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Vermiculture with Automation Technology

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***Abstract*—This article presents the design and implementation of an automated monitoring and control system for vermiculture using IoT technology. An ESP32 microcontroller, low-cost sensors, and LoRa communication are employed to monitor critical environmental variables such as temperature, humidity, pH, and leachate level. The data enable autonomous actuation of devices, optimizing cultivation conditions to improve humus productivity and worm well-being. The results validate the system's effectiveness for both rural and urban environments, promoting sustainable agriculture.**

***Index Terms*—IoT, ESP32, LoRa, Vermiculture, Automation, Smart Agriculture**

I. Introduction

Vermiculture is an agroecological technique based on the use of worms, particularly *Eisenia fetida*, for the transformation of organic waste into valuable products such as worm humus and leachates. This process not only contributes to the sustainable management of organic solid waste but also promotes soil regeneration, enhances natural fertility, and supports sustainable, agrochemical-free agricultural production [1], [2]. As a clean production alternative, vermiculture aligns with the principles of the circular economy and offers both environmental and economic benefits, especially in rural or peri-urban areas with high generation of organic waste and limited access to synthetic fertilizers.

However, one of the main challenges in vermiculture practice is the proper management of environmental conditions necessary for the worms' well-being and productivity. Variables such as temperature, substrate moisture, pH, gas concentration, and sunlight exposure must be controlled within optimal ranges to ensure the quality of the produced humus and avoid worm mortality [2], [3]. In many cases, these conditions are manually controlled, which requires time, technical knowledge, and constant monitoring, and is subject to human error that can negatively impact the process.

In this context, the incorporation of emerging technologies such as the Internet of Things (IoT) represents a viable alternative for the automation and real-time monitoring of biological systems like vermiculture. IoT enables remote collection of environmental data through distributed sensors, integration with automatic control systems, storage of information in local or cloud databases, and visualization of variables through graphical interfaces accessible from any connected device [4]. These capabilities offer significant advantages in terms of operational efficiency, reduced supervision costs, data-driven decision-making, and improved animal welfare.

Low-power, high-performance devices such as the ESP32 microcontroller, along with long-range, low-energy wireless communication modules like LoRa (Long Range), have been widely used in smart agriculture applications, particularly in rural environments with limited connectivity [5], [6]. These technologies not only provide extended coverage without relying on cellular networks, but also enable the implementation of decentralized, resilient, and scalable solutions.

This work presents the design, development, and implementation of an IoT-based automated vermiculture system that enables both remote monitoring and autonomous actuation over critical environmental variables. Through an architecture composed of environmental sensors, electrical actuators, a local database, and a web interface, the system constitutes a comprehensive solution aimed at improving vermiculture productivity, reducing human intervention, and ensuring optimal real-time operating conditions.

II. Theoretical Framework

Maintaining optimal environmental conditions in a vermiculture setup is essential to ensure the proper development of worms and to guarantee the production of high-quality humus. Variables such as temperature, humidity, pH, and leachate levels play a decisive role in the biological cycle of worms, directly affecting their activity, reproduction, and survival [7].

The ideal temperature range for the development of *Eisenia fetida* is between 18°C and 26°C. Temperatures above 30°C can cause thermal stress and even lead to worm mortality, while values below 15°C significantly reduce metabolism, organic matter ingestion, and reproduction rate. Additionally, substrate moisture must be maintained between 70% and 90%, as worms breathe through their skin and rely on a moist environment for oxygen absorption and nutrient transport. On the other hand, the optimal pH of the substrate is between 6.0 and 7.0; deviations from this range promote pathogen proliferation and negatively impact the organic waste decomposition process.

To ensure proper control of these variables, it is necessary to integrate an electronic system that enables monitoring and automatic response to critical deviations. The ESP32 microcontroller is one of the most efficient solutions in this context due to its low cost, dual-core processing, integrated Wi-Fi and Bluetooth connectivity, and compatibility with multiple communication protocols such as I2C, SPI, and UART, which facilitates easy integration with sensors and actuators [8].

