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Smart Fertigation System: Integrating Sensors, Raspberry Pi, Microcontroller (ESP32S3 and ESP8266), Message Queuing Telemetry Transport (MQTT) protocol, Node-RED and Large Language Model (LLM) for Sweet Potato (*Ipomoea batatas*) Cultivation Management

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ABSTRACT : *Sweet potato planting using fertigation system using burnt paddy husk requires strict monitoring of electrical conductivity (EC), moisture, and environmental climates. This paper presents an integrated Internet of Things (IoT) architecture tailored for open fertigation sweet potato (Ipomoea batatas) cultivation. The hardware deployment combines four RS485 8-in-1 soil sensors paired with four ESP32-S3 nodes across four field zones for root-zone monitoring (soil moisture, temperature, electric conductivity (EC), pH, salinity and Nitrogen, Phosphorus and Potassium, alongside dual ESP8266 node equipped with BME280 and BH1750 sensors for ambient climate monitoring. Data telemetry is handled via MQTT and processed by Node-RED as dashboard on a Raspberry pi 5 acts as a server. To overcome the static threshold limitations of traditional alerts, a quantized TinyLlama:1.1B Language Model (LLM) is deployed locally to act as an interactive agronomic assistant. The assistant ingests real-time telemetry context to generate automated situation alerts and respond to natural language farmer queries. Experimental results demonstrate system reliability, telemetry latency, and the effectiveness of LLM-guided fertigation.*

KEYWORDS *Monitoring system, fertigation system, IoT application, Large Language Model (LLM)*

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I. INTRODUCTION

Fertigation systems using organic substrates like burnt paddy husk and cocopeat combined with precision drip fertigation—the simultaneous application of irrigation water and soluble fertilizers—have emerged as a transformative agricultural approach to maximize crop yield, prevent soil-borne diseases, and optimize resource-use efficiency (Sportelli et al., 2024). In tropical agricultural settings, the open-field cultivation of high-value tuber crops such as sweet potato (*Ipomoea batatas*) demands strict, real-time monitoring of root-zone dynamic properties, including volumetric soil moisture, electrical conductivity (EC), pH, salinity, and macronutrient concentrations (Nitrogen, Phosphorus, and Potassium), alongside climate environmental parameters like ambient temperature, relative humidity, and light intensity (Inayah et al., 2026; Mahmudin & Mohammad Radzi, 2025). Conventional manual irrigation and fixed-schedule fertilization techniques frequently suffer from nutrient leaching, water inefficiency, and severe yield fluctuations caused by dynamic weather variations and human error (García et al., 2020; Obaideen et al., 2022). Integrating smart Internet of Things (IoT) sensing technology into fertigation system establishes an automated, data-driven framework capable of maintaining optimal root-zone conditions, enhancing fertilizer utilization efficiency and driving sustainable agricultural digitalization (Nor, Isa, et al., 2024; Nor, Jumali, et al., 2024; Oguntoye et al., 2024).

To ensure accurate environmental data collection across field zones, modern smart farming relies on modular hardware architectures powered by high-performance, low-power microcontrollers (García et al., 2020). For root-zone telemetry, multi-parameter soil sensors—such as RS485 8-in-1 probes operating on Modbus RTU or SDI-12 industrial protocols—interface directly with advanced 32-bit dual-core

microcontrollers like the Espressif Systems ESP32-S3 to acquire precise measurements of soil moisture, temperature, EC, pH, salinity, and NPK (Azwa Mahmudin & Mohammad Radzi, 2025; Zailani et al., 2021). Concurrently, secondary microcontroller nodes, such as the ESP8266, are deployed with dedicated environmental sensors—including the BME280 for ambient temperature and relative humidity, and the BH1750 for solar irradiance (Azman et al., 2023; Ariffin & Zin, 2021). Decoupling the sensing architecture into dual specialized nodes separates heavy root-zone telemetry processing from ambient atmospheric monitoring, ensuring operational stability, reducing energy consumption, and avoiding bottlenecks in field deployments (Samsuri et al., 2024).

