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PAPER

Internet of Things and NodeMCU Devices to Enhance Laboratories Enabling Mycological Research in an Educational Context

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ABSTRACT

Scientific experimentation is essential for both science education and the generation of new knowledge. However, many institutions face infrastructure limitations that hinder its implementation. This paper presents the design and development of an electronic system for conducting experiments to explore the effects of light conditions on fungal growth, based on physical computing technologies and the Internet of Things (IoT). The experimental platform consists of eight smart incubators, each equipped with sensors for critical environmental parameters such as temperature, humidity, CO_2, and light intensity, managed by NodeMCU ESP8266 microcontrollers. The architecture operates on a local WiFi network and a central server using the IoT platform ThingsBoard, enabling real-time data collection and visualization in an educational context. The results demonstrate that the use of electronic and IoT devices facilitates scientific experimentation in both educational and research settings, while also promoting the development of technological competencies among students and teachers. This proposal shows that meaningful scientific research is achievable with accessible resources, contributing to comprehensive training in science and technology.

KEYWORDS

Internet of Things (IoT), embedded systems, smart incubators, fungal growth, STEM education

1 INTRODUCTION

Scientific experimentation is indispensable for the learning and advancement of science—both within the classroom and in frontier scientific research conducted at universities and major research centers. The underlying idea is that better learning outcomes are achieved when students build their scientific knowledge in ways that reflect how scientific knowledge is actually developed and constructed [1].

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For experimentation activities to be meaningful for learning, they must be authentic [2]. That is, they should not merely showcase spectacular or sensational scientific phenomena as a pedagogical hook [3]. Rather, activities should incorporate complex contextual elements that give authentic meaning to inquiry and experimentation, fostering diverse knowledge and broadening the range of situations that need to be addressed [4].

However, authentic inquiry and experimentation require laboratory infrastructure that is not always available in institutions due to budget constraints or the demands of highly specific and complex experiments that exceed the design scope of existing laboratories. A practical solution is to integrate electronic devices into inquiry activities to enable experiments that would otherwise be impossible.

Scientific literature includes examples of how the integration of Single Board Computers (SBCs) like the Raspberry Pi [5], [6], [7], [8] or System on a Chip (SoC) devices such as Arduino, NodeMCU, and ESP32 [9], [10], [11], [12], [13], [14], [15] has facilitated scientific experimentation. In each case, the adoption of such technologies supported the authentic inquiry necessary for the construction of new scientific knowledge. More recently, specialized IoT software has also been introduced [16], [17], [18], [19], [20], creating a conducive environment for scientific experimentation nearly anywhere.

This paper describes the development and implementation of an enhanced electronic system for conducting experiments to explore the effects of environmental conditions on fungal growth in a postgraduate educational setting. Building on the work of Zárate-Moedano [8], the proposed architecture features an IoT management system (ThingsBoard) hosted on a personal computer server and eight incubators equipped to monitor and control temperature, humidity, CO_2, and light intensity using NodeMCU microcontrollers and BME280, MQ135, and BH1750 sensors.

The educational approach centers on experiments involving the production of fruiting bodies from several species of basidiomycetes, in which light intensity and photoperiod are varied while maintaining acceptable levels for humidity, temperature, and CO_2 in each incubator. This system may address a wide range of future projects regarding diverse medicinal and/or edible mushrooms.

2 TECHNICAL LIMITATIONS FOR FUNGAL EXPERIMENTATION

Light is a highly relevant—yet often forgotten—environmental condition that determines several aspects of fungal biology. Different complex processes, such as spore germination, the growth of vegetative hyphae, or the development of reproductive structures (both sexual and asexual), are sensitive to changes in illumination. Additionally, light acts as a signal to regulate fungal metabolism and enzyme biosynthesis [21], [22].

There is a growing body of evidence suggesting the influence of light intensity and photoperiod on the shape, biomass production, and even nutritional value of a wide diversity of cultivated mushrooms [23], [24], [25]. Therefore, it is of paramount importance for applied mycology postgraduate students to be trained in the design and execution of experiments that explore the effects of light conditions on fungal growth.

