# Design and Evaluation of a Smart Greenhouse Control System for Hemp (Hemp plant) Seed and Fiber Production

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## Abstract

This study aimed to design and evaluate the performance of a smart greenhouse control system for hemp (Hemp plant) cultivation for seed and fiber production, based on the principles of Controlled Environment Agriculture (CEA) and Good Agricultural Practices (GAP). The experiment was conducted in a closed greenhouse measuring 3 meters by 6 meters, containing 72 hemp plants cultivated in pots with one plant per pot defined as the experimental unit, evaluated using a completely randomized design (CRD) with $n = 24$ independent biological replicates per treatment. An automated control system was employed to regulate key environmental parameters, including lighting, irrigation, and air circulation. Because lighting duration, irrigation volume, and air circulation were manipulated simultaneously across treatments, this study evaluated the combined synergistic effects of these microclimatic factors rather than isolated individual main effects. The experimental design consisted of three treatment levels: low (L1–W1–A1), medium (L2–W2–A2), and high (L3–W3–A3), under a controlled light intensity ranging from 5,000 to 7,000 lux. Data were analyzed using one-way analysis of variance (ANOVA), and mean comparisons were performed using Duncan's Multiple Range Test (DMRT) at a significance level of less than 0.05. The results demonstrated that the medium-level treatment (L2–W2–A2), consisting of 8 hours per day of

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lighting, 20 minutes per day of irrigation, and 8 hours per day of air circulation, was statistically identified as the best-performing combination condition among the tested set. Under this treatment, plants achieved an average stem height of 165 ± 10 centimeters, an average total leaf area per plant of 320 ± 25 square centimeters, and the highest average seed yield of 62 ± 7 grams per plant, along with superior fiber quality (tensile strength of 385 ± 28 MPa and fiber yield of 14.2 ± 1.1 g/plant). In contrast, the low-level treatment (L1–W1–A1) induced physiological stress and resulted in a substantially lower seed yield of 28 ± 5 grams per plant. Although the high-level treatment (L3–W3–A3) produced the greatest stem height (180 ± 12 centimeters), it significantly reduced seed yield to 45 ± 6 grams per plant, likely due to imbalanced vegetative growth and etiolation. In conclusion, the balanced regulation of light, water, and air through a statistically validated automated control system plays a critical role in optimizing hemp growth performance and seed productivity. These findings provide a scientifically grounded guideline for precision-controlled environmental management in small-scale smart greenhouse systems.

**Keywords:** Hemp, Smart greenhouse, Environmental control system, Analysis of variance (ANOVA), Controlled environment agriculture (CEA)

## Introduction

Hemp (Hemp plant) has gained increasing recognition as a high-value economic crop in many countries, including Thailand, due to its wide range of industrial applications in textiles, bioproducts, food, cosmetics, and construction materials. In particular, the production of high-quality fiber and genetically pure seeds represents a rapidly expanding market with significant commercial potential (Ketpet et al., 2024; Kaveeta et al., 2004). However, the quality of hemp fiber and seed is highly dependent on environmental conditions during cultivation, including light intensity, relative humidity, water availability, and temperature. These factors play critical roles in physiological processes such as cell division, stem elongation, fiber development, and seed formation (Yanaphan, 2019). Under open-field conditions, hemp cultivation is frequently exposed to climatic variability, including rainfall, wind, storms, excessive humidity, and insufficient light. These environmental fluctuations can adversely affect fiber length and mechanical strength, as well as seed germination and overall crop productivity (Yanaphan et al., 2023). As a result, greenhouse cultivation has emerged as an effective approach to

stabilizing environmental conditions, particularly for seed production that requires high genetic purity and protection from unintended pollen contamination.

Despite these advantages, conventional greenhouse systems often lack precision in environmental management, as they typically rely on manual operation. This can result in inconsistent control of key factors, such as inappropriate lighting duration, over- or under-irrigation, insufficient ventilation, and temperature levels exceeding optimal thresholds. Such limitations not only reduce crop yield and quality but also increase production costs. Consequently, recent advances in agricultural technology have emphasized the development of smart greenhouse systems, which utilize automated control through sensors and microcontrollers to maintain optimal environmental conditions in a continuous and precise manner (Suphan et al., 2024). Within this context, a smart greenhouse system refers to an engineered structure that integrates automated environmental control technologies. Functionally, smart greenhouses can be categorized into two primary architectural types: 1) Time-Based Automated Systems, which execute control commands based on pre-programmed operational schedules to offer simple, accessible, and cost-effective automation suitable for smallholder farmers, and 2) Sensor-Based Feedback Control Systems, which continuously process real-time sensor measurements to dynamically trigger actuators. For hemp cultivation, environmental control is particularly critical. Light regulation governs photoperiod responses, directly influencing flowering initiation and fiber quality. Precision irrigation management helps prevent root diseases and promotes uniform plant growth, while effective air circulation maintains temperature and relative humidity within optimal ranges for fiber development and seed maturation (Jansote et al., 2024; Yanaphan et al., 2023).

