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IoT-Based Programmable LED Light Controller for Tissue-Culture Lighting Applications

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ABSTRACT:
Background: Light is one of the most critical environmental parameters influencing plant growth and indoor tissue-culture cultivation depends heavily on artificial lighting when natural light is unavailable. Light-Emitting Diodes (LEDs) are increasingly preferred for this purpose owing to their low power consumption and high conversion efficiency, yet most reported tissue-culture lighting arrangements still lack an integrated, remotely programmable means of setting and verifying both light intensity and photoperiod together.
Purpose: This paper presents the design and development of an IoT-based smart instrumentation system built around a programmable LED light controller intended for tissue-culture lighting applications. An ESP32 microcontroller serves as the core processing unit, a BH1750 digital light sensor measures light intensity in real time, an RTC DS3231 module maintains photoperiod timing and a phase-controlled optocoupler/TRIAC circuit regulates the LED load, allowing light intensity to be set and controlled across a 500–4000 lux range with a variable ON/OFF photoperiod.
Methods: A cloud-connected web interface, comprising login, monitoring and feedback pages, enables the intensity and timing parameters to be set, monitored and logged remotely. The system's performance was verified through circuit simulation in Proteus 8 Professional, breadboard and PCB-level hardware testing and Variac-based calibration of light intensity against applied AC voltage at varying sensor distances, confirming stable, repeatable proportional control of LED intensity consistent with expected optical and phase-control behaviour.
Results: Compared with the single-parameter or non-remote lighting controllers reported in prior work, the developed system combines intensity control, photoperiod scheduling and IoT-based remote monitoring within a single low-cost instrument.
Conclusion: While the present validation covers the electronic and optical performance of the controller, the platform establishes a practical, low-cost, energy-efficient foundation for future biological validation of tissue-culture plant response under precisely controlled and remotely managed lighting regimes.

Keywords: LED Light Controller, Internet of Things (IoT), Light Intensity, Photoperiod, Tissue Culture, ESP32

1. Introduction

Healthy plant growth requires maintaining several environmental parameters within suitable ranges, including light, fertilization, water, temperature, humidity and ventilation. Among these, light plays a particularly crucial role in micropropagation and the energy consumed for lighting depends strongly on the type of light source and how it is used. Light-Emitting Diodes (LEDs) have emerged as the preferred lighting source for plant cultivation because of their long durability, high conversion ratio and low energy consumption [1].

Prior studies motivate this work along three lines. First, light intensity itself is a strong determinant of tissue-culture outcomes: micropropagation success is influenced by nutrients, plant growth regulators, temperature, light intensity and exposure time [2] and intensity effects are species-dependent — higher intensity improved photosynthesis and branch growth in Epimedium pseudowushanense while lower intensity favoured leaf-area growth [3], propagation ratios varied with intensity and growth regulators in Haworthia [4] and wheat grown for closed-ecosystem studies

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showed increasing plant height with intensity up to an optimum of 600μmol m^{-2} s^{-1} [5]. Second, controlled-environment cultivation is increasingly used to obtain high-quality plants [6], since light is the primary energy source for photosynthesis and governs both photoperiodism and photomorphogenesis [7,8], while nutrient control remains costly to achieve precisely in laboratory settings [9]. Third, spectral composition matters as much as intensity -lettuce under blue and red LED wavelengths showed the greatest light absorption (85–95%) and blue light most strongly enhanced biomass and photosynthesis [10] and combining plant growth regulators with controlled light has been shown to improve callus growth [11]. Taken together, these studies establish that intensity, photoperiod and (separately) spectral quality all need to be controlled precisely for reliable tissue-culture outcomes, yet none of the cited instrumentation approaches combines automated intensity control, programmable photoperiod scheduling and IoT-based remote access in one low-cost platform - the gap this work addresses.

Tissue culture technology enables plants to be grown in a controlled artificial environment and is widely used to study plant growth in laboratories. It offers advantages such as faster growth, disease-free propagation and the potential for mass production and continues to present significant research opportunities. Because the required artificial environment depends on accurate monitoring and control of environmental parameters, smart instrumentation that captures multi-parameter sensor data enables suitable growing conditions to be maintained consistently.

