

Research Article

Design and Development of a Microcontroller-Based Control System for a Semi-Automatic Bean Sprout Cultivation Machine

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ABSTRACT

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The cultivation of high-quality bean sprouts is often hindered by inconsistent environmental control and hazardous chemical contamination. This research develops a closed-loop environmental control system, utilizing an Arduino Mega 2560 microcontroller to actively manage the microclimate within a semi-automatic cultivation machine. The system integrates thermoelectric (Peltier) cooling to effectively dissipate accumulated metabolic heat, combined with a precision humidity control mechanism. Performance was evaluated in triplicate ($n = 3$) against traditional timer-based irrigation systems. Statistical analysis (one-way ANOVA, $p < 0.05$) demonstrated that the prototype successfully stabilized water temperature (22–25 °C) and relative humidity (80–90%) throughout the cultivation period. These optimal conditions led to a 31–65% increase in total net yield compared to traditional chemical-free methods. While this yield remains slightly lower than intensive commercial practices that rely on growth-accelerating chemicals, laboratory tests by an ISO/IEC 17025 accredited facility confirmed undetectable levels of formaldehyde and sulfur dioxide. This study provides a novel engineering framework for chemical-free precision agriculture, demonstrating significant potential for enhancing food safety and reducing manual labor in commercial-scale production.

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1. Introduction

Bean sprouts are a widely consumed economic crop, valued for their high nutritional content and their rapid cultivation cycle of only three to four days. However, cultivating high-quality and uniform bean sprouts requires strict environmental control (Wannawas and Riansut, 2020). Traditional cultivation methods are heavily reliant on manual labor, requiring continuous monitoring and watering every two to three hours. Suboptimal temperatures or insufficient humidity often result in poor-quality yields, characterized by excessively long roots, thin stems, or a high susceptibility to fungal rot.

To mitigate these issues, commercial producers frequently resort to the illicit application of hazardous chemicals to reduce spoilage and artificially enhance the physical appearance of the sprouts. For instance, formaldehyde is commonly used to improve crispness and extend shelf life, while sulfur dioxide (SO_2) serves as a bleaching agent to maintain a fresh aesthetic.

These substances pose severe health risks. Notably, the World Health Organization (WHO) classifies formaldehyde as a known human carcinogen, strictly prohibiting its use as a food additive (World Health Organization, 2006). A preliminary laboratory analysis conducted in this study on a 600-gram random sample of commercially available bean sprouts detected formaldehyde contamination at levels up to 0.5 mg/kg. This finding underscores an urgent public health issue that directly motivates the objective of this study: to replace chemical dependency with precise, automated control of the physical cultivation environment.

Biologically, the seed germination process is exothermic, releasing substantial amounts of metabolic heat that accumulates within the cultivation environment (Mirek *et al.*, 2023). Maintaining ambient and water temperatures between 22 and 25 °C is intended to dissipate this accumulated heat, thereby limiting the conditions that favor rot-causing microorganisms and reducing the need for

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chemical interventions. Furthermore, water temperature strongly influences the germination, stem elongation, and yield of mung bean sprouts (Hanif *et al.*, 2019), whereas a high relative humidity (maintained at 80–90% in this study) minimizes seedling transpiration and promotes cellular expansion, resulting in longer sprouts and a significantly higher fresh weight than those grown under low-humidity conditions (Amitrano *et al.*, 2020).

To achieve these optimal conditions and overcome the limitations of manual labor, automated technologies are increasingly being integrated into bean sprout cultivation systems. For example, Bamrungkul (2021) demonstrated that an automated cultivation machine, utilizing a timer-controlled water pump operating at three-hour intervals, reduced energy consumption while yielding robust sprouts. The application of microcontrollers in this domain is also well-documented. Hakim *et al.* (2023) developed a prototype automated watering system using an open-source Arduino-based controller, which significantly reduced labor time and increased crop yields compared to traditional practices.

However, a critical knowledge gap remains. While previous studies have successfully implemented automated irrigation to manage humidity, they primarily rely on open-loop or simple timer-based strategies. Consequently, these systems lack precise, systematic, and closed-loop control over both water and ambient temperatures. Although solid-state thermoelectric cooling has emerged as a viable, eco-friendly solution in hydroponics (Kanasri, 2018), its integration into closed-loop sprout cultivation, specifically to actively counteract metabolic heat, remains largely underexplored.

To bridge this technological gap and address the aforementioned health concerns, this study aims to design and develop a closed-loop environmental control system for a chemical-free, semi-automatic bean sprout cultivation machine. Distinct from previous prototypes that focused mainly on irrigation frequency, this research introduces an integrated climate-control framework designed to actively dissipate metabolic heat, a critical factor often overlooked in existing designs. The proposed system regulates relative humidity and water temperature in real-time through a coordinated sensor-actuator network. The novelty of this work lies in the integration of thermoelectric cooling within a closed-loop logic to maintain thermal stability, thereby ensuring optimal morphology and food safety without chemical dependency. This approach offers a more sophisticated and scalable engineering solution than current timer-based systems, establishing a new baseline for precision sprout cultivation.

2. Materials and Methods

This section details the design and development of a microcontroller-based system for a chemical-free, semi-automatic bean sprout cultivation machine. The system utilizes embedded technology to maintain an optimal microclimate for plant growth.

The research methodology comprises five primary phases: physical structure design, hardware architecture design, equipment sizing and calculation, algorithm development, and performance evaluation.

2.1 Physical structure design

The physical architecture of the cultivator was designed based on vertical farming principles, which optimize spatial efficiency and environmental control in closed systems (Beacham *et al.*, 2019). The cultivation chamber consists of an opaque container measuring 31 × 58 × 37.5 cm (width × length × height), yielding a total volumetric capacity of 0.067 m³. The use of an opaque enclosure is a critical design parameter, as it prevents light-induced greening of the sprouts; light exposure increases the accumulation of chlorophylls and carotenoids and reduces dry matter compared with dark-grown sprouts (Mastropasqua *et al.*, 2020). The interior is engineered as a closed-loop environment to facilitate precise temperature and humidity regulation. As illustrated in Figure 1, the structure is functionally compartmentalized into four primary zones.