To fulfill this need, a laboratory system with up to eight distinct combinations of photoperiod and light intensity conditions is proposed, as well as the capacity to maintain controlled levels of temperature, humidity, and CO_2. This type of experimental design requires substantial laboratory resources and generates significant volumes of data, necessitating automation of both the process and data recording.

Challenges include a lack of sufficient laboratory equipment (e.g., thermometers, hygrometers), the need to repurpose existing tools and spaces into specific configurations, and limited access to experimental data.

To address these issues, it is proposed to build eight incubators inspired by Vega Negrete [26], using electronic components to monitor and control the necessary environmental variables. This approach resolves the lack of laboratory tools, provides each incubator with its own monitoring system, and allows data to be centrally stored and accessed by multiple users concurrently. Moreover, custom sensor-actuator setups per incubator facilitate tailored procedures in each experimental unit.

3 SMART INCUBATOR DESIGN FOR FUNGAL GROWTH

To support the development of the scientific experiment with minimal investment and disruption for instructors, students, or researchers, it is proposed a modular inquiry platform managed by a central server that coordinates multiple incubators. Each incubator is an independent unit controlled by a headless NodeMCU ESP8266 device connected to sensors that monitor and regulate the environmental variables of interest, all over a local WiFi network capable of operating even without internet connection. The software backbone is the reliable and robust IoT platform ThingsBoard.

Regarding the hardware, incubators function as an independent entity. It is controlled by a headless device based on the NodeMCU microcontroller, integrated with BME280, DHT11, MQ135, and BH1750 sensors, and equipped with relays acting as actuators to manage the lighting and ventilation systems. All data is processed in real time by the central server.

On the other hand, the software used is the community edition of the ThingsBoard IoT system. An open-source platform designed for data collection, processing, visualization, and device management [27]. Its minimum system requirements include Linux Ubuntu 24.04 LTS, a PostgreSQL database, Java 17 JDK, and 4 GB of RAM.

Figure 1 presents the general configuration proposed for the development of the electronic laboratory.

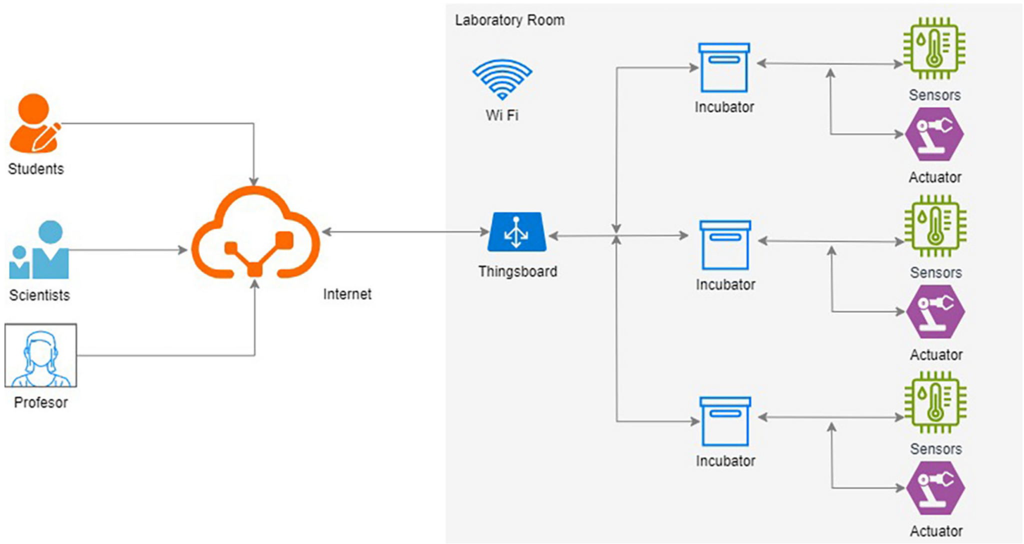

Fig. 1. General configuration diagram: A concept of smart incubators connected to a IoT server platform

3.1 Hardware architecture

Each smart incubator consists of a plastic receptacle with a lid, LED lighting, and a ventilation fan, plus instrumentation for measuring temperature, humidity, CO_2, and light intensity. The sensor suite includes BME280, DHT11, BH1750, and MQ135 sensors, all interfaced via a NodeMCU 12f microcontroller located at the control panel (see Figure 2).