At present, smart greenhouse systems specifically designed for hemp seed and fiber production under the frameworks of Controlled Environment Agriculture (CEA) and Good Agricultural Practices (GAP) remain limited in Thailand (Suthiphasilp, 2024). Existing national studies predominantly focus on medical cannabinoid (CBD/THC) extraction or general horticultural crops, leaving a critical knowledge gap regarding how integrated microclimatic control synergistically affects fiber mechanical properties and seed yield in industrial hemp. Therefore, the development of integrated environmental control systems is essential. Such systems should include light regulation tailored to specific growth stages, irrigation management based on soil moisture or hydroponic sensor feedback (Rayaraddi et al. 2018), and air control mechanisms to stabilize temperature and relative humidity (Suphan et al.,

2024; Noonong, 2014). Accordingly, this study aims to advance hemp cultivation from conventional greenhouse practices toward an accessible time-based smart greenhouse system. By systematically evaluating combined microclimatic treatments, this research addresses two specific objectives: 1) to design and evaluate the operational performance of a time-based smart greenhouse control system, and 2) to compare the vegetative growth, seed yield, and fiber characteristics of hemp across three combined environmental control treatment levels. It should be noted that this study evaluates the synergistic impact of these integrated environmental control sets, rather than investigating the independent effects of lighting duration, irrigation runtime, and ventilation schedules separately.

## Research Methodology

### Design of the Greenhouse for Hemp Cultivation.

The smart greenhouse utilized in this study measured 3 meters in width and 6 meters in length, as illustrated in Figure 1(A). It was specifically designed for hemp (Hemp plant) cultivation aimed at seed and fiber production under a closed-environment control system. The system emphasizes the systematic regulation of environmental factors to minimize production variability and enhance cultivation efficiency (Chansrakoo, 2020). In general form, the greenhouse dimensions can be defined as W meters in width and L meters in length (Ketu-u, 2024). The total cultivation area of the greenhouse ($A_{total}$) is calculated using Equation (1):

$$A_{total} = W \times L \quad (1)$$

where: W = Greenhouse width (m)

L = Greenhouse length (m)

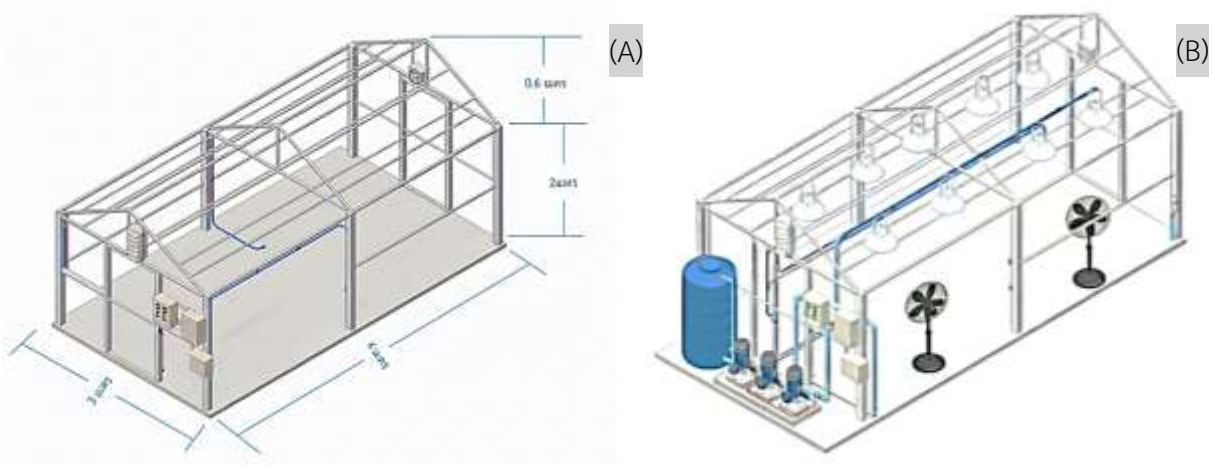



**Figure 1** Greenhouse design for hemp cultivation: (A) Determination of greenhouse dimensions, (B) Smart greenhouse control system