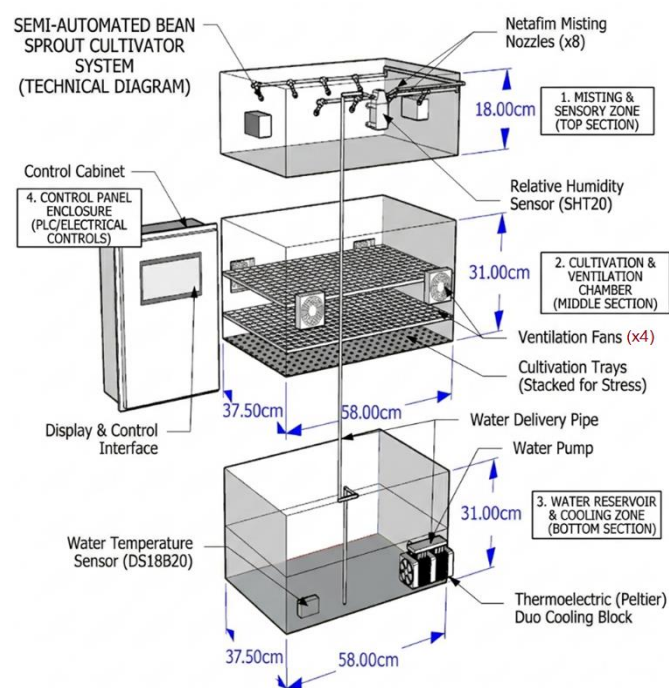


Figure 1 The physical structure and functional zones of the semi-automatic bean sprout cultivation machine.

2.1.1 Top section (Misting and sensory zone)

Located at the ceiling of the chamber, this zone is equipped with eight Netafim misting nozzles. These nozzles are evenly distributed along the container's length to ensure uniform spray coverage over the cultivation area, effectively eliminating dry spots. An SHT20 temperature and relative humidity sensor is also mounted in this uppermost area. This placement protects the sensor from direct exposure to water droplets while allowing for accurate measurement of the chamber's ambient conditions.

2.1.2 Middle section (Cultivation and ventilation chamber)

Serving as the primary cultivation area, this zone accommodates a three-tier stacked planting grid. This

configuration maximizes spatial efficiency and utilizes the weight of the upper tiers to exert constant physical stress on the underlying sprouts. Applying mechanical stress is a proven agricultural technique to stimulate lateral stem expansion and suppress excessive vertical elongation, yielding thicker sprouts that meet commercial quality standards (Biddington, 1986). In addition, four 12 VDC ventilation fans are integrated into the side walls to exhaust accumulated carbon dioxide and metabolic heat, thereby mitigating the risk of mold growth associated with excess moisture.

2.1.3 Bottom section (Water reservoir and cooling zone)

The lower compartment acts as a water reservoir and recirculating sump, collecting excess runoff from the upper cultivation tiers via a gravity drain system. A solid-state thermoelectric (Peltier) module is integrated into the reservoir wall to actively extract heat from the circulating water. Additionally, a submersible DS18B20 temperature sensor provides continuous real-time feedback to the microcontroller, ensuring that the recirculated misting water is strictly maintained within the optimal 22–25 °C range.

2.1.4 Control box and HMI zone

The control system is housed in an isolated enclosure, entirely separated from the high-humidity cultivation chamber. This physical isolation is essential to prevent electrical short circuits and protect sensitive electronic components. The control box contains the main processing unit (Arduino Mega 2560), power driving modules, a switching power supply, and solid-state relays (SSRs). For system interaction, an ESP32-S3 touchscreen is mounted on the front panel at an ergonomic viewing angle, serving as the primary Human-Machine Interface (HMI) for real-time monitoring and operational mode configuration.

2.2 Hardware architecture and control system

The control system architecture of the semi-automatic bean sprout cultivation machine employs a centralized processing design with robust power distribution. The system manages data and signal flow according to a logical framework comprising four functional domains: processing, inputs, outputs, and bi-directional communication (as illustrated in Figure 2). This framework ensures that environmental regulation remains precise, safe, and resilient against electromagnetic interference (EMI) (Horowitz and Hill, 2015). The hardware architecture is divided into the following primary components.

2.2.1 Power management system

To guarantee stable operation, the power distribution and electrical circuit isolation were designed as follows:

Main DC power distribution: A 50 A switching power supply converts the 220 VAC mains input into 12 VDC to drive high-current actuators, including four ventilation fans, the thermoelectric (Peltier) cooling module, and the circulating water pump. Simultaneously, a step-down converter (Hi-Link module)

provides a stable 5 VDC regulated supply for the Arduino Mega 2560 and the ESP32-S3 HMI, protecting sensitive logic components from voltage fluctuations.

High-voltage isolation for the misting pump: The misting system pump operates on a dedicated 12 VDC adapter. To mitigate EMI generated by this inductive load, the pump is switched on the alternating current (AC) side using a solid-state relay (SSR). This provides galvanic isolation, ensuring that high-voltage switching transients do not interfere with the microcontroller's logic operations (OMRON Corporation, n.d.).

2.2.2 Main processing unit (Process)

An Arduino Mega 2560 microcontroller serves as the central processing unit of the system. It functions as the core logic hub, executing embedded environmental control algorithms to process acquired sensor data and independently command the various actuator modules based on real-time conditions.

2.2.3 Signal acquisition and parameter measurement system (Input system)

The signal acquisition system facilitates real-time, unidirectional data transfer from high-precision sensors to the microcontroller, ensuring continuous, low-latency monitoring of the internal microclimate. The system relies on two primary sensing modules:

Water temperature sensing: A submersible DS18B20 sensor monitors the temperature of the recirculating water. Operating via the 1-Wire protocol through a specialized adapter board, this digital sensor provides high noise immunity and ensures accurate temperature feedback, which is essential because water temperature significantly affects the germination rate, stem length, and yield of mung bean sprouts (Hanif *et al.*, 2019).

Ambient humidity and temperature measurement: Two SHT20 digital sensors measure the air temperature and relative humidity inside the cultivation chamber. Because both sensors share identical hardware addresses, they communicate with the microcontroller via a TCA9548A I2C multiplexer to prevent data collisions. This architectural choice allows the Arduino Mega 2560 to switch communication channels effectively, maintaining high signal integrity and reliable data synchronization across multiple sensing nodes (Texas Instruments, 2014).

Before installation, all sensors were calibrated against standard laboratory instruments to ensure measurement accuracy. Furthermore, the control system was programmed with a data sampling interval and control loop frequency of 60 seconds.