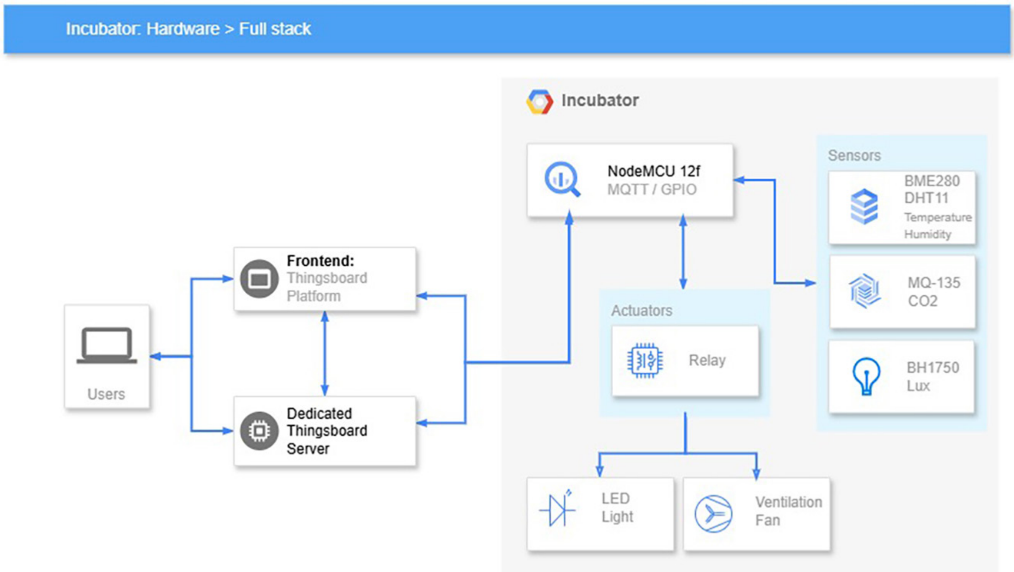

Fig. 2. Incubator and IoT hardware architecture

Sensor details:

- BME280 and BH1750 use the I2C protocol [28] for temperature, humidity, and light measurements.
- MQ135 handles CO_2 detection via analog input.
- DHT11 provides redundant humidity and temperature readings over a digital GPIO pin.

Actuators include opto-isolated dry contact relays that safely interface the 5V DC control circuit with the 125V AC lighting system. Relay control is unidirectional, triggered by a NodeMCU GPIO pin.

The NodeMCU communicates with the server via the MQTT protocol over a TCP/IP wireless network. It gathers sensor data in real time, preprocesses it, and sends JSON-formatted messages to the server. It also receives control commands from the server to adjust operational parameters accordingly.

3.2 Software architecture

To facilitate sensor-microcontroller connections, support communication protocols, ensure security and authentication, and manage data acquisition, analysis, and visualization [12], the ThingsBoard IoT platform was adopted. Installed on a central Ubuntu server, it functions as the system coordinator. Its open-source community edition (v3.6.2) meets the requirements for this project (see Figure 3).

The architecture comprises:

- MQTT Protocol for data transport
- A rule engine for data processing
- The ThingsBoard core and GUI
- A PostgreSQL database