The middleware layer of intelligent fertigation systems depends on reliable communication protocols and localized edge processing server nodes (Zare & Iqbal, 2021). Distributed sensor nodes transmit telemetry payloads over Wi-Fi using the lightweight Message Queuing Telemetry Transport (MQTT) protocol, which facilitates low-latency, asynchronous publish-subscribe messaging between edge nodes and centralized brokers (Sportelli et al., 2024; Zare & Iqbal, 2021). To overcome the vulnerability of intermittent internet connectivity in rural agricultural sites, a local single-board computer—specifically a Raspberry Pi 5—serves as the local server hosting an on-device Mosquitto MQTT broker (Zare & Iqbal, 2021). The Raspberry Pi runs Node-RED, an open-source visual flow middleware, to execute real-time telemetry processing, store time-series data locally, and power an interactive visual dashboard for supervisory control and immediate root-zone parameter tracking (Mohd Darus et al., 2025; Zare & Iqbal, 2021).

Despite the growth of automated IoT monitoring, conventional fertigation control systems remain limited by static threshold alerts, basic PID controllers, or rigid Fuzzy Logic rules that lack contextual adaptability to dynamic crop development stages or erratic climates (Ali et al., 2025; Oguntoye et al., 2024). While artificial intelligence and machine learning models have increasingly been integrated into smart irrigation to optimize water and nutrient allocation (Ali et al., 2025), traditional machine learning models lack conversational interpretability for non-technical farmers. Deploying a quantized Large Language Model (LLM), such as TinyLlama:1.1B, locally on the Raspberry Pi server introduces a dynamic decision-support capability. By continuously analyzing incoming MQTT telemetry streams, the LLM generates automated, context-aware situation alerts and answers natural language agronomic queries, transforming raw sensor data into actionable decision-making for precision sweet potato fertigation that assist farmers on making real time decisions (Ali et al., 2025; Inayah et al., 2026).

II. MATERIALS AND METHODS

System design

The proposed system architecture for open fertigation sweet potato cultivation in a soilless medium using burnt paddy husk substrate employs a multi-tiered design combining node sensing, lightweight telemetry, LLM integration, and local server management (Inayah et al., 2025; Zamora-Izquierdo et al., 2019). At the hardware perception layer, four ESP32-S3 nodes paired with an RS485 8-in-1 soil sensors measures root-zone parameters—specifically soil moisture, temperature, electrical conductivity (EC), pH, salinity, and Nitrogen, Phosphorus, and Potassium (NPK)—while two ESP8266 nodes—dedicated separately to a BME280 atmospheric sensor and a BH1750 solar irradiance sensor—track ambient climate conditions. Another ESP8266 connected to a relay module acts as the water pump control node (Adamo et al., 2025).

Data telemetry is transmitted via the MQTT protocol (Ahmad et al., 2019) to a central Raspberry Pi 5 local server, which runs Node-RED as a real-time monitoring and processing dashboard. To overcome the static threshold limitations of conventional alerts, a quantized TinyLlama:1.1B Large Language Model (LLM) is deployed locally on the server to function as an interactive agronomic assistant, ingesting real-time telemetry context to generate automated situation alerts, respond to natural language farmer queries, and guide fertigation to maintain optimal root-zone parameters based on real-time sensor readings.

List of Components

Overall, the system consists of a server and seven nodes: six sensor nodes and one water pump control node. The major components used in building the fertigation system include a Raspberry Pi 5 with 8 GB of RAM, ESP32-S3-RS485-CAN-U (Zailani et al., 2021), ESP8266, RS485 8-in-1 soil sensor, BME280 sensor, BH1750 sensor, relay module, 100W monocrystalline solar panel, 30A solar charge controller, and a 12.8V 12Ah LiFePO4 lithium battery. Solar energy power as a source for the node consisting of the ESP32-S3-RS485-CAN-U and RS485 8-in-1 soil sensor.