2.2.4 Actuator control and output system

The central processing unit regulates the internal microclimate by transmitting digital control signals to various power-driving modules. These modules serve as intermediaries to drive high-current actuators based on predefined

environmental set-points. The output architecture comprises the following sub-systems:

Humidity and ventilation control: To mitigate excessive relative humidity (RH) and accumulated metabolic heat, the microcontroller interfaces with a MOSFET D4184 electronic switch module. This module controls four 12 VDC ventilation fans, which are activated when the ambient RH exceeds 90%. This facilitates rapid air exchange, removing the moisture and metabolic heat that accumulate in the closed chamber (Mirek *et al.*, 2023) and thereby limiting the stagnant, high-moisture conditions often associated with fungal proliferation.

Water temperature regulation: A 2-channel electro-mechanical relay module controls the cooling sub-system, comprising a thermoelectric (Peltier) plate and a circulation pump. This setup maintains the reservoir water within the optimal 22–25 °C range. The relay provides robust switching capable of handling the Peltier module's high current demands, ensuring efficient heat extraction (Zhao and Tan, 2014).

Misting system control: A solid-state relay (SSR) manages the high-pressure misting pump to maintain adequate humidity. When the sensor detects an RH below 80%, the SSR activates the pump, delivering atomized water through eight misting nozzles. An SSR is specifically utilized here for its ability to endure frequent switching cycles without mechanical wear and to suppress electromagnetic interference (EMI) that could otherwise compromise sensor accuracy (OMRON Corporation, n.d.).

Operational status notification: A piezoelectric buzzer provides audible feedback to the user. It is programmed to emit

a continuous rhythmic alert upon the completion of a cultivation cycle, signaling that the sprouts are ready for harvest.

2.2.5 Human-machine interface and bi-directional communication

The system employs bi-directional communication between the touchscreen interface and the main processing unit, enabling direct user interaction and real-time monitoring. An ESP32-S3 HMI module equipped with a capacitive touchscreen communicates with the Arduino Mega 2560 via the I2C protocol. This master-slave architecture ensures reliable data exchange and bus integrity, adhering to standard practices for multi-microcontroller embedded systems (Ibrahim, 2006). The HMI operations are divided into two primary functions:

User input (Command interface): Operators can select predefined cultivation modes—such as TON1 for short-stemmed sprouts or TON2 for long-stemmed sprouts—directly via the touchscreen. These commands are transmitted to the Arduino Mega 2560, which updates the operational logic accordingly.

Data visualization (System monitoring): The ESP32-S3 serves as a real-time dashboard, displaying critical environmental parameters (water temperature, air temperature, and relative humidity) alongside the elapsed operational time received from the main controller. This visual feedback aligns with precision agriculture monitoring principles, facilitating immediate process evaluation and fault detection (Shamshiri *et al.*, 2018).

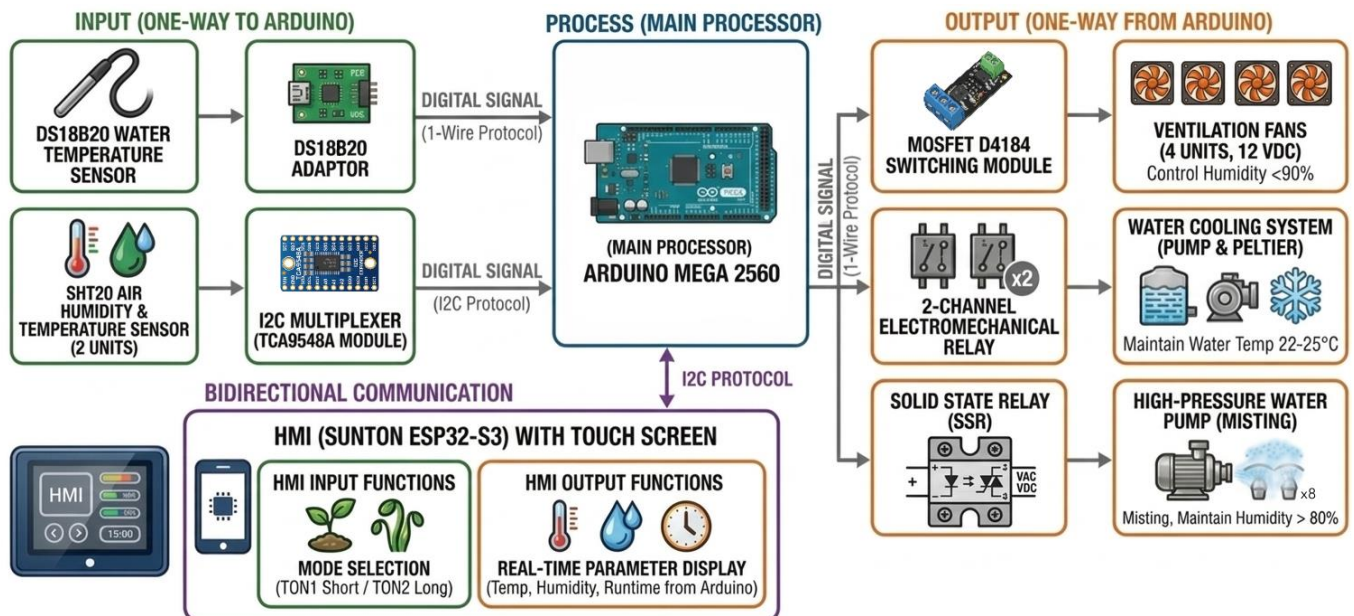


Figure 2 Block diagram of the hardware architecture and control system for the semi-automatic bean sprout cultivation machine.

2.3 Engineering calculations and equipment sizing

To design an effective environmental control system for the semi-automatic bean sprout cultivation machine, engineering parameters were calculated to determine precise equipment

specifications. These calculations ensure that component capacities align with both the operational loads and the biological requirements of the plants. The key sizing and design procedures are detailed below.

2.3.1 Cultivation chamber sizing

The cultivation chamber was designed as a closed system to minimize external environmental disturbances and ensure control system stability. The chamber dimensions are 31 × 58 × 37.5 cm (width × length × height), yielding a total volume of 0.067 m³. The interior features a vertical arrangement of three cultivation trays (N_{layer}), providing a net surface area of 5,394 cm². This capacity was evaluated to accommodate a maximum initial seed weight of 600 grams, distributed equally at 200 grams per tier. This spatial distribution minimizes seed overlap and facilitates uniform moisture penetration throughout the cultivation area.