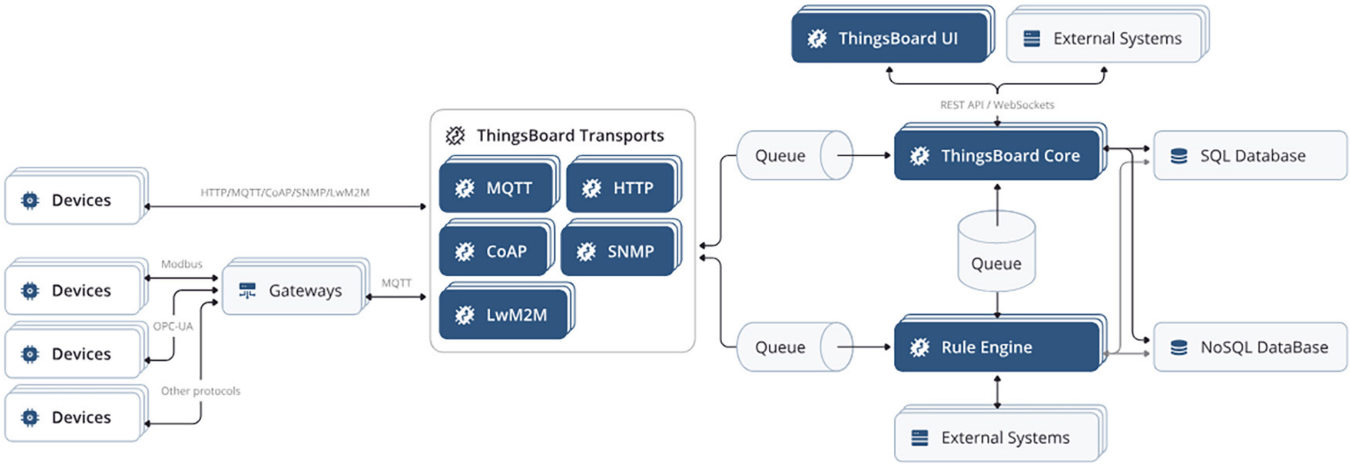

Fig. 3. ThingsBoard IoT platform architecture [27]

The microcontrollers run custom firmware developed in the Arduino IDE, integrating the ThingsBoard SDK and sensor libraries. This firmware includes all the necessary routines for incubator operation—even in case of temporary server disconnection.

4 IMPLEMENTATION

Each incubator transmits telemetry data to the central server over WiFi using MQTT. The wiring diagram (see Figure 4) shows how the NodeMCU is connected to its respective sensors and actuators.

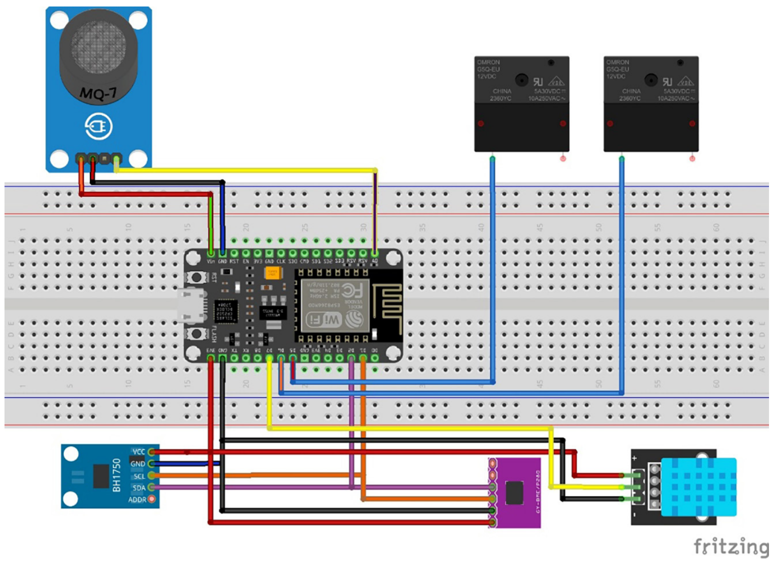

Fig. 4. Incubator physical wiring diagram

4.1 Experimental system features

All eight incubators were deposited inside a thermally isolated room to reduce the temperature fluctuations. The temperature is monitored in each incubator and controlled by an external room heating device, which can be set from 18 to 35ºC depending on the needs of the fungal strain used.

The system can be configured to control up to eight different combinations of light intensity and photoperiod conditions depending on the experimental goals. The light intensity varies from 0 to 1350 lux, while the photoperiods range considered includes 16h light/ 8h darkness (similar to the summertime); 8h light/16h darkness (wintertime-like); 12h light/ 12h darkness, as well as 24h light and 24h darkness.