Extending this body of research, the present study proposes and develops an IoT-based smart instrumentation system with a programmable LED light controller to provide precise, automated and remotely accessible lighting conditions - light intensity and variable photoperiod - for tissue-culture applications. The principal results reported here are the successful calibration and closed hardware/simulation validation of the intensity-control circuit and the working IoT monitoring interface; the main conclusion is that the developed instrument reliably and repeatably regulates LED intensity in proportion to a user-defined setpoint while enabling remote scheduling and monitoring, providing a ready platform onto which biological (plant-response) validation can subsequently be built.

2. Method & Materials

2.1. Description of Materials

When natural light is insufficient for indoor plants, artificial lighting becomes necessary to support photosynthesis. Table 1 compares the three light-source technologies considered before selecting LEDs for this system.

LEDs were selected for this system on this basis, operating across the visible, ultraviolet and infrared regions with a substantially longer lifetime than the alternatives.

Internet of Things (IoT) connectivity was used to enable wireless remote setting, monitoring and control of the system parameters — an approach already established across domains such as healthcare monitoring [12], industrial process control [13], precision agriculture [14] and home automation [15]. The system follows a typical four-layer IoT architecture: a Sensing Layer where hardware devices sense physical status; a Network Layer providing wireless connectivity; a Service Layer managing cloud-based data and services; and an Interface Layer delivering front-end/application services through a GUI.

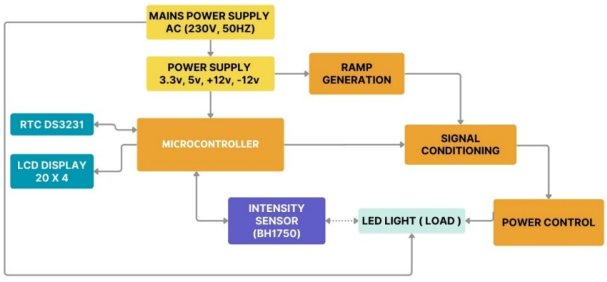


Figure 1: Architecture of the Developed Instrumentation of Programmable Light Controller.

Figure 1 shows the architecture of the developed instrumentation, built around an ESP32 core controller with a focus on proportional control of light intensity. A BH1750 light sensor continuously measures the LED's light intensity (in lux) and reports it to the controller,

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Table 1: Comparison of Common Artificial Light Sources

Light Source	Principle	Efficiency	Typical Lifespan
Incandescent lamp	Thermal radiation from a heated metal filament (2500–3000 K)	7–10%	750–1,500 hours
Fluorescent bulb	UV light from ionised mercury-vapour / argon gas, converted by phosphor coating	Higher than incandescent	8,000–11,000 hours
LED	Spontaneous electron–hole recombination at a semiconductor P–N junction	High; operates at 1.2–3.6 V	>35,000 hours

while an RTC DS3231 provides real-time reference for switching the light ON/OFF at set times. A 20×4 LCD displays operating parameters and pushbuttons and a potentiometer allow the user to select modes and set the desired ON/OFF time and light intensity. A regulated power supply (+12V, +5V) powers all ICs and components. LED intensity is controlled via an optocoupler circuit driven from a digital output pin of the controller. All sensor data is transmitted to a cloud-connected web server, allowing parameters to be monitored and controlled remotely through the controller's IP address.

2.2. Description of Procedure in Logical Order

The power-supply circuit (Figure 3a) provides fixed ±5 V/±12 V rails and a variable 0 to ±12 V dual supply using a step-down transformer, bridge rectifier, filter and regulator stages, with transistors added to boost current capacity and output capacitors for smoothing. The microcontroller board (Figure 3b) is designed around the ESP32's 25 GPIO pins, with dedicated slots for the I2C LCD, OLED, BH1750 sensor and RTC DS3231, four load/actuator outputs with LED indicators and connections for pushbuttons, toggle switches and potentiometers. The ramp-generation circuit (Figure 4a) uses an RC pair with an operational amplifier and a variable potentiometer to produce a ramp of approximately 7.0 V amplitude. In the signal-conditioning circuit (Figure 4b), the controller output is applied to the non-inverting input of U1 for low-pass filtering and amplification and its output is compared with the ramp signal by comparator U2 to generate the triggering pulse. The power-control circuit (Figure 4c) feeds this trigger to a MOC3010 optocoupler, whose output drives a BT136 TRIAC connected to the load and mains supply; the TRIAC's firing angle sets the load voltage level [22].