2.3.2 Cooling load calculation and Peltier sizing

The cooling system is designed to reduce the supplied water temperature from ambient levels to the optimal range for bean sprout growth. The specific target is to cool a 15 kg water mass from 30 °C to 22 °C within 30 minutes. The minimum sensible heat load is calculated using the fundamental heat transfer equation (Çengel and Boles, 2015):

$$Q_{water} = \frac{m \cdot c \cdot \Delta T}{t} \quad (1)$$

where:

- Q_{water} = Heat load or energy to be extracted from the water (Watts or J/s)
- m = Mass of the supplied water in the system (15 kg)
- c = Specific heat capacity of water (4,184 J/kg. °C)
- ΔT = Required temperature reduction (30 °C - 22 °C = 8 °C)
- t = Target cooling time (30 minutes = 1,800 seconds)

Based on Equation (1), the system requires a minimum energy of approximately 278.93 W to compensate for heat loss and the latent heat generated by plant respiration. Consequently, the system was designed to utilize two 12 V, 178 W thermoelectric (Peltier) modules operating in tandem. This configuration provides a combined theoretical maximum cooling capacity of 356 W. Because the total cooling capacity exceeds the required heat load (356 W > 278.93 W), it ensures that the system possesses sufficient reserve capacity to achieve and maintain the target water temperature at 22–25 °C.

2.3.3 Misting system and water film thickness calculation

The irrigation system was designed to provide comprehensive coverage across the cultivation area while preventing waterlogging. Eight Netafim misting nozzles were utilized, operating at a nominal flow rate of 0.125 L/min per unit, based on the manufacturer's technical specifications (Netafim, 2022). The water volume per spray cycle and the resulting water film thickness are calculated as follows:

1) Water volume per spray cycle (V_{spray})

$$V_{spray} = (N_{nozzle} \times q_{nozzle}) \times \frac{t_{spray}}{60} \times 1000 \quad (2)$$

where:

- V_{spray} = Water volume sprayed in one operational cycle (cm³ or ml)
- N_{nozzle} = Number of misting nozzles (8 nozzles)
- q_{nozzle} = Water flow rate per nozzle (0.125 L/min)
- t_{spray} = Pump operation time per cycle (10 seconds)

Applying Equation (2) yields an approximate water volume of 166.67 cm³ per cycle (a rounded reference value of 166 cm³ was utilized for subsequent structural designs).

2) Water film thickness (h)

$$h = \frac{V_{spray}}{W \times L \times N_{layer}} \quad (3)$$

where:

- h = Average thickness of the water film falling on the cultivation area (cm)
 - W = Width of the cultivation tray (31 cm)
 - L = Length of the cultivation tray (58 cm)
 - N_{layer} = Number of stacked cultivation layers (3 layers)
- (Note: The total cross-sectional area of the 3-layer cultivation is 5,394 cm²)

Using Equation (3), the average water film thickness evaluates to approximately 0.0307 cm, or 0.31 mm.

These calculations demonstrate that a 10-second misting duration generates an average water film of just 0.31 mm. This micro-layer is adequate to sustain the target relative humidity of 80–90% without inducing waterlogging. Furthermore, this specific thickness promotes optimal oxygen diffusion into the plant roots, mitigating the risk of root rot. These parameters strictly align with established water management criteria for soilless culture systems (Grewal *et al.*, 2011; Lakhier *et al.*, 2018; Design Innovation Center, 2020).

2.3.4 Main DC power supply sizing

The primary power supply delivers direct current (DC) to all system components, excluding the high-pressure water pump, which is galvanically isolated via an SSR. To determine a safe operational power rating, the system was evaluated under maximum load conditions—specifically when both the thermoelectric cooling sub-system and the ventilation fans operate concurrently:

$$P_{total} = P_{peltier} + P_{fan} + P_{control} \quad (4)$$

where:

- P_{total} = Maximum total power required by the system (W)
- $P_{peltier}$ = Combined power consumption of two thermoelectric modules (2 × 178 W = 356 W)
- P_{fan} = Combined power consumption of four 12 V, 0.3 A ventilation fans (4 × 3.6 W = 14.4 W)
- $P_{control}$ = Estimated power consumption of the microcontroller, sensors, and relay modules (≈15 W)

According to Equation (4), the maximum operational load (P_{total}) is 385.4 W. To ensure power supply longevity and effectively accommodate transient surge currents, a Safety Factor (S.F.) of 1.25 was applied. This strictly adheres to standard electrical engineering practices for continuous loads (NFPA, 2020), as modeled in Equation (5):

$$P_{supply} \geq P_{total} \times S.F. \quad (5)$$

Applying Equation (5), the minimum required power supply rating is 481.75 W. Consequently, a 12 V, 50 A industrial switching power supply was selected, providing a maximum capacity of 600 W. Because this capacity comfortably exceeds the minimum requirement (600 W > 481.75 W), this oversizing approach mitigates the risk of voltage drops during full-load operations, thereby preserving the accuracy and long-term stability of the logic and sensory systems.

2.4 Algorithm and control logic design

The software control system employs a closed-loop architecture to stabilize the microclimate within the cultivation chamber, tailored specifically for automated sprout production (Shamshiri *et al.*, 2018; Hakim *et al.*, 2023). The Arduino Mega 2560 continuously monitors environmental variables, comparing real-time sensor data against predefined set-points. To ensure efficient multitasking and real-time responsiveness, the control logic implements non-blocking timing functions. This programming approach allows the microcontroller to execute multiple sensor-actuator tasks concurrently without stalling the main program loop. The sequential logic and operational steps of the overall control system are illustrated in the flowchart in Figure 3. The system operates in two primary modes:

2.4.1 TON1 mode (2-day short sprout cultivation)

Initiating the TON1 mode via the ESP32-S3 touchscreen transmits an I2C command to the Arduino Mega 2560, starting a 48-hour master timer. The microcontroller then concurrently executes two environmental regulation loops:

Water temperature control loop: Although a proportional-integral-derivative (PID) control system could offer higher precision, an on-off control strategy with a predefined hysteresis band was intentionally selected. This approach effectively maintains the water temperature between 22 and 25 °C, a set-point range selected to continuously remove the metabolic heat released by the germinating seeds (Mirek *et al.*, 2023), since water temperature is a key factor governing the germination, stem elongation, and yield of mung bean sprouts (Hanif *et al.*, 2019). The controller activates the Peltier cooling modules at the upper control limit (UCL) of 25 °C and deactivates them at the lower control limit (LCL) of 22 °C. This hysteresis approach prevents rapid relay toggling (short cycling), thereby extending the operational lifespan of the switching components (Dorf and Bishop, 2011).