System server

The central server infrastructure is powered by a high-performance Raspberry Pi 5 (8 GB RAM) single-board computer acting as an on-site local server, designed to provide resilient, low-latency data management independent of cloud connectivity (Fig.1) (Lean et al., 2024; Zamora-Izquierdo et al., 2019). At the core of its

middleware stack, an on-device Mosquitto MQTT broker acts as the lightweight messaging hub, ingesting incoming asynchronous telemetry streams transmitted by the field-deployed ESP32-S3 and ESP8266 microcontroller nodes (Ahmad et al., 2019). Running alongside the broker, Node-RED serves as the visual flow editor and processing controller; it parses raw JSON telemetry payloads, renders an intuitive web-based supervisory dashboard for real-time tracking, and manages local data persistence. To ensure long-term time-series record keeping and straightforward offline data evaluation without external database overhead, Node-RED continuously appends all calibrated sensor readings—including soil moisture, EC, pH, NPK, temperature, humidity, and light intensity—into structured CSV log files saved directly to local storage. The Raspberry Pi 5 is connected to a router and configured with Tailscale software allowing secure remote connectivity via desktop computers, laptops, and smartphones.

To enhance traditional rule-based fertigation with contextual intelligence, the Raspberry Pi 5 incorporates Ollama as an efficient, localized execution engine for edge AI inference. Operating entirely offline on the local server, Ollama hosts a quantized TinyLlama:1.1B Large Language Model (LLM) tuned to serve as an interactive agronomic assistant. Node-RED automatically feeds real-time CSV log summaries and active MQTT telemetry snapshots into Ollama's local API prompts. This setup enables the LLM to continuously interpret root-zone dynamic shifts, evaluate environmental stresses against ideal sweet potato growth parameters, push automated situation-based alerts beyond static thresholds, and respond to natural-language queries from farm operators directly through the Node-RED visual interface.



Fig.1. Raspberry pi 5 used as local server in the system

ESP32-S3-RS485-CAN-U and RS485-8-in-1 soil sensor

At the hardware perception layer of the root-zone monitoring node, the ESP32-S3-RS485-CAN-U development board serves as an integrated, low-power microcontroller unit equipped with dedicated onboard RS485 transceivers to directly interface with an RS485 8-in-1 multi-parameter soil sensor (Fig.2). Communicating via the Modbus RTU protocol over the differential RS485 bus, the 8-in-1 probe collects real-time root-zone telemetry including volumetric soil moisture, temperature, electrical conductivity (EC), pH, salinity, and Nitrogen, Phosphorus, and Potassium (NPK) concentrations (Agustirandi et al., 2024). To ensure continuous, autonomous field operation in remote sweet potato plots without reliance on grid power, the node is integrated with a solar power supply system—consisting of a photovoltaic solar system deliver stable voltage outputs to both the ESP32-S3 board and the sensor probe. This solar-powered architecture guarantees uninterrupted sensor sampling and low-latency MQTT data transmission to the Raspberry Pi server even during prolonged periods of overcast weather.

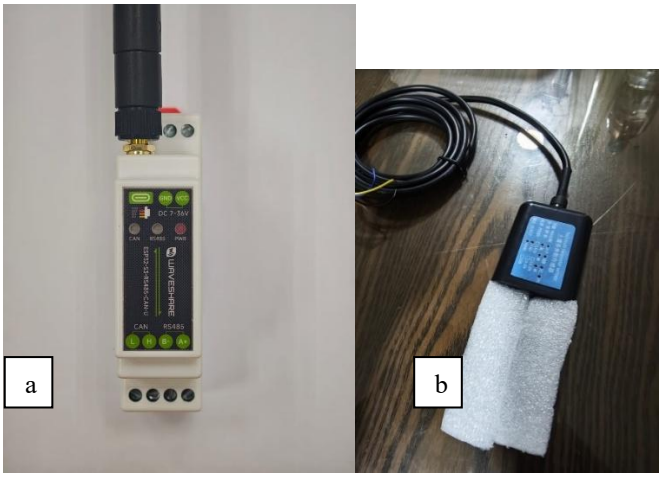


Fig.2. ESP32-S3-RS485-CAN-U microcontroller (a) and RS48 5 8 in 1 soil sensor (b) using in the system