Figure 5. shows the process flow of the developed instrumentation, covering both hardware and software. On power-up, the controller and connected peripherals (RTC, light sensor, LCD) are initialised via their respective libraries, variables are declared and each peripheral is assigned its communication address. The user sets the desired ON/OFF time and light intensity and the controller continuously compares the current time against these set points; the LED light turns ON at the set ON time and OFF at the set OFF time.

2.3. Detailed Procedure

Calibration procedure: To verify the relationship between AC supply voltage and LED light intensity, a Variac-based calibration setup was used together with a digital multimeter and a digital lux meter. Light intensity was recorded at AC voltages between 0–230 V at sensor distances of 12–39 cm from the light source, so that the resulting intensity–voltage relationship could be evaluated across multiple distance sets.

Circuit testing procedure: Each developed circuit was first tested individually on a breadboard and calibrated — the ramp-generation and signal-conditioning/amplification circuits in particular required fine calibration to produce a proper triggering

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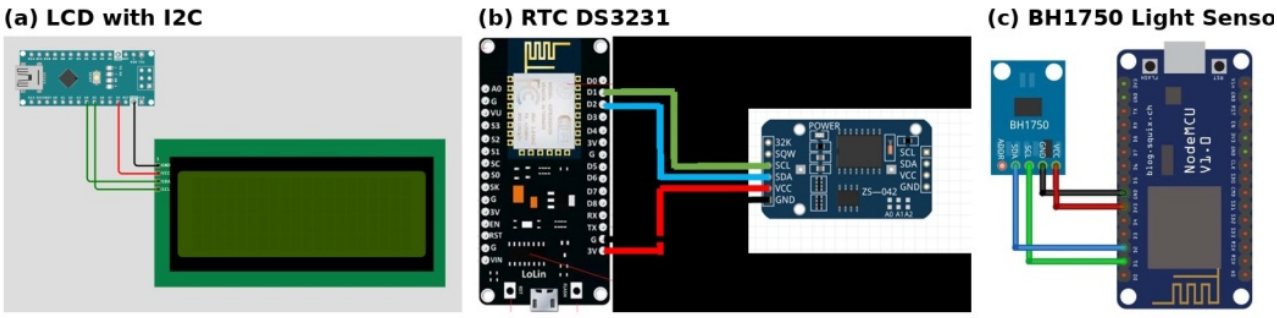


Figure 2: Interface Modules: (a) LCD with I2C, (b) RTC DS3231, (c) BH1750 Light Sensor.

Table 2: Key System Components and Specifications

Component	Model / Type	Key Specification	Function
Microcontroller	ESP32 Dev Board	48 pins (25 GPIO, 5 power); I2C/I2S/SPI, DAC/ADC, PWM, 10 touch pins, on-board Wi-Fi/Bluetooth [16]	Core processing and IoT connectivity
Display	20×4 LCD (I2C)	5–12 V; 4 pins (VCC, GND, SCL, SDA) [17,18]	Displays operating parameters
Real-time clock	DS3231	3.3 V, I2C, battery-backed [19]	Photoperiod / ON-OFF timing reference
Light sensor	BH1750	16-bit digital, 1–65,532 lux range, 1.8–3.3 V [20]	Measures LED light intensity
Power control	MOC3010 optocoupler + BT136 TRIAC	Phase-controlled AC switching [22]	Isolates control signal and regulates LED intensity
LED load	230 V AC LED lamp	40 W, 6500 K CCT, up to 4000 lux	Light source under control
Power supply	Multi-rail regulated supply	+5 V, −5 V, +12 V, −12 V over-current protected	Powers all sub-circuits