For data transmission in rural environments where traditional networks may be non-existent or unstable, LoRa (Long Range) technology has proven to be a reliable option. This wireless communication protocol allows data transmission over long distances (up to 10 km under ideal conditions), with low energy consumption and excellent penetration in environments with physical obstacles [9]. Its implementation is particularly useful in precision agriculture projects, enabling distributed environmental variable monitoring without the need for complex infrastructure.

For measuring ambient temperature and humidity, digital sensors such as the DHT22 are used, offering basic readings with good accuracy, or more advanced sensors like the SHT35, which provides higher resolution and stability in high-humidity environments. For substrate moisture, capacitive sensors such as the SEN0193 are preferred over resistive ones due to their greater resistance to corrosion and durability. Leachate levels can be monitored using waterproof ultrasonic sensors such as the JSN-SR04T, which allows distance measurement in humid environments without direct contact with the liquid. For pH measurement, specific analog electrodes adaptable to reading modules are employed.

The system's automatic response is carried out through electric actuators such as fans for thermal control, solenoid valves and peristaltic pumps for liquid handling, and servomotors for the opening and closing of gates or mechanical systems. These elements are controlled via electromechanical relays or PWM controllers that allow precise regulation of their operation according to the conditions detected by the sensors [10].

The integration of all these elements allows the development of a robust environmental monitoring and control system that optimizes vermiculture conditions, reduces human intervention, and improves the overall efficiency of the biological composting process.

III. Methodology

A. System Design

The system architecture was designed using Autodesk Inventor, integrating sensors, actuators, and physical structures. Gates, compartments, trays, and moving mechanisms were modeled, allowing virtual validation of their functionality, accessibility, and maintenance.

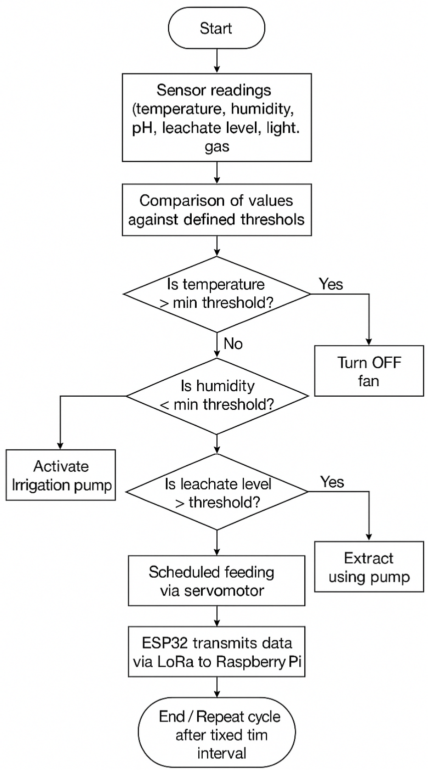

Figure 1: Flowchart of the automated system.

B. IoT Node Configuration

The main node, based on the ESP32 DevKit, was programmed using the Arduino environment. Sensors were integrated to measure:

- Ambient temperature and humidity (DHT22)
- Substrate moisture (capacitive sensor SEN0193)
- Substrate temperature (DS18B20)
- Leachate level (JSN-SR04T)
- Compost pH
- Air quality (SGP30)
- Ambient light (BH1750)

Four actuators were used: a 12V fan, a solenoid valve for irrigation, a micropump for leachate collection, and a servomotor for feeding control. The system was validated using control logic based on thresholds and events.

C. Web Interface and Local Server

A local server was deployed on a Raspberry Pi 4 using the Flask microframework. The relational database was developed in MariaDB and stores sensed data with timestamps. The HTML interface allows the user to visualize real-time variables, manually control actuators, and access historical reports.

Figure 2: Web interface of the system.