Humidity and ventilation control loop: Using data from the SHT20 sensors, the system regulates internal moisture levels through two response pathways. First, if the relative humidity (RH) falls below the 80% threshold, the system triggers a 10-second misting cycle. This fine-mist irrigation facilitates adequate moisture absorption and root oxygen diffusion (Lakhiar *et al.*, 2018). Conversely, if the RH exceeds 90%, the system activates the ventilation fans via the MOSFET module. This rapid air exchange exhausts excess moisture and accumulated carbon dioxide (CO₂), together with the metabolic heat released by the germinating seeds (Mirek *et al.*, 2023), thereby reducing the conditions that promote fungal growth and anaerobic root rot in closed systems.

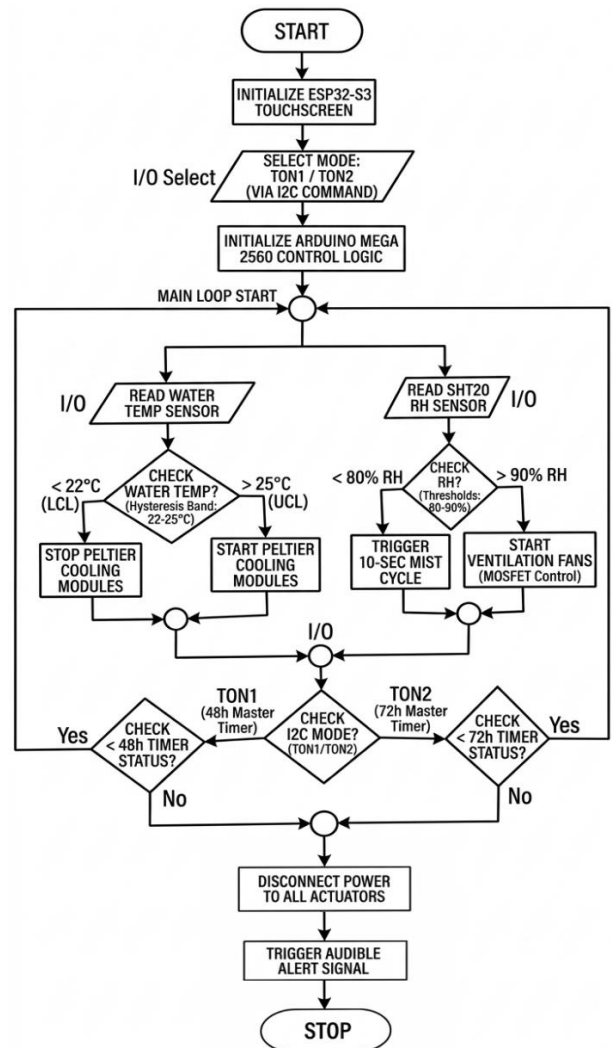


Figure 3 Logic flow of the dual-mode environmental regulation system based on non-blocking timing functions.

Upon concluding the 48-hour cycle, the microcontroller enters a termination state. It safely disconnects power to all actuator loads and triggers an audible alert to notify the user.

2.4.2 TON2 mode (3-day long sprout cultivation)

The TON2 control algorithm uses the same environmental thresholds and logic loops as TON1. The only software distinction is the extension of the master timer to 72

hours (3 days). This extended duration provides the sprouts with sufficient time for hypocotyl elongation and structural stem development prior to system termination.

2.5 Experimental design and evaluation

To evaluate the performance of the developed technology, a comparative experiment was designed between two cultivation systems, as depicted in Figure 4:

Semi-automatic cultivation machine with environmental control (Prototype): This system actively controls both water temperature and relative humidity.

Traditional cultivation machine (Control setup): This system simulates conventional commercial bean sprout cultivation methods commonly used in local markets.

While traditional methods typically rely on chemicals or plant hormones to enhance stem thickness, no chemicals or additives were utilized in either system during this experiment. This strict condition was established to empirically demonstrate the growth outcomes derived exclusively from the precise control of the physical environment. To ensure the reliability and reproducibility of the results, all experimental cases were conducted in triplicate ($n = 3$ independent batches).

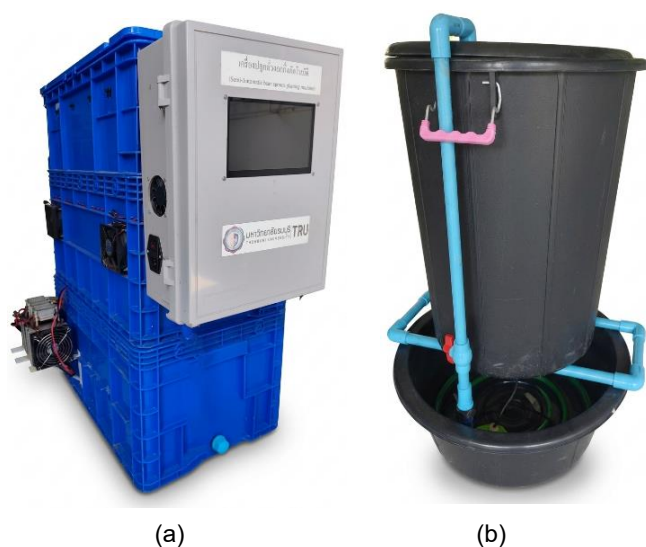


Figure 4 The cultivation systems used in the comparative experiment: (a) semi-automatic machine with environmental control and (b) traditional cultivation machine.

The experimental conditions and evaluation metrics were established as follows:

2.5.1 Determination of variables and experimental conditions

The experiment utilized black mung beans. The controlled variables, identical across both systems, included an initial seed weight of 600 grams and a total water volume of 10 liters per cycle. The cultivation period was divided into two specific durations: a 2-day period (for short bean sprouts) and a 3-day period (for long bean sprouts). The watering condition, a critical independent variable in this study, varied based on the operational mechanism of each system:

Semi-automatic machine with environmental control (Figure 4(a)): This system employed a feedback control mechanism. The water pump was automatically activated only when the sensor detected the relative humidity inside the cultivation chamber dropping below 80%. During each activation, the watering duration lasted for exactly 10 seconds, a setting designed to conserve both water resources and energy.

Traditional cultivation machine (Figure 4(b)): This system utilized a timer-based watering approach. The watering frequency was divided into three distinct intervals: every 2, 4, and 6 hours. For each watering event in this setup, the duration was set to 10 minutes.