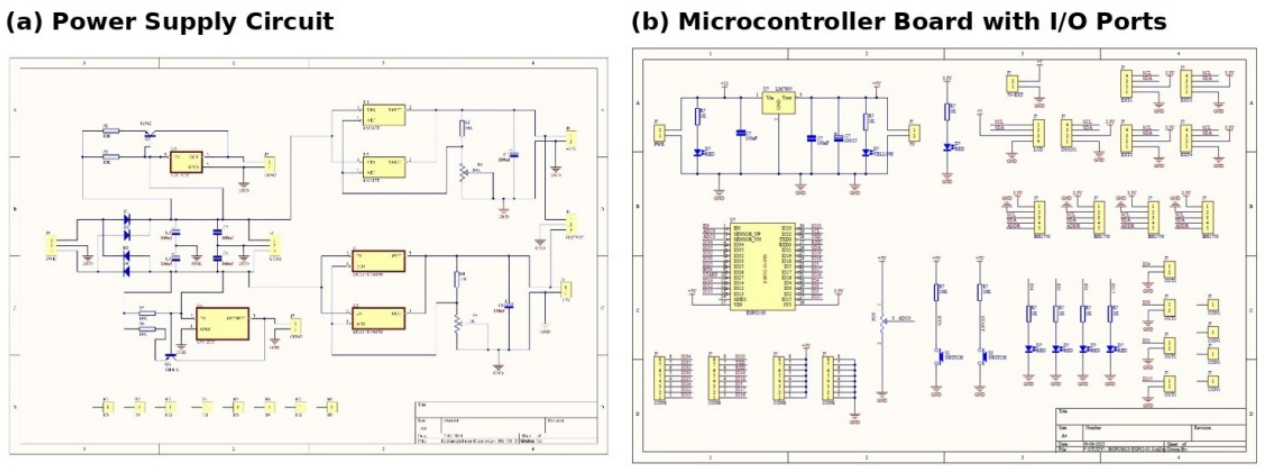


Figure 3: Schematics of (a) Power Supply Circuit, (b) Microcontroller Board with I/O Ports

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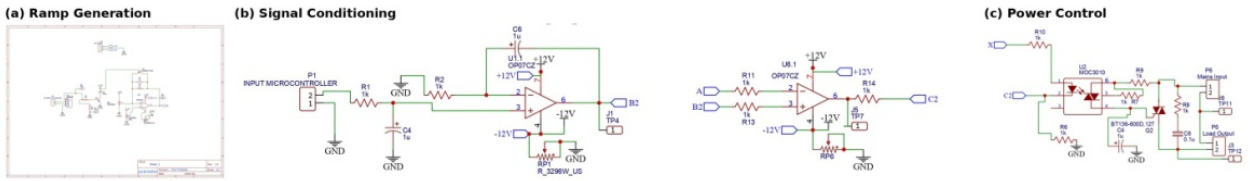


Figure 4: Schematics of (a) Ramp Generation, (b) Signal Conditioning, (c) Power Control Circuits

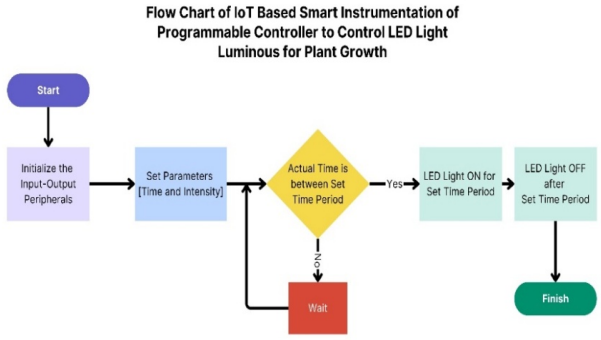


Figure 5: Process Flow Chart

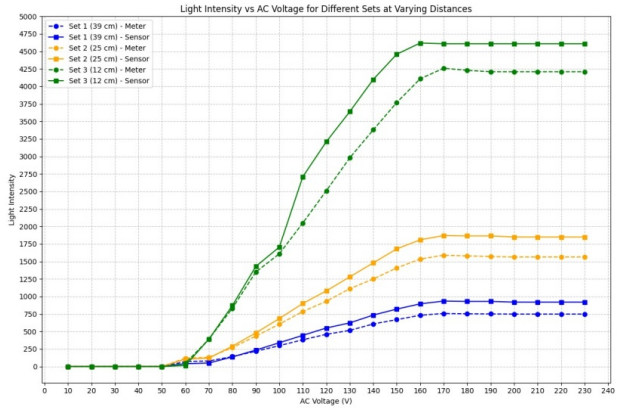


Figure 6: Light Intensity vs AC Voltage for Different Sensor Distances

signal. Once verified individually, the circuits were implemented on PCBs, retested and then integrated to confirm combined performance.

IoT integration procedure: A web-based interface was developed for remote access to the device via the IP address assigned to the ESP32 [23]. The interface comprises a Login page, a Home page and a Feedback page. Users authenticate on the Login page — using a plain username-and-password check validated locally on the ESP32 — to reach the Home page, where ON/OFF timing and LED intensity can be set. The Feedback page provides live monitoring of LED status and measured light intensity [24], with the sensor data logged and refreshed at a 1-minute update interval, and the resulting data logged to a downloadable Excel file directly from the web page.