By substituting the specified dimensions, the total cultivation area ($A_{total}$) was calculated as 3 meters × 6 meters, resulting in an area of 18 square meters. This size is consistent with experimental configurations commonly employed in studies of small-scale smart greenhouses for high-value crop production. In accordance with hemp cultivation practices for seed and fiber production under the frameworks of Good Agricultural Practices (GAP) and Controlled Environment Agriculture (CEA) (Suthiphasilp, 2024), appropriate plant spacing is essential to minimize competition for light, water, and nutrients (Rayaraddi et al. 2018; Chansrakoo, 2020). For this purpose, the recommended planting distance is defined as Sx × Sy (Ketu-u et al., 2024). The cultivation area allocated per plant (A<sub>plant</sub>) can therefore be calculated using Equation (2):

$$A_{plant} = S_x \times S_y \quad (2)$$

where: $S_x$ = Planting distance along the width (m)

$S_y$ = Planting distance along the length (m)

By substituting the specified values, the cultivation area per hemp plant ($A_{plant}$) was calculated as 0.5 meters × 0.5 meters, resulting in 0.25 square meters per plant. For hemp cultivation aimed at seed and fiber production, a planting distance of 0.5 meters × 0.5 meters is therefore recommended. This spacing is considered optimal for promoting stem strength and fiber quality, while ensuring vigorous plant growth and minimizing competition for light, water, and nutrients. The total number of hemp plants that can be accommodated within the greenhouse (N) is determined as the ratio of the total cultivation area to the area allocated per plant (Ketu-u et al., 2024), as expressed in Equation (3):

$$N = A_{total} / A_{plant} \quad (3)$$

By substituting the specified values, the cultivation area per hemp plant ($A_{plant}$) was calculated as 0.5 meters × 0.5 meters, resulting in 0.25 square meters per plant. Accordingly, the total number of plants (N) that can be accommodated within the greenhouse was calculated as 18 square meters divided by 0.25 square meters per plant, yielding a total of 72 plants. Based on the greenhouse dimensions and the recommended planting spacing for hemp seed and fiber production, a smart greenhouse measuring 3 meters by 6 meters can therefore accommodate 72 hemp plants. This planting density is considered appropriate for

promoting optimal plant growth, maintaining effective environmental control, and achieving high-quality yields (Noonong, 2014).

As illustrated in Figure 1(B), the smart greenhouse control system was designed as an integrated system comprising three main subsystems: lighting control, irrigation control, and air control. The lighting control subsystem was configured to operate automatically during nighttime using ten light-emitting diode (LED) spotlights. Given a greenhouse height of 2.6 meters, the lighting units were installed on the roof structure at an approximate height of 2.3 meters above ground level to ensure uniform light distribution across the plant canopy. The irrigation control subsystem was programmed for automatic operation during the morning period. Water delivery was regulated through a solenoid valve in combination with a water pump (Ketu-u et al., 2024). Irrigation nozzles were positioned approximately 15 centimeters from the base of each plant and mounted at a height of about 40 centimeters above ground level to optimize water distribution to the root zone. The air control subsystem was designed to regulate internal airflow, temperature, and relative humidity within the greenhouse environment (Jansote et al., 2024). This subsystem consisted of four circulation fans, including two units installed on the side walls at a height of approximately 1.8 meters above ground level and two units positioned at ground level to enhance air circulation throughout the cultivation area.

**Design of the Smart Greenhouse Control System.**

The experiment was evaluated using a completely randomized design (CRD) to compare three combined environmental treatment levels: Low (L1–W1–A1), Medium (L2–W2–A2), and High (L3–W3–A3). The experimental unit was strictly defined as one hemp plant grown in an individual pot. Each treatment comprised 24 independent biological replicates (n = 24), yielding a total sample size of 72 plants across the three treatments (3 X 24 = 72 plants). Because the operational durations for lighting, irrigation, and air ventilation were adjusted simultaneously within each treatment level, this experimental design specifically evaluated the combined synergistic effects of these microclimatic factors on hemp growth, rather than isolating individual main effects. The programmed environmental parameters for each combination level are detailed.