Humidity and CO_2 are monitored in each incubator to maintain acceptable levels for the fungal strain used. Finally, CO_2 might also be used as a dependent variable in some experimental designs, since it is an indirect measure of fungal metabolism.

Figure 5 shows the main control panel. This panel integrates all the logical control functions of the incubators, including both DC and AC power supplies, as well as the power control stage responsible for switching the lighting of each incubator on and off. Figure 6 shows the incubators along with their associated instrumentation.

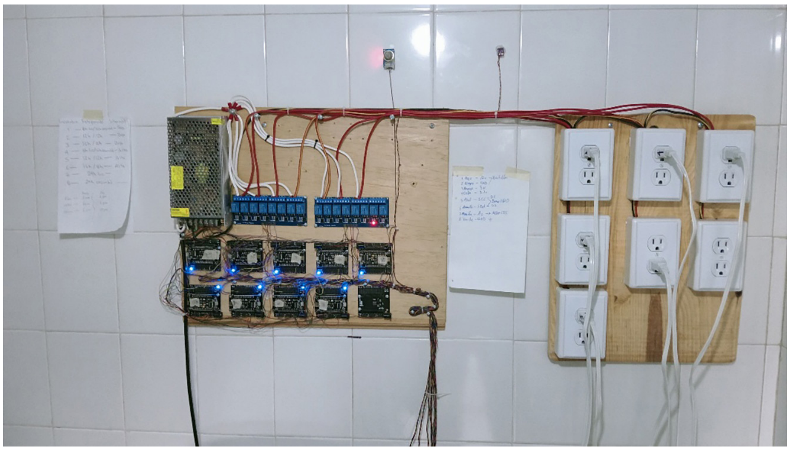

Fig. 5. Incubators centralized control panel

Fig. 6. Incubators receptacle and instrumentation

4.2 Incubator management and data acquisition

ThingsBoard facilitates open-source device management for connected devices. Installed on Ubuntu, it was configured via its web-based admin interface using available documentation and video tutorials. The dashboard aggregates real-time data and provides line graphs (see Figure 7) to compare incubator performance, identify outliers, and understand environmental behavior relative to configured photoperiods (see Figure 8).

Fig. 7. Integrated real-time data charts dashboard

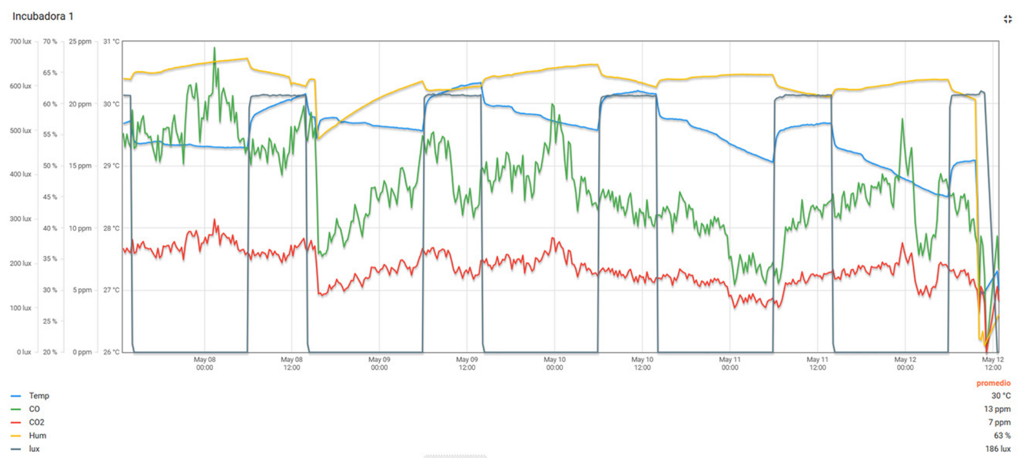

Fig. 8. An all-data incubator real-time chart

As can be seen, ThingsBoard dashboard allows easy access to incubator data, enabling continuous monitoring of the experimental variables. Aggregated graphs and individual incubator views reveal temporal correlations between environmental conditions and experimental settings.