2.5.2 Data collection of yield and physical characteristics

Upon completion of the cultivation periods (2 and 3 days), bean sprouts from each experimental condition were harvested to collect the following data:

Total yield weight: The net fresh weight was measured using a digital scale to compare the growth rates across different conditions.

Physical characteristics: For each batch, 30 bean sprouts were randomly sampled daily (10 sprouts from each of the three cultivation layers), totaling 90 samples per experimental condition ($n = 90$). The stem length and diameter were measured using a digital Vernier caliper. This measurement aimed to evaluate the physical quality against commercial market standards.

2.5.3 Food safety assessment

To verify the prototype's efficacy in eliminating chemical dependency, bean sprout samples produced by the prototype (Sample A) and samples randomly purchased from a local fresh market (Sample B) were sent to an accredited laboratory for chemical residue analysis. The analysis focused on two specific contaminants: formaldehyde (analyzed using a Test Kit, with a Limit of Detection (LOD) of 0.50 mg/kg) and sulfur dioxide (analyzed using the In-house method TE-CH-018 based on AOAC 2023 990.28, with an LOD of 3.00 mg/kg).

3. Results and Discussion

This study evaluated the performance of the microcontroller-based environmental control system designed for the semi-automatic bean sprout cultivation machine (Prototype: Case 1) in comparison to a traditional timer-based cultivation system. The traditional system served as the control setup and was divided into three distinct operational conditions: watering every 6 hours (Case 2), every 4 hours (Case 3), and every 2 hours (Case 4). To strictly isolate the effects of the physical environment, neither system utilized any chemicals or growth hormones throughout the cultivation process. The experiments were conducted under ambient conditions, characterized by temperatures ranging from 30–35 °C and a relative humidity (RH) of approximately 70%.

The evaluation covered environmental parameters, the morphological characteristics of the yield, and food safety assessments. All cultivation experiments were conducted in triplicate ($n = 3$ independent batches) to ensure reproducibility. For morphological parameters, 30 sprouts were randomly sampled daily (10 per cultivation layer) per batch, totaling 90 sprouts per condition. Statistical differences among the experimental cases were analyzed using one-way Analysis of Variance (ANOVA) followed by Tukey's post-hoc test, with a significance level set at $p < 0.05$. Furthermore, the percentage of improvement was calculated using Equation (6). All data are presented as Mean $\pm$ Standard Deviation (SD).

$$POI(\%) = \left(\frac{V_P - V_T}{V_T} \right) \times 100 \quad (6)$$

where:

V_P = The measured value from the prototype machine (Case 1).

V_T = The measured value from the traditional timer-based systems (Control setup: Cases 2, 3, or 4).

POI = The percentage of improvement (%).

3.1 Water temperature profile

The water temperature within the system was continuously monitored at one-hour intervals throughout the cultivation period, which spanned 48 hours for the TON1 mode (short bean sprouts) and 72 hours for the TON2 mode (long bean sprouts).

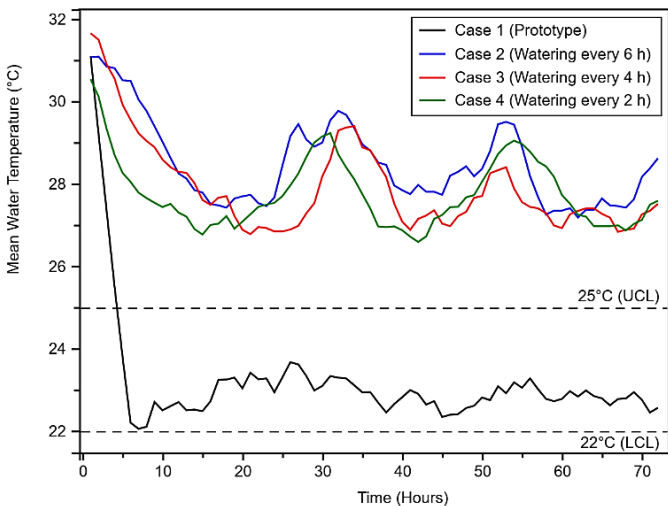


Figure 5 Water temperature profiles (°C) in the prototype and traditional systems. The prototype maintained a high stability with an overall average of 23.17 ± 0.38 °C.

As illustrated in Figure 5, the prototype machine (Case 1) effectively controlled and maintained the water temperature within the target range of 22–25 °C with high stability, achieving an average temperature of 23.17 ± 0.38 °C. The thermoelectric (Peltier) cooling system successfully reduced the temperature to the desired set-point within the first five hours of operation. Maintaining this optimal temperature supports the seed germination process, which is an exothermic reaction. This

thermal regulation facilitates the dissipation of metabolic heat (Mirek *et al.*, 2023) and is therefore expected to mitigate the risk of pathogenic microbial proliferation.

Conversely, the traditional systems (Cases 2–4) exhibited significantly higher average water temperatures of 28.49 ± 1.00 °C, 27.91 ± 0.82 °C, and 27.75 ± 0.78 °C, respectively ($p < 0.05$). Although increasing the watering frequency slightly reduced the temperature via evaporative cooling, it failed to lower the temperature to the optimal range due to the overriding influence of the ambient heat. These findings clearly demonstrate the inherent limitations of timer-based irrigation systems lacking active cooling mechanisms, as the metabolic heat released by the germinating seeds continues to accumulate within the cultivation environment (Mirek *et al.*, 2023).

3.2 Relative humidity profile

Relative humidity (RH) within the cultivation chamber is a critical factor influencing plant transpiration.

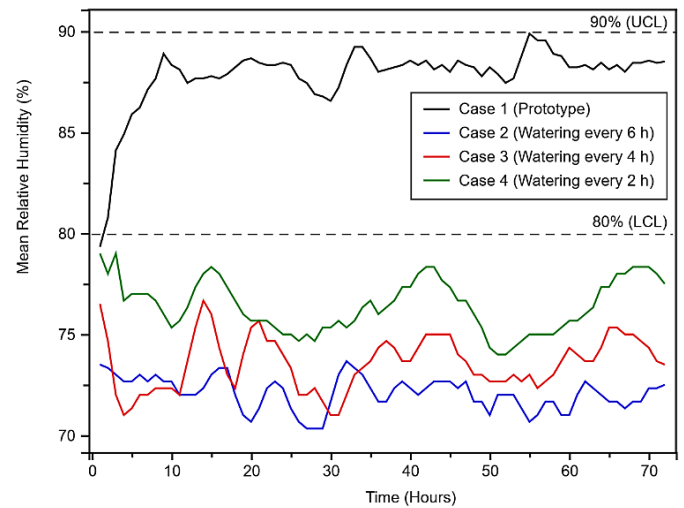


Figure 6 Relative humidity profiles (%) in the prototype and traditional systems. The prototype maintained a stable microclimate with an overall average of $87.82 \pm 0.36\%$.