Data obtained from all experimental treatments were expressed as mean values ± standard deviation. To evaluate the effects of lighting, irrigation, and air control levels on hemp growth performance, the data were analyzed using one-way analysis of variance

(ANOVA). When statistically significant differences were detected at a significance level of less than 0.05, Duncan's Multiple Range Test (DMRT) was applied for post-hoc comparisons to identify differences among treatment means. This inferential statistical approach ensures that variations observed in stem height, leaf area, and seed yield are statistically significant and supports the identification of optimal cultivation conditions.

The operational workflow of the smart greenhouse control system was designed based on principles of automatic control in electrical engineering, as illustrated in Figure 2. The system operates through a sequential process consisting of system initialization, control execution, environmental regulation, and completion of the operational cycle (Ketu-u et al., 2024; Viboonpanich, 2017).

Process 1: System Initialization, The system begins with the configuration of operating schedules through a central controller. This controller defines the timing and operational conditions for the lighting, irrigation, and ventilation subsystems. All preset parameters are stored in the controller's memory and used as reference values for automated system operation (Suphan et al., 2024).

Process 2: Control Stage, Once activated, the central controller functions as the main processing unit, continuously comparing real-time conditions with the programmed schedule. Based on this comparison, the controller generates electrical control signals, which are transmitted to the actuators of each subsystem to regulate their operation accordingly (Noonong, 2014).

Process 3: Command Distribution, Control signals generated by the central controller are distributed through three primary subsystems to regulate environmental conditions within the greenhouse. First, in the water distribution subsystem, control signals activate or deactivate the solenoid valve and water pump to deliver water to the root zone according to the predefined duration. Second, in the lighting control subsystem, signals are used to switch light-emitting diode (LED) lamps on or off, thereby regulating the duration and continuity of light exposure to support optimal plant growth. Third, in the ventilation subsystem, control signals operate exhaust and circulation fans to maintain appropriate airflow, temperature, and relative humidity within the greenhouse environment.

Process 4: End of Cycle and Controlled Plant Growth, At the end of the designated operating period, the system automatically deactivates all subsystems and transitions to standby mode. The system remains in this state until the next programmed cycle begins on

the following day. This automated and cyclical operation ensures that environmental conditions are consistently regulated, thereby supporting stable and controlled plant growth throughout the cultivation period.