D. *Prototype*

The image in Figure 3 shows the prototype, where the central area displays the physical structure of the vermiculture system, equipped with sensors and actuators controlled by an ESP32 microcontroller. On both sides, two laptops display the web interface, from which the monitored variables (temperature, humidity, leachate level, among others) can be visualized in real time and the system can be controlled.

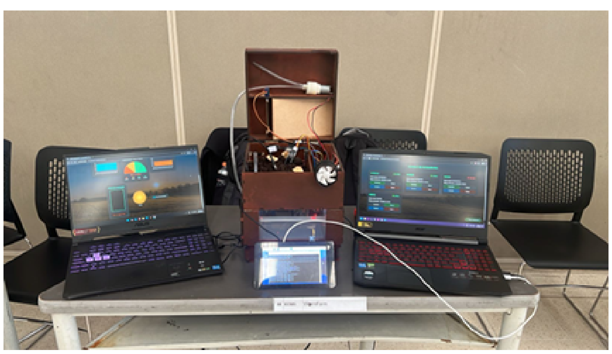

Figure 3: System prototype

IV. Results and Discussion

The results obtained after 30 days of continuous monitoring validate the effectiveness of the implemented automated system. The internal temperature was maintained within an optimal range (22–25°C) through the use of a sensor-controlled fan, which is essential for the metabolism of the worms. The substrate humidity stabilized between 75 and 88%, favoring the decomposition of organic waste and microbial activity without creating harmful saturation conditions.

The micropump successfully collected 5.2 liters of leachate, representing a consistent production of liquid fertilizer derived from the vermicomposting process. In parallel, 2.3 kilograms of high-quality solid humus were obtained, demonstrating the system's efficiency in transforming organic waste into useful agricultural products.

A particularly noteworthy result was the increase in the worm population, growing from 1,000 to over 3,000 individuals. This exponential growth suggests suitable environmental conditions and a constant availability of food. Finally, connectivity tests with the LoRa RYLR998 modules [11] confirmed a range of up to 400 meters with a success rate above 95%, supporting their suitability for distributed agricultural applications, especially in semi-urban areas where traditional communication technologies may present limitations [12], [13].

Table I: Summary of results after 30 days of testing under real conditions

Parameter	**Result**
Internal temperature	22–25°C (automatically controlled via fan)
Substrate humidity	75–88% (maintained by automatic activation of the solenoid valve)
Volume of leachate collected	5.2 L (via programmed micropump)
Solid humus production	2.3 kg (suitable for agricultural use)
Worm population growth	From 1,000 to over 3,000 individuals
LoRa communication range	400 m with more than 95% transmission success in semi-urban environment

V. Conclusions

The implementation of the automated vermiculture system based on IoT technologies proved to be an effective and low-cost solution for the real-time monitoring and control of critical environmental variables such as temperature, humidity, leachate level, and environmental quality. The use of the ESP32 microcontroller, along with accessible sensors and LoRa communication, enabled the development of a robust, reliable system suitable for rural environments, with stable performance and low energy consumption.

The results obtained during testing showed a significant improvement in the efficiency of the vermiculture process, highlighted by increased humus and leachate production, as well as notable growth in the worm population. Automation made it possible to optimize resources and reduce human intervention, thus supporting the operational sustainability of the system.

Integration with an intuitive web interface facilitated remote supervision, allowing for continuous system monitoring as well as the ability to make manual or automatic adjustments in real-time. Furthermore, the system's flexible and modular architecture allows for easy adaptation to different cultivation scenarios, adjusting control thresholds and operating logic according to specific needs.

Likewise, the combination of analog and digital sensors provided a comprehensive view of environmental conditions, enhancing the system's responsiveness to environmental changes. This feature, along with the scalability of the design, paves the way for future extensions and integrations with other agricultural technologies.

Altogether, the results validate the potential of IoT technologies applied to precision agriculture, demonstrating that it is possible to modernize production processes in low-tech infrastructure contexts, thereby promoting smarter, more efficient, and more sustainable agriculture.

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