As illustrated in Figure 6, the prototype machine (Case 1) successfully maintained an average RH of $87.82 \pm 0.36\%$, remaining consistently within the target range of 80–90%. The implementation of a feedback control mechanism, which triggers a 10-second misting cycle when the RH drops below 80% and activates the ventilation fans when the RH exceeds 90%, enabled the system to achieve an equilibrium state within approximately one hour. Maintaining this optimal moisture level effectively mitigates transpiration stress and promotes cellular expansion in the plants (Amitrano *et al.*, 2020).

In contrast, the traditional systems (Cases 2–4) recorded substantially lower average RH values of $72.09 \pm 0.35\%$, $73.57 \pm 0.85\%$, and $76.41 \pm 1.00\%$, respectively ($p < 0.05$). Although increasing the watering frequency contributed to a slight elevation in humidity, none of the traditional setups were able to consistently sustain the RH within the appropriate threshold. This finding

underscores the inefficiency of fixed-interval watering methods in maintaining a stable microclimate (Lakhiar *et al.*, 2018).

3.3 Growth in sprout length

As previously detailed, a total of 90 bean sprouts ($n = 90$ from 3 independent batches) were randomly sampled daily to measure their average length, as presented in Table 1 and Figure 7.

On Day 1, sprouts cultivated in the prototype machine were slightly shorter than those in the traditional systems, reflecting an initial adaptation phase of the seeds to the controlled environment. However, by Day 2 (the conclusion of the TON1 mode), the average sprout length in the prototype rapidly increased to 47.18 ± 1.65 mm, exceeding the average of the traditional systems by 50.4% (statistically significant at $p < 0.05$). This growth trend became substantially more pronounced on Day 3 (the conclusion of the TON2 mode), with the prototype achieving an average length of 118.16 ± 2.44 mm, which was 73.9% longer than the traditional control setups ($p < 0.05$). This accelerated growth is directly attributed to optimal environmental regulation coupled with the applied mechanical stress technique, which synergistically stimulated uniform structural development (Biddington, 1986; Hanif *et al.*, 2019).

Table 1 Average length (mm) of bean sprouts throughout the cultivation period (Mean $\pm$ SD).

Time (Days)	Case 1 (Prototype)	Case 2 (Every 6h)	Case 3 (Every 4h)	Case 4 (Every 2h)	Mode
Day 1	14.36	15.65	15.96	20.62	-
Day 2	47.18 ± 1.65	30.90 ± 0.85	32.14 ± 1.42	31.08 ± 0.93	TON1
Day 3	118.16 ± 2.44	57.20 ± 1.80	60.10 ± 1.66	86.51 ± 2.24	TON2

3.4 Growth in sprout diameter

Stem thickness is a crucial indicator of commercial quality. The diameter measurement results from the sampled groups ($n = 90$) are presented in Table 2 and Figure 8.

Table 2 Average diameter (mm) of bean sprouts throughout the cultivation period (Mean $\pm$ SD).

Time (Days)	Case 1 (Prototype)	Case 2 (Every 6h)	Case 3 (Every 4h)	Case 4 (Every 2h)	Mode
Day 1	1.93	1.94	1.99	2.06	-
Day 2	2.52 ± 0.12	2.12 ± 0.11	2.19 ± 0.09	2.26 ± 0.10	TON1
Day 3	2.75 ± 0.15	2.33 ± 0.12	2.39 ± 0.13	2.45 ± 0.13	TON2

The morphological development of the sprouts is illustrated in Figure 9 (a: 1-day-old, b: 2-day-old, c: 3-day-old). On Days 2 and 3, the prototype machine produced bean sprouts that were significantly thicker ($p < 0.05$), by approximately 15%, than those from the traditional systems (achieving 2.75 ± 0.15 mm on Day 3 compared to 2.33–2.45 mm in traditional setups). This enhanced plumpness supports the primary hypothesis that maintaining high relative humidity (80–90%) coupled with precise temperature control actively stimulates lateral cellular expansion. Consequently, this controlled environment yields sprouts of high commercial quality without the need for chemical additives.

3.5 Total net yield

The post-harvest fresh weight from all three cultivation trays ($n = 3$ independent batches) was evaluated to determine the total yield, as presented in Table 3 and Figure 10.

The prototype machine (Case 1) produced the highest total yield in both the TON1 (2.48 ± 0.19 kg) and TON2 (4.93 ± 0.37 kg) modes, outperforming the 2-hour and 6-hour interval traditional cultivation methods by 31.4% and 63.2%, respectively ($p < 0.05$). However, when examining the physical appearance in Figure 11, although the sprouts cultivated in the prototype exhibited a higher biomass than those from the chemical-free traditional systems, the total yield remained lower than that of commercial productions utilizing growth-accelerating chemicals (which typically achieve a yield ratio of 1:10, or 6.00 kg). Nevertheless, these results demonstrate that the engineered system can effectively increase production yield and significantly reduce manual labor, consistent with previous reports that automated irrigation improves sprout quality compared with traditional practices (Hakim *et al.*, 2023).

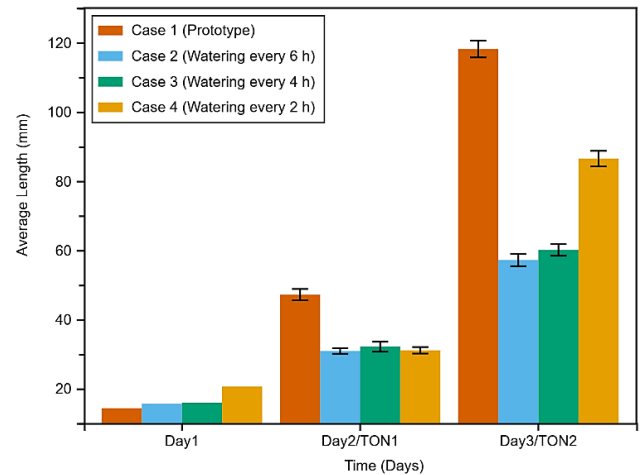


Figure 7 Average length (mm) of bean sprouts in the prototype and timer-based systems (Mean $\pm$ SD). Error bars represent standard deviation (SD).