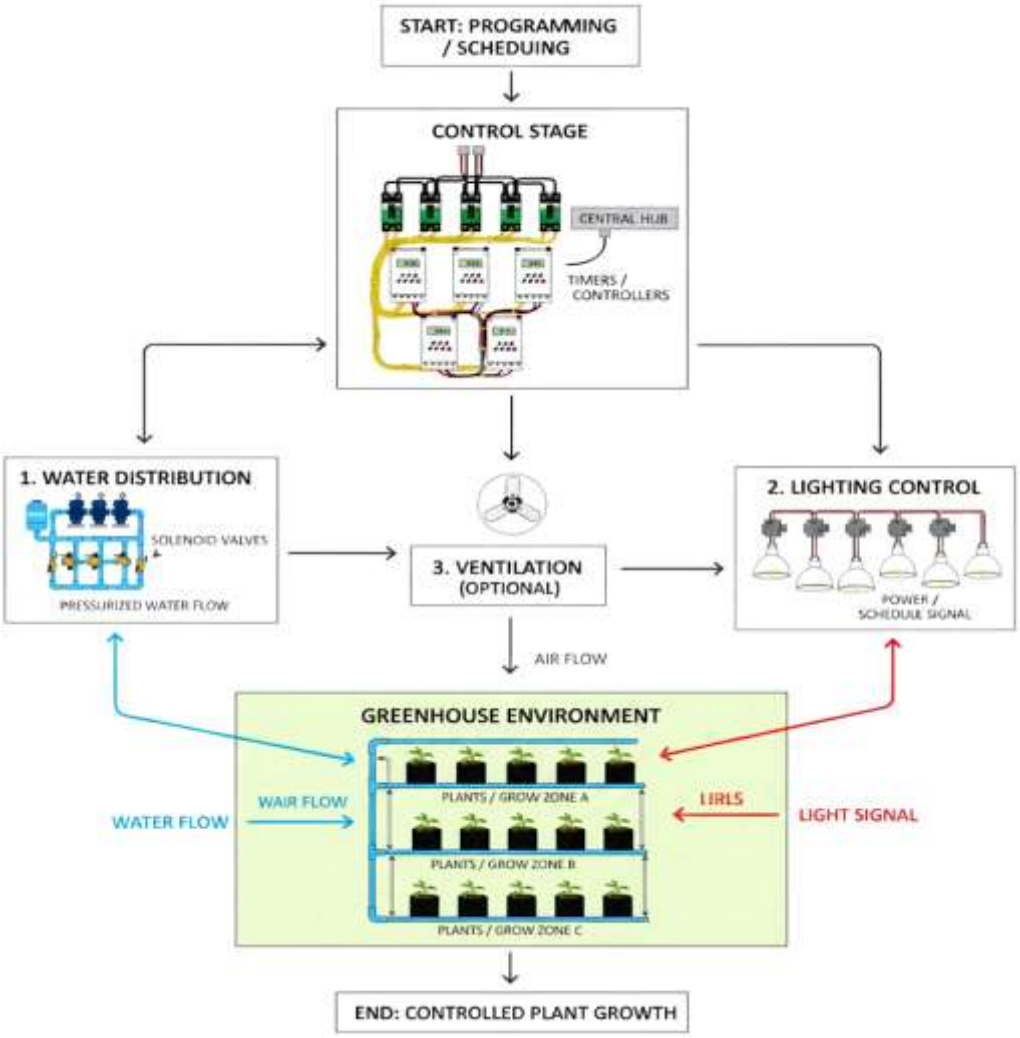



**Figure 2** Workflow of the smart greenhouse control system.

## Preparation of the Cultivation Area and Experimental Hemp Planting

### Preparation of the Cultivation Area for Hemp Cultivation

#### 1. Preparation of Greenhouse Structure

The greenhouse utilized in this study was designed as a closed-system structure constructed with a circular steel frame, selected for its structural strength, durability under varying environmental conditions, and its capacity to support the installation of automated environmental control systems. This design is consistent with the principles of precision agriculture and Controlled Environment Agriculture (CEA). The primary structural components

were fabricated from galvanized steel pipes to prevent corrosion and extend the operational lifespan of the greenhouse (Viboonpanich, 2017).

The walls and roof were covered with transparent polyethylene film, a material widely used in agricultural greenhouse construction. This material provides high light transmittance, allowing approximately 85 percent to 90 percent of natural sunlight to penetrate the structure, thereby enhancing photosynthetic efficiency. In addition, the polyethylene film is ultraviolet-stabilized, offering protection against ultraviolet radiation and contributing to long-term material durability (Chansrakoo, 2020). The installation of the polyethylene covering was performed under uniform tension to minimize the accumulation of water droplets on the surface and to improve the uniform distribution of light within the greenhouse. This installation approach follows established greenhouse design principles aimed at reducing microclimatic variability and lowering the risk of plant disease development.

**2. Preparation of Planting Beds and Growing Media**

Step 1: Greenhouse Floor Preparation and Layout, The greenhouse floor was leveled with a slight slope to facilitate efficient water drainage. A plastic sheet or rubber lining was installed to prevent moisture infiltration from the underlying soil and to minimize contamination from pathogens and weeds, in accordance with closed-system greenhouse management principles. Planting pots were arranged along the longitudinal axis of the greenhouse to ensure uniform light distribution, effective air circulation, and consistent irrigation (Jung & Arar, 2023). Pathways approximately 60 centimeters in width were maintained between rows to facilitate crop management and experimental data collection.

Step 2: Pot Specifications, The containers used in the experiment were black, ultraviolet-resistant plastic pots with a diameter of approximately 35 centimeters and a depth of approximately 40 centimeters, providing a volume of approximately 30 liters. This capacity was sufficient to support root development for hemp cultivated for seed and fiber production. Drainage holes were incorporated at the base of each pot to prevent waterlogging, which is a major contributing factor to root rot in container-based cultivation systems.

Step 3: Growing Medium Preparation, The growing medium consisted of a mixture of loam soil, composted manure, and organic amendments, such as rice husk charcoal or coconut coir, at a volumetric ratio of 2:1:1. This composition provided adequate porosity, water retention, and drainage properties to support optimal root growth (Wei et al., 2023;

Ketpet et al., 2024; Yanaphan, 2023). Prior to use, the pH of the medium was measured and adjusted to a range of 6.0 to 7.0, which is optimal for nutrient availability and uptake in hemp cultivation.