ESP8266, BME280 sensor and BH1750 sensor

The climate monitoring node integrates a low-power, Wi-Fi-enabled ESP8266 microcontroller paired with a precision BME280 atmospheric sensor and a BH1750 ambient light sensor to track environmental parameters critical for sweet potato crop growth (Fig.3) (Guntaka et al., 2021). Communicating over a shared digital I2C bus interface, the BME280 sensor captures real-time measurements of ambient air temperature, relative humidity, and barometric pressure, while the BH1750 sensor measures ambient solar illuminance (light intensity in Lux). The ESP8266 processes these combined climate inputs and publishes the telemetry via the lightweight MQTT protocol over Wi-Fi to the central server (Ahmad et al., 2019). To ensure continuous, autonomous field deployment in open-field plots without grid dependency, the node is powered by a solar energy harvesting system—combining a solar system and a DC-DC converter to maintain a steady supply voltage during night-time operation and prolonged overcast conditions. Both BME280 and BH1750 sensors were built separately into two nodes but share the same power source.

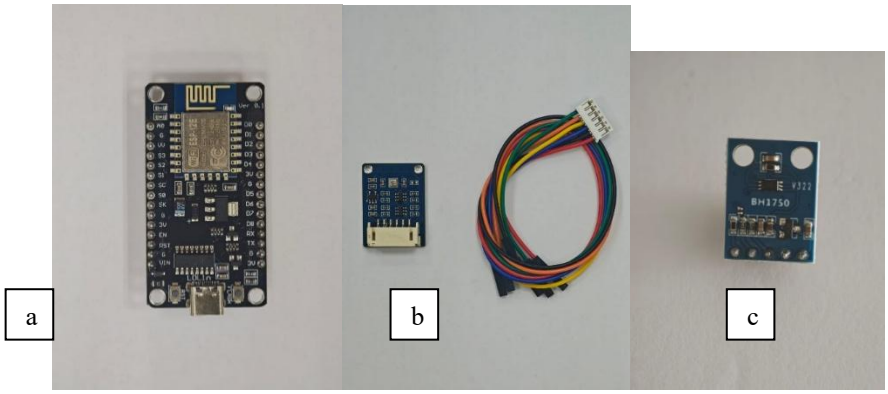


Fig.3. ESP8266 microcontroller (a); BME 280 sensor (b) for environment temperature, humidity and pressure reading; and BH1750 sensor for light intensity reading.

ESP8266 water pump control

The actuation layer for automated fertigation is managed by a dedicated water pump control node powered by an ESP8266 microcontroller interfaced with a digital relay module that energizes a magnetic contactor to switch the 2.0 HP water pump (Fig.4). Functioning as a subscribed client within the MQTT broker network, this node listens for specific control payload commands dispatched from the central Node-RED middleware running on Raspberry Pi 5. When an irrigation event is triggered via dashboard button, time scheduling, or LLM-assisted agronomic prompts, Node-RED transmits an execution message to ESP8266. The microcontroller processes the payload and toggles the relay state to energize or de-energize the magnetic contactor to turn on or off the fertigation pump, delivering precise volumes of water and nutrient solution directly to the burnt paddy husk substrate.

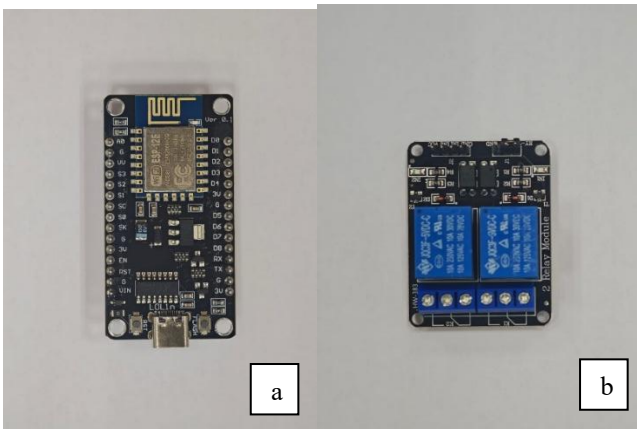


Fig.4. ESP8266 microcontroller (a) combines with relay module (b) for water pump control