3. Results and Analysis

Figure 6. shows the relationship between light intensity and AC voltage for the different distance sets. Intensity increases with applied AC voltage and decreases with distance from the sensor, consistent with expected optical behaviour, confirming that the calibration is physically consistent and repeatable across the tested range.

3.1. Simulation of the System

The system was simulated in Proteus 8 Professional [25], using an Arduino Uno as the programmer board with all required peripherals connected to their designated ports. The simulation reproduced ramp generation, triggering-signal generation and output control via the power devices, with virtual CRO probes placed at all test points; conditions were matched as closely as possible to the physical setup.

Figure 7. shows the four simulated signals for three potentiometer settings. At 0% (a), the trigger signal 'C' rises exactly at the falling edge of 'A' and Lamp L1 remains largely OFF. As the potentiometer increases to 3% (b) and 7% (c), the trigger signal shifts progressively further right of the falling edge of 'A', delaying the ON period and changing the phase angle at which the load is switched, so that Lamp L1 glows at correspondingly higher intensity.

3.2. Hardware Testing and Final Product

The completed prototype and its installation are shown in Figure 10. The front panel houses the LCD display, a neon mains-power indicator and the pushbuttons, switches and potentiometer used to set the ON/OFF period and light intensity, while the rear panel carries

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Table 3: Light-Intensity Calibration Summary

Sensor Distance (cm)	AC Voltage Range (V)	Measured Intensity Range (lux)	Observed Trend
12	0–230	0-4610	Intensity increases with voltage
25	0–230	0-1850	Intensity increases with voltage
39	0–230	0-920	Intensity increases with voltage, lower overall than at 12 cm

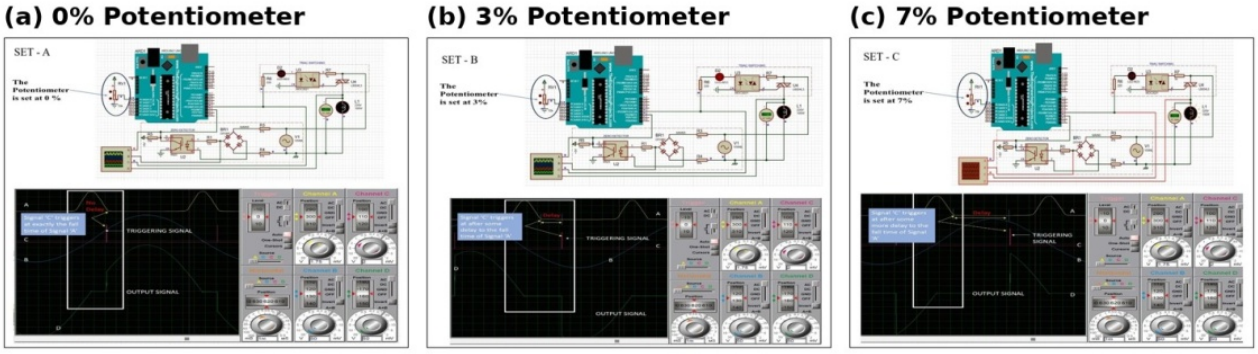


Figure 7: Simulation Waveforms — Ramp (A), AC Mains Input (B), Trigger (C), Output (D)