Step 4: Sowing and Seedling Selection, Hemp seeds were sown directly into the pots at a depth of 2 to 3 centimeters per seed. The seeds were then covered with the prepared growing medium and irrigated until the moisture content reached approximately 60 percent to 70 percent of field capacity to promote germination. After seedling emergence, the most vigorous plant was selected and retained in each pot to ensure adequate space for stem development and fiber formation (Nanakhon, 2021; Atoloye et al., 2022).

Step 5: Plant Spacing and Arrangement, The pots were arranged at a spacing of 0.5 meters by 0.5 meters, which is considered optimal for hemp cultivation aimed at seed and fiber production. This spacing minimizes competition for light, water, and nutrients while facilitating effective environmental control under experimental conditions (Chansrakoo, 2020). Based on this arrangement, a greenhouse measuring 3 meters by 6 meters can accommodate a total of 72 pots, corresponding to 72 plants.

**Experimental Hemp Cultivation under the Smart Greenhouse Control System**

This study developed a smart greenhouse control system for hemp (Hemp plant) cultivation aimed at seed and fiber production. The system was designed to regulate key environmental parameters, including lighting, irrigation (Viboonpanich, 2017), and air control, as illustrated in Figure 3(A).

Lighting Control in the Greenhouse, As shown in Figure 3(B), the lighting subsystem was programmed to operate automatically during nighttime and was divided into three treatment levels, designated as L1, L2, and L3, as described in Table 1. These treatments were designed to evaluate the effects of light duration on stem development, fiber quality, and flowering behavior in hemp, while minimizing excessive stem elongation. This approach is consistent with the photoperiod-sensitive characteristics of hemp (Hall et al., 2012).

The lighting system consisted of ten light-emitting diode (LED) spotlights, each with a power rating of 1,000 watts, providing full-spectrum white light. Light intensity was maintained within a range of 5,000 to 7,000 lux, which is appropriate for crop production under controlled environment conditions (Proietti et al., 2021). In a greenhouse with a height of 2.6 meters, the lighting units were installed on the roof structure at approximately 2.3 meters above ground

level, resulting in an average distance of approximately 1.0 meter between the light sources and the plant canopy (Measured vertically using a measuring tape from the LED light fixtures down to the apical meristem of the plants). This configuration ensured uniform light distribution ( Evaluated by calculating the percentage ratio of minimum-to-average light intensity (Minimum Lux / Average Lux × 100) and minimized the risk of light-induced stress. The lighting units were arranged along the longitudinal axis of the greenhouse to provide consistent illumination across the entire cultivation area. Light intensity was measured using a calibrated lux meter at canopy level at multiple positions (Structured as a 9-point spatial grid covering the front, center, and rear sections across the left, middle, and right rows of the greenhouse) within the greenhouse to assess the uniformity of light distribution (Jung & Arar, 2023).




**Figure 3** Experimental hemp cultivation for seed and fiber production: (A) Hemp cultivation in the smart greenhouse, (B) Lighting control, (C) Ventilation control system, and (D) Irrigation control.

Air Control in the Greenhouse, As illustrated in Figure 3(C), the air control subsystem consisted of two side-mounted exhaust fans and two internal circulation fans. This system was designed to regulate airflow, temperature, and relative humidity within the greenhouse environment. The operation of the system was programmed at three levels, designated as A1, A2, and A3, as specified in Table 1. These operational levels were aligned with periods during which external temperatures were typically elevated. The fans were installed above the plant canopy to reduce the accumulation of heat and humidity, thereby minimizing the risk of disease development in the closed cultivation system. Environmental parameters, including temperature and relative humidity, were continuously monitored using sensors installed at canopy level. Data were recorded throughout the experimental period in accordance with Controlled Environment Agriculture (CEA) management principles to ensure precise environmental regulation.

Irrigation Control in the Greenhouse, As shown in Figure 3(D), the irrigation subsystem was programmed to operate automatically during the morning period. Three irrigation levels, designated as W1, W2, and W3, were implemented, as described in Table 1. These irrigation schedules were designed to minimize water loss through evaporation and to reduce plant water stress (Yang et al., 2021; Osakabe et al., 2014). Irrigation nozzles were positioned near the base of each plant to ensure efficient water delivery directly to the root zone while minimizing excess moisture accumulation around the stem. This design is consistent with best practices in greenhouse water management and Good Agricultural Practices (GAP). The performance of the irrigation system was evaluated using soil moisture sensors installed at the root zone level (Jansote et al., 2024), in conjunction with assessments of root system development and observable plant water stress symptoms.