Large Language Model

To overcome the static threshold limitations of conventional rule-based alerts and provide intuitive decision support, the system incorporates Large Language Model (LLM) framework running directly on the Raspberry pi 5 server. Operating entirely offline via the local Ollama inference engine, a quantized TinyLlama:1.1B model is utilized to deliver real-time agronomic reasoning within the memory and compute constraints of the Raspberry Pi 5 (Fig.5). The Node-RED middleware continuously constructs contextual prompt payloads containing real-time MQTT telemetry snapshots—such as root-zone soil moisture, EC, pH, and macronutrients, alongside climate ambient temperature, humidity, and lux levels and transmits them to Ollama's local REST API. By evaluating dynamic substrate and atmospheric conditions against target sweet potato (Ipomoea batatas) growth stages, the LLM generates automated, context-aware situation alerts and responds to natural language queries posed by farm operators via the Node-RED dashboard interface. This local AI integration transforms raw IoT sensor streams into actionable agronomic insights and guiding precision fertigation.

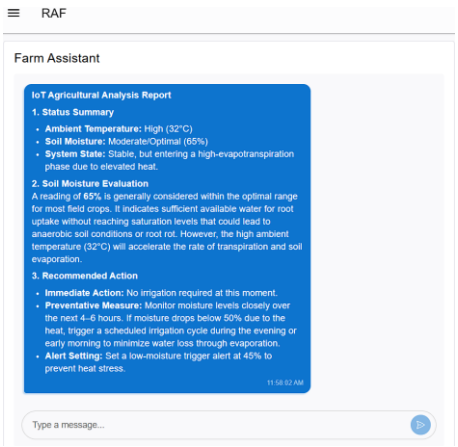


Fig.5. LLM model using Ollama with a quantized TinyLlama:1.1B model act as farm assistant

Node-Red Dashboard

The supervisory control, data visualization, and middleware integration layer is driven by a web-based Node-RED dashboard hosted on the central Raspberry Pi 5 server (Fig.6) (Lean et al., 2024). Functioning as the operational command hub, Node-RED subscribes to asynchronous telemetry streams managed by the local Mosquitto MQTT broker, automatically parsing raw JSON payloads received from four ESP32-S3 root-zone nodes and the dual ESP8266 climate nodes. The interactive graphical user interface (GUI) provides farm managers with real-time visual tracking, displaying dynamic time-series charts, gauge displays, and status indicators for vital sweet potato (Ipomoea batatas) cultivation parameters—including substrate moisture, EC, pH, NPK concentrations, ambient temperature, relative humidity, and light intensity. In addition to handling local data persistence through automated append-logging into structured CSV files, Node-RED embeds a custom chat interface that facilitates interactive, two-way communication with the local Ollama-hosted TinyLlama LLM API. Through this unified flow architecture, Node-RED processes agronomic feedback and threshold triggers to automatically dispatch execution payloads to the ESP8266 water pump relay node,

allowing both automated fertigation control and secure, remote supervisory across mobile and desktop devices via Tail scale networking.



Fig.6. System dashboard using web-based Node-Red hosted in Raspberry Pi

System deployment

The physical system deployment was conducted in an open-field sweet potato (Ipomoea batatas) experimental plot located in MARDI Serdang, Selangor, Malaysia. The system deployment involved 2,000 polybags of sweet potato planted using burnt paddy husk substrates integrated with a precision drip fertigation delivery network. The deployment ran from 1 May until 1 September 2026. The ESP32-S3 root-zone sensing node was installed alongside the RS485 8-in-1 multi-parameter probe inserted vertically into the substrate core to continuously monitor root-zone moisture, temperature, EC, pH, salinity, and NPK levels (Fig.7). Four units of ESP32-S3 root-zone node were used in the deployment, representing four zones in the field. Concurrently, the dual ESP8266 atmospheric nodes equipped with BME280 and BH1750 sensors were positioned in the field to record ambient temperature, relative humidity, barometric pressure, and solar irradiance. All field-deployed controller nodes were enclosed in IP65-rated weatherproof housings and powered by off-grid solar power systems. Telemetry streams were transmitted via MQTT over a localized Wi-Fi network to the central Raspberry Pi 5 server hosting Node-RED and Ollama, which coordinated automated drip pump actuation via the ESP8266 relay node while facilitating secure remote monitoring and management across mobile and desktop devices using Tailscale VPN.