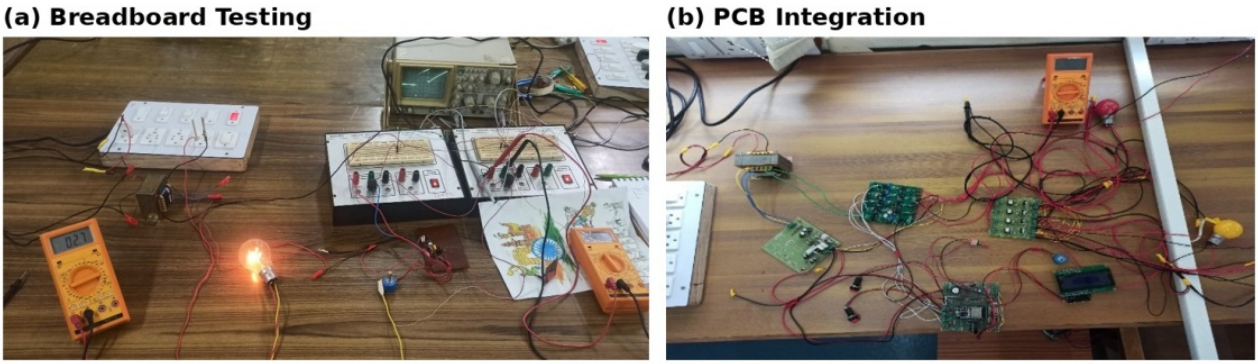


Figure 8: (a) Breadboard Testing, (b) PCB Integration of Designed Circuits

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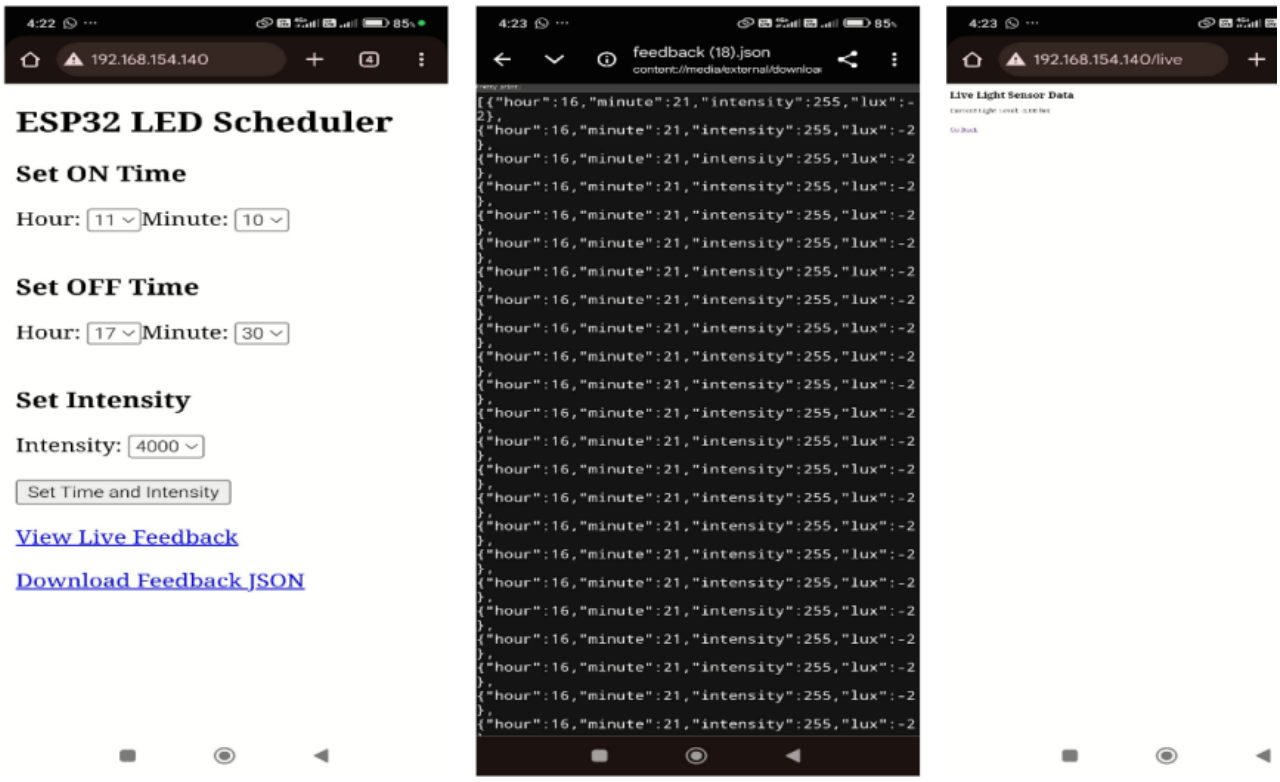