**Table 1** Experimental Variable Settings

| Independent Variable | Treatment Levels |
|---|---|
| Lighting Control System | |
| L1 | Light duration 6 h/day (18:00–00:00) |
| L2 | Light duration 8 h/day (18:00–02:00) |
| L3 | Light duration 10 h/day (18:00–04:00) |
| Irrigation Control System | |
| W1 | Irrigation 08:00–08:10 (10 min/day) |
| W2 | Irrigation 08:00–08:20 (20 min/day) |
| W3 | Irrigation 08:00–08:30 (30 min/day) |
| Greenhouse Air Control System | |
| A1 | Air system 6 h/day (08:00–14:00) |
| A2 | Air system 8 h/day (08:00–16:00) |
| A3 | Air system 10 h/day (08:00–18:00) |

## Results

The effects of three lighting duration levels L1 (6 hours per day), L2 (8 hours per day), and L3 (10 hours per day)—under a controlled light intensity range of 5,000 to 7,000 lux are presented in Table 2. This light intensity range is considered optimal for hemp cultivation under controlled environment conditions. The results indicate that the average light intensity measured at the plant canopy varied depending on the duration of light exposure. Treatment L2 produced an average light intensity of approximately 6,200 lux and demonstrated the highest light distribution uniformity, at approximately 92 percent. Uniformity of light distribution is a critical factor influencing photosynthetic efficiency and overall plant productivity (Proietti et al., 2021).

In terms of plant response, treatment L2 resulted in uniform stem growth, an appropriate number of internodes, and the absence of abnormal elongation. These findings are consistent with previous studies indicating that optimal photoperiod management supports stable plant morphology and enhances fiber quality in hemp. In contrast, treatment L1 provided insufficient light exposure, leading to reduced stem growth and limited fiber development. Although treatment L3 involved a longer duration of light exposure, it promoted excessive stem elongation, which may negatively affect structural integrity and fiber quality over time (Kaveeta et al., 2004).

**Table 2** Measured light intensity under different light duration treatments

| Light Level | Duration (h/day) | Average Light Intensity (lux) | Light Uniformity (%) | Plant Response |
|---|---|---|---|---|
| L1 | 6 | 5,100 ± 320 | 78 | Growth slowed |
| L2 | 8 | 6,200 ± 280 | 92 | Most suitable |
| L3 | 10 | 6,800 ± 450 | 85 | Stem elongation tendency |

A comparison of three irrigation durations—W1 (10 minutes per day), W2 (20 minutes per day), and W3 (30 minutes per day) as presented in Table 3, revealed significant differences in soil moisture levels measured using soil moisture sensors. Treatment W2 resulted in an average soil moisture content of approximately 30 percent, which falls within the optimal range for hemp growth under greenhouse conditions and aligns with water management practices recommended under Good Agricultural Practices (GAP). This treatment supported adequate root development and efficient nutrient uptake.

In contrast, treatment W1 produced soil moisture levels below the optimal range, leading to intermittent water stress and incomplete root development. Periodic water deficiency limited root growth and reduced the efficiency of nutrient absorption. Conversely, treatment W3 resulted in elevated soil moisture levels, increasing the risk of excessive water accumulation in the growing medium. Such conditions may promote the development of soil-borne diseases, including root rot, particularly in closed cultivation systems with limited ventilation (Suphan et al., 2024; Jung and Arar, 2023).

**Table 3** Soil moisture levels under different irrigation durations

| Irrigation Level | Duration (min/day) | Average Soil Moisture (%) | Root Condition | Suitability |
|---|---|---|---|---|
| W1 | 10 | 22 ± 3 | Short roots | Low |
| W2 | 20 | 30 ± 2 | Well-developed roots | Best |
| W3 | 30 | 38 ± 4 | Risk of root rot | Moderate |

The effects of air control were evaluated under three fan operation durations A1 (6 hours per day), A2 (8 hours per day), and A3 (10 hours per day) as presented in Table 4. The results indicate that treatment A2 maintained the most favorable environmental conditions within the greenhouse. Under this treatment, the average temperature was

approximately 29.5 degrees Celsius, and the relative humidity was approximately 65 percent, both of which fall within the optimal range for hemp growth under greenhouse cultivation.