Fig.7. Deployment of node one: ESP32-S3-RS485-CAN-U and RS48 5 8 in 1 soil sensor in the sweet potato cultivation using fertigation system

III. RESULTS AND DISCUSSION

The system was created to automate irrigation management and continuously monitor root-zone and environmental conditions. Microcontroller nodes collect data from the multiple sensors and publish it via MQTT to the Raspberry Pi server, which acts as the MQTT broker using the Mosquitto service (Lean et al., 2024). The data is then processed and displayed on the Node-RED dashboard in real-time. The system successfully enhanced resource utilization and offered insightful information through LLM for well-informed decision-making, according to the real-time sensor readings.

Dashboard and data sensor collection

The web-based Node-RED dashboard hosted on the local Raspberry Pi 5 server served as the central human-machine interface (HMI), delivering reliable real-time visualization, telemetry processing, and supervisory control throughout the 3-month deployment at MARDI Serdang. Telemetry data published by the four ESP32-S3 root-zone nodes (representing four distinct field zones) and dual ESP8266 atmospheric nodes were parsed from raw JSON strings and updated across the dashboard widgets (Edwin et al., 2022). Dynamic gauge components and live time-series charts displayed critical root-zone parameters (volumetric moisture, EC, pH, temperature, and NPK levels)—calculated as a real-time mean average across the four root-zone sensors to provide an aggregated field status—alongside climate metrics (ambient temperature, relative humidity, barometric pressure, and light intensity). Nevertheless, telemetry data from each individual zone were continuously logged and stored separately in local time-series records to allow granular spatial analysis. This continuous visual feedback allowed farm operators to rapidly assess overall substrate conditions across the 2,000 sweet potato polybags and verify that root-zone parameters remained within target agronomic thresholds. Users can determine the sensor reading interval with five duration selections from 10 seconds, 1, 15, and 30 minutes, up to 1 hour (Figure 8). Automated append-logging into local CSV files operated continuously without data corruption or memory leaks, capturing complete time-series records for post-trial agronomic analysis (Fig.9) (Lean et al., 2024).