4.3 Proof of concept

As a proof of concept for our system, we developed a short experimental design to explore the influence of light intensity and photoperiod on basidiocarp growth of a medicinal mushroom belonging to the *Ganoderma* genus. The experimental design was a 2 × 3 factorial; the first factor, referring to light intensity, had two levels (I: 350 lux and II: 1350 lux), while the second factor, photoperiod, had three levels (A: 8h light/16h darkness; B: 12h light/12h darkness; and C: 16h light/8h darkness). In addition to the aforementioned conditions, two controls were included for comparison: 24h of darkness and 24h of light (600 lux). During the experiment development, the system monitored each incubator to maintain optimal environmental conditions, such as temperature (29–30°C), relative humidity (70–80%), and CO_2 air concentration (400–500 ppm).

The strain GH-16-012, isolated and identified as *Ganoderma curtisii* by Serrano-Márquez et al. [29], was cultivated on *Quercus* sp. sawdust inside sterile polypropylene bags as described by Stamets [30]. After inoculation, the polypropylene bags were kept in the dark until the substrate was fully colonized and then randomly assigned to the incubator corresponding to each experimental condition. On day 70, after the beginning of the experiment, the length of each basidiocarp was measured as the dependent variable. All results were analyzed using R version 4.3.3, "Angel Food Cake." After confirming the assumptions of normality (Shapiro-Wilk test) and homogeneity of variances (Levene test), a two-way factorial ANOVA was used, followed by a Tukey *post hoc* test. The differences were considered statistically significant when $p < 0.01$.

All the basidiocarps grew in the elongated antler form instead of the characteristic kidney-shaped form of the wild mushroom, yet those that grew in complete darkness were slightly deformed (see Figure 9). However, the ANOVA results show a statistically significant effect for the photoperiod ($F = 57.3662$, $p < 0.001$) and the interaction between photoperiod and light intensity ($F = 12.8461$, $p < 0.001$) on basidiocarp length. The differences in the mean basidiocarp length of each treatment are depicted in Figure 10.

Regardless of their physiological implications (which certainly deserve further in-depth studies), these results demonstrate the feasibility of our system as an educational tool for postgraduate applied mycology students to design and execute a wide range of experiments regarding the effect of different illumination conditions on diverse cultivated mushrooms.