Figure 9: Developed Web Page Interface

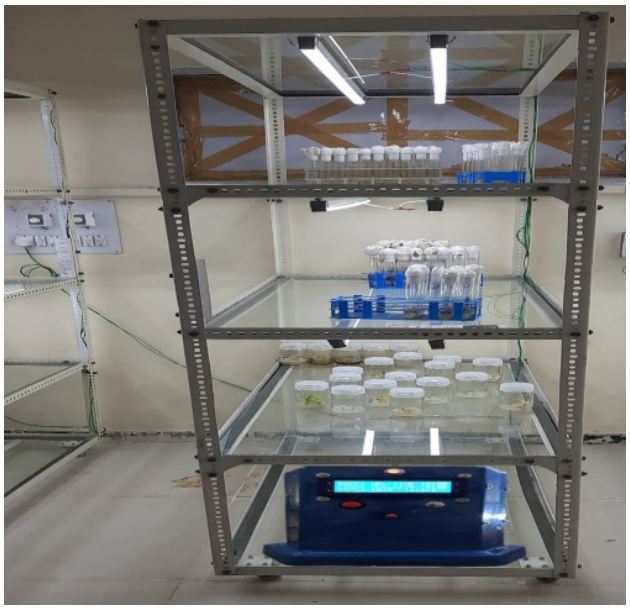


Figure 10: Final Prototype Model

the load connection. The user interface was kept deliberately simple to support straightforward operation.

4. Discussion

The calibration, simulation and hardware-testing results together show a consistent, repeatable relationship between the applied control signal and LED light intensity: intensity scales with the phase angle set by the potentiometer and with applied AC voltage and falls off with distance from the sensor in the expected optical manner. This agrees with the phase-control principle underlying the optocoupler/TRIAC power stage [22] and with prior IoT-based monitoring and control systems reported for other domains [12-15,23,24], extending that approach specifically to programmable, dual-parameter (intensity and photoperiod) control of a tissue-culture-relevant light source.

Compared with the light–growth studies reviewed in the Introduction [2–11], which establish that intensity, exposure time and (for some species) spectral quality strongly affect tissue-culture outcomes, the present system directly addresses the intensity and

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photoperiod dimensions with programmable, remotely verifiable control - a capability not reported together in the single-parameter or manually operated systems typically used in tissue-culture laboratories.

Several limitations should be acknowledged. First and most importantly, this study validates the electronic and optical performance of the controller only; no biological (plant-response) trial has yet been conducted under the system's light regimes, so any claim of benefit to tissue-culture plant growth remains to be demonstrated rather than shown here. Second, the system controls the intensity of a single white LED light source; it does not yet provide spectral (wavelength) control, even though the literature reviewed above indicates that spectral composition - particularly the blue/red balance - has a substantial independent effect on plant response [10]. Third, the demonstrated control loop sets intensity via a fixed potentiometer/setpoint relationship rather than continuous closed-loop feedback that automatically corrects for LED degradation or ambient drift over time; the BH1750 sensor data is logged and can be monitored remotely, but the present implementation does not describe automatic setpoint correction from that feedback.

These limitations point directly to future work: (i) a controlled biological trial comparing plantlet growth (e.g., shoot length, leaf area, chlorophyll content) under two or more of the system's programmed lighting regimes against a conventional light source; (ii) extension to multi-channel or tunable-spectrum LEDs to allow independent control of intensity and wavelength; (iii) closed-loop correction of LED output using the BH1750 feedback signal; and (iv) a quantified energy-consumption comparison against fluorescent and incandescent baselines to substantiate the energy-efficiency claims made for the system.

5. Conclusion

The developed IoT-based smart instrumentation for a programmable LED light controller performed satisfactorily at the electronic and optical level, providing an adjustable light-intensity range of 500–4000 lux together with accurate, monitorable and remotely controllable ON/OFF timing. Simulation, calibration and hardware waveform results confirmed that the phase-controlled optocoupler/TRIAC approach reliably regulates LED intensity in proportion to the applied control signal, while the IoT interface enables convenient remote setting and monitoring. This prototype provides a practical, low-cost instrumentation platform for controlling and logging light exposure; biological validation of its benefit to tissue-culture plant growth is identified as the necessary next step to fully realise the interdisciplinary aim of this work.

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Authorship Contribution

Yatrikkumar S. Patel — conceptualization, hardware design and fabrication, simulation, testing, writing (original draft).

Shahera S. Patel — supervision, guiding for hardware Design, methodology, validation, writing (review & editing).

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Conflict of Interest

The authors declare no conflict of interest.

Similarity Index Declaration

The authors confirm zero similarity index in the Abstract and Conclusion sections, with overall similarity below 10% and no individual source contributing more than 2%, in accordance with the journal's requirements.

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