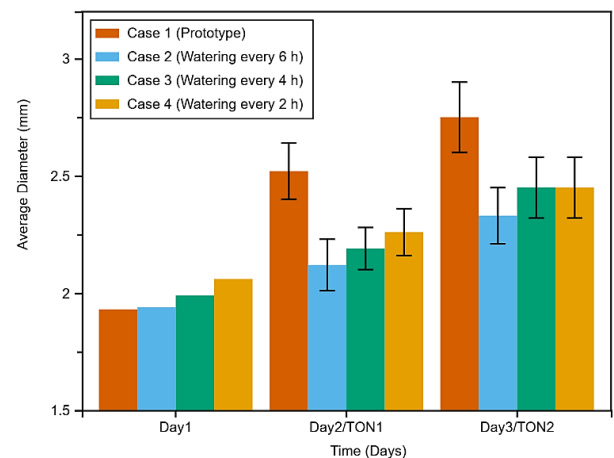


Figure 8 Average diameter (mm) of bean sprouts in the prototype and timer-based systems (Mean $\pm$ SD). Error bars represent standard deviation (SD).

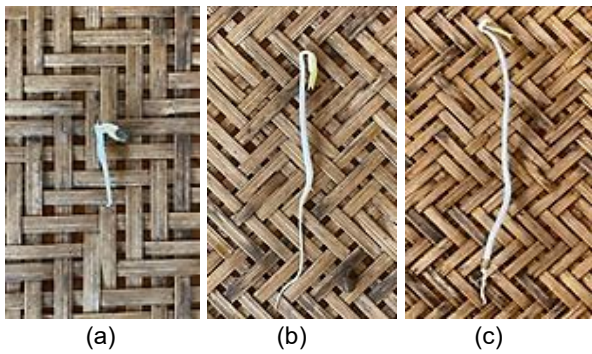


Figure 9 Morphological development of bean sprouts from the prototype machine at (a) day 1, (b) day 2 and (c) day 3.

Table 3 Average total fresh weight (kg) at harvest from an initial seed mass of 600 g (Mean $\pm$ SD).

Time (Days)	Case 1 (Prototype)	Case 2 (Every 6h)	Case 3 (Every 4h)	Case 4 (Every 2h)	Mode
Day 1	-	-	-	-	-
Day 2	2.48 $\pm$ 0.19	1.50 $\pm$ 0.13	2.11 $\pm$ 0.17	2.31 $\pm$ 0.17	TON1
Day 3	4.93 $\pm$ 0.37	3.02 $\pm$ 0.25	3.17 $\pm$ 0.27	3.75 $\pm$ 0.27	TON2

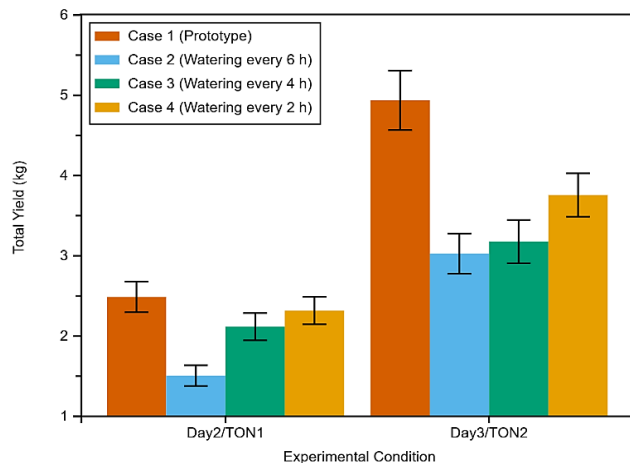


Figure 10 Average total fresh weight (kg) of bean sprouts across different cultivation cases (Mean $\pm$ SD). Error bars represent standard deviation (SD).

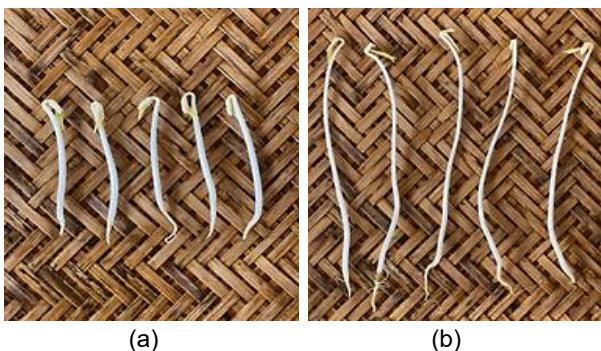


Figure 11 Bean sprouts from the prototype (Case 1): (a) 2-day-old short sprouts (TON1), and (b) 3-day-old long sprouts (TON2).

3.6 Food safety and chemical residue test results

To ensure consumer safety, two groups of bean sprout samples-Sample A (from the prototype machine) and Sample B (randomly selected from a local fresh market)-were sent for testing at the Central Laboratory (Thailand) Co., Ltd. The

samples were analyzed for formaldehyde and sulfur dioxide (SO₂) contamination in accordance with the ISO/IEC 17025:2017 standard.

Table 4 Comparison of chemical residue test results in bean sprout samples.

Sample Group	Formaldehyde		Sulfur Dioxide: SO ₂	
	(Test Result)	LOD (mg/kg)	(Test Result)	LOD (mg/kg)
Sample A	Not Detected	0.5	Not Detected	3.0
Sample B	Detected	0.5	Not Detected	3.0

(Note: Formaldehyde testing was conducted using a test kit. Sulfur dioxide testing utilized the in-house method TE-CH-018 based on AOAC (2023) 990.28.)

4. Conclusion

This study successfully developed a microcontroller-based closed-loop environmental control system for a semi-automatic bean sprout cultivation machine. The system demonstrated superior performance in stabilizing critical microclimate parameters compared to traditional timer-based methods, leading to significantly enhanced growth and higher yields without chemical dependency. Laboratory validations confirmed that the harvested sprouts strictly adhered to international food safety standards. The principal contribution of this research is the provision of an integrated engineering framework that ensures high-quality, chemical-free production while effectively reducing manual labor. Future work should focus on optimizing energy efficiency and conducting a comprehensive economic evaluation, including a formal break-even point (BEP) analysis, to fully establish its commercial viability and scalability.

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