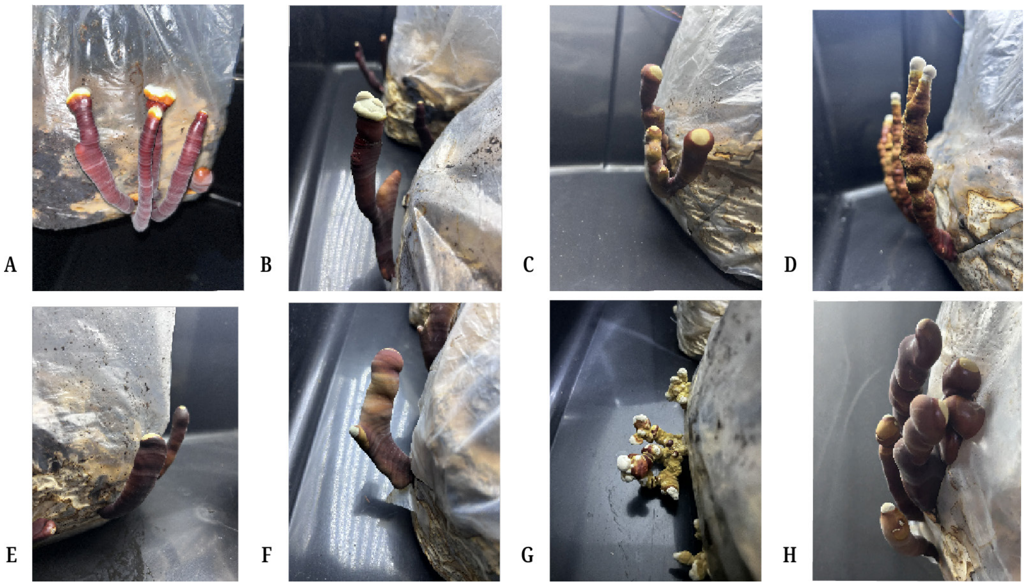

Fig. 9. *Ganoderma curtisii* basidiocarps cultivated under different light intensity and photoperiod conditions: **A:** 350 lux – 8 h light/ 16 h darkness; **B:** 350 lux – 12 h light/ 12 h darkness; **C:** 350 lux – 16 h light/ 8 h darkness; **D:** 1350 lux – 8 h light/ 16 h darkness; **E:** 1350 lux – 12 h light/ 12 h darkness; **F:** 1350 lux – 16 h light/ 8 h darkness; **G:** 24 h darkness; **H:** 24 h light (600 lux)

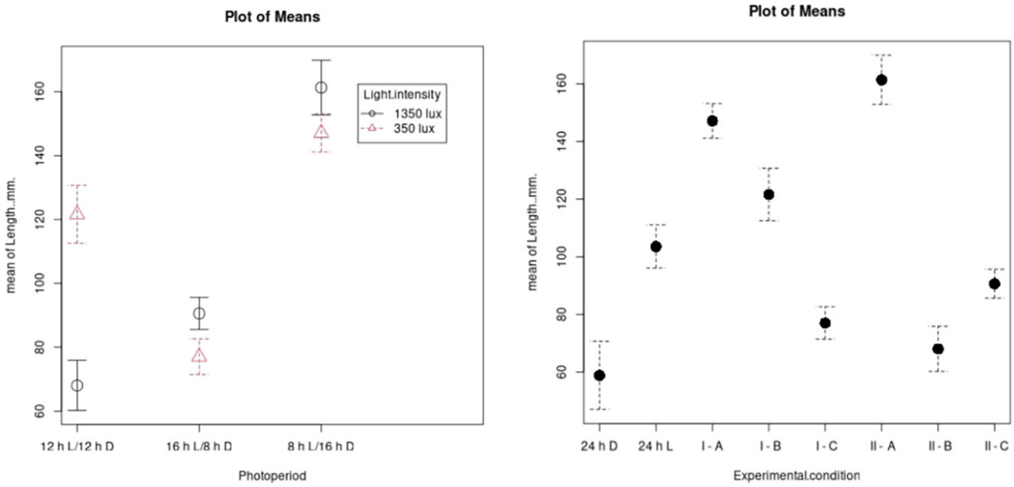

Fig. 10. Graph of the means of basidiocarp length: **Left panel:** Effect of photoperiod and light intensity on basidiocarp length. **Right panel:** Comparison between treatments and controls. **I-A:** 350 lux – 8 h light/ 16 h darkness; **I-B:** 350 lux – 12 h light/ 12 h darkness; **I-C:** 350 lux – 16 h light/ 8 h darkness; **II-A:** 1350 lux – 8 h light/ 16 h darkness; **II-B:** 1350 lux – 12 h light/ 12 h darkness; **II-C:** 1350 lux – 16 h light/ 8 h darkness

Note: The error bars represent standard error.

5 CONCLUSION

The integration of electronic devices in scientific research facilitates experimentation by students, educators, and researchers due to its flexibility and adaptability for diverse configurations. Data quality depends on the sensors used, offering a trade-off between precision and cost. This modular approach supports complex setups and reliable performance using combinations of affordable or high-end components.

Beyond generating scientific insights into specific fungal physiology, the project fosters broader educational experiences, including IoT concepts, basic electronics, sensor-actuator systems, and data management protocols. So that, to maintain focus on authentic inquiry, we recommend technical support from experts in physical computing during system design and deployment, as previously advised by Ga [12].

6 CONFLICT OF INTEREST

Authors disclose no conflicts of interest and affirm that the research was conducted with self-funding.

7 DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS

During the preparation of this work, the authors used ChatGPT by OpenAI in order to assist with English translation and academic style editing. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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