sustainable Development Goals 2 and 13.

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