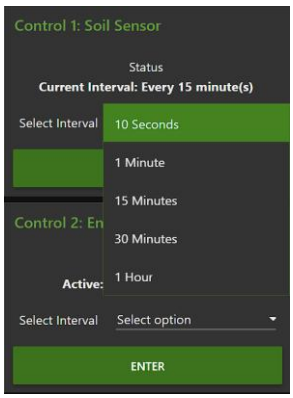


Fig.8. Control setting for sensor reading interval

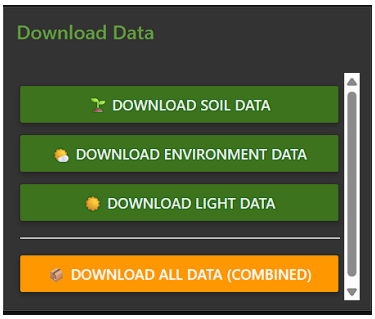


Fig.9. Graphical user interface (GUI) for data sensor file download

Large Language Model assistant

A core functional innovation of the dashboard was the integration of a custom chat component connected directly to the local Ollama execution engine running the quantized TinyLlama:1.1B model. Operators interacted seamlessly with the system using natural language queries to request irrigation advice or parameter summaries and receiving context-aware recommendations. Processing latency was observed in the response received due to hardware resource limitations when executing on-device LLM inference on the Raspberry Pi 5 (8 GB RAM). Nevertheless, this conversational framework significantly reduced operator cognitive load by translating raw numeric trends into actionable insights, aligning with emerging Artificial Intelligence of Things (AIoT) framework developments in smart farming (Muhammed et al., 2025; Wang et al., 2025). Currently, the model communicates via MQTT to ESP32-S3-RS485-CAN-U and ESP8266 solely based on explicit user prompts. However, a current system constraint is that the base model has not been fine-tuned on sweet potato (*Ipomoea batatas*) agronomic practices. Future iterations will incorporate domain-specific fine-tuning or a Retrieval-Augmented Generation (RAG) architecture to improve reasoning precision. Once fine-tuned, the system will transition from manual query-based actuation to fully autonomous control over the

ESP8266 pump relay. This will allow the model to automatically trigger fertigation cycles in response to critical sensor anomalies, such as rapid substrate EC accumulation or severe moisture depletion during peak solar irradiance.

Water management

In addition to telemetry monitoring and AI interaction, the dashboard demonstrated robust operational control, local data persistence, and remote access capabilities. The interactive control panel provided both automated schedule-based triggers and manual supervisory overrides to actuate the 2.0 HP water pump via the ESP8266 relay node and magnetic contactor (Joseph et al., 2017). Remote connectivity via Tailscale VPN allowed farm managers to monitor live dashboard updates, receive alerts, and execute pump overrides from smartphones and laptops off-site without compromising local network security or requiring public static IP. (Monica et al., 2017; Tangwannawit & Saengkrajang, 2021).

Agricultural output

The crop yield performance was evaluated using the commercial sweet potato (*Ipomoea batatas*) variety 'Hukabeni' cultivated across the 2,000-polybag fertigation setup. Harvesting was successfully conducted 90 days after planting (DAP), corresponding to the optimal biological maturity period for this cultivar under tropical open-field conditions. The system recorded an average fresh root tuber yield of 0.7 kg per polybag, yielding a total actual production of 1.4 tonnes (1400 kg) across the experimental plot (Fig.10). The high yield uniformity and root quality demonstrate that the smart drip fertigation architecture—maintaining stable root-zone moisture, electrical conductivity (EC), and pH within the burnt paddy husk substrate—provided optimal physical and chemical conditions to accelerate tuber enlargement and maximize resource-use efficiency within a concise 90-day cropping cycle.



Fig.10. Sweet potato harvest planted using smart fertigation system integration

IV. CONCLUSION

This study successfully demonstrated an end-to-end, smart fertigation system framework tailored for open-field sweet potato cultivation in burnt paddy husk substrate. By integrating specialized microcontroller nodes—four ESP32-S3 nodes for multi-parameter root-zone monitoring and dual ESP8266 nodes for climate tracking and 2.0 HP water pump relay actuation—the system established a resilient, low-latency monitoring network powered autonomously by solar energy. Operating locally on a Raspberry Pi 5 server, the Mosquitto MQTT broker and Node-RED middleware effectively managed real-time data persistence, interactive visual telemetry, flexible logging intervals, and secure remote access via Tailscale VPN across a 2,000-polybag field trial at MARDI Serdang.

The deployment of a local, quantized TinyLlama:1.1B LLM via the Ollama inference engine introduced dynamic decision-support capabilities, translating complex sensor streams into conversational agronomic advice and query-driven pump control. Despite processing latency attributable to hardware constraints on the Raspberry Pi 5 (8 GB RAM), the AI chat interface significantly reduced operator cognitive load without relying on external cloud connectivity. The system's precise root-zone management maintained optimal moisture, EC, and pH levels within the substrate, yielding a total fresh tuber output of 1.4 metric tonnes (0.7 kg/polybag) over a 90-day cropping cycle.

To address current constraints, future research will focus on fine-tuning of the LLM using sweet potato agronomic practices or implementing a Retrieval-Augmented Generation (RAG) architecture. Once fine-tuned,

the system will transition from manual, query-based pump actuation to fully autonomous, closed-loop fertigation triggers capable of mitigating critical root-zone stresses—such as rapid EC accumulation or substrate moisture depletion during peak solar irradiance—in real time.

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