In contrast, treatment A1 provided insufficient ventilation, resulting in the accumulation of heat and humidity during daytime conditions. This environment increased the risk of heat stress and the incidence of plant diseases (Yang et al., 2021). Although treatment A3 was effective in reducing internal temperature, it led to increased transpiration and water loss from plants, thereby disrupting plant water balance and negatively affecting overall growth performance (Nikolaou et al., 2019).

**Table 4** Temperature and relative humidity inside the greenhouse

| Air Control Level | Duration (h/day) | Temperature (°C) | Relative Humidity (%) | Environmental Stability |
|---|---|---|---|---|
| A1 | 6 | 33.5 ± 2.1 | 78 ± 5 | Low |
| A2 | 8 | 29.5 ± 1.3 | 65 ± 4 | Best |
| A3 | 10 | 27.8 ± 1.6 | 55 ± 6 | High plant water loss |

Based on the overall results presented in Table 5, a comparative analysis of hemp growth under three controlled environmental treatments low level (L1–W1–A1), moderate level (L2–W2–A2), and high level (L3–W3–A3) incorporating lighting, irrigation, and air control systems, can be summarized as follows.

Stem height reflects the combined effects of cell division and cell elongation, both of which are directly influenced by light duration, water availability, and greenhouse air conditions. The results indicate that the moderate-level treatment (L2–W2–A2) produced an optimal stem height with the lowest variability (165 ± 10 centimeters), suggesting that a balanced environment promotes stable growth without abnormal elongation. In contrast, the low-level treatment (L1–W1–A1) resulted in significantly shorter stems (120 ± 8 centimeters), likely due to insufficient light and limited water availability. Although treatment L3–W3–A3 produced the greatest stem height (180 ± 12 centimeters), the excessive elongation observed under this condition indicates unbalanced growth, which may compromise stem strength and fiber quality (Jareczek et al., 2023).

Leaf area is a critical indicator of photosynthetic capacity and biomass accumulation. The findings demonstrate that the moderate-level treatment (L2–W2–A2) produced the largest average leaf area (320 ± 25 square centimeters), characterized by healthy, dark green leaves, indicating high photosynthetic efficiency. This condition contributed to improved fiber

development and increased seed yield. In contrast, the low-level treatment (L1–W1–A1) resulted in the smallest leaf area (180 ± 20 square centimeters), reflecting limitations in resource availability. The high-level treatment (L3–W3–A3) produced a moderate leaf area (260 ± 30 square centimeters); which was lower than that of L2–W2–A2 due to high transpiration demand induced by prolonged ventilation (10 h/day), forcing partial stomatal closure to prevent water loss and limiting carbon assimilation. Additionally, excessive light duration redistributed photoassimilates preferentially toward stem elongation rather than leaf expansion; however, the presence of elongated and thinner leaves suggests etiolation, which originated from an imbalance in photomorphogenesis and microclimatic stress. Prolonged artificial illumination (10 h/day) continuously stimulated auxin-driven stem cell elongation while suppressing lateral leaf lamina expansion. Concurrently, high ventilation (10 h/day) paired with excessive root-zone moisture (30 min/day) induced physiological stress, disrupting nutrient uptake particularly magnesium required for chlorophyll synthesis and resulting in slender, pale, and elongated vegetative structures. This structural distortion ultimately reduced the effective photosynthetic surface area (Ketpet et al., 2024).

Seed yield serves as a direct indicator of physiological performance during the reproductive stage. The results show that the moderate-level treatment (L2–W2–A2) achieved the highest seed yield (62 ± 7 grams per plant), consistent with its optimal stem height and leaf area. This indicates efficient carbohydrate accumulation and effective allocation of energy from vegetative growth to reproductive development. In contrast, the low-level treatment (L1–W1–A1) produced the lowest seed yield (28 ± 5 grams per plant), primarily due to environmental stress. The high-level treatment (L3–W3–A3) resulted in a moderate seed yield (45 ± 6 grams per plant), suggesting that excessive vegetative growth does not necessarily translate into increased reproductive output (Yanaphan, 2019).

**Table 5** Comparative quantitative growth performance of hemp

| Control System | Stem Height (cm) | Leaf Area ($cm^2$) | Seed Yield (g/plant) | Fiber Quality | Overall Performance |
|---|---|---|---|---|---|
| L1–W1–A1 | $120 \pm 8^{c}$ | $180 \pm 20^{c}$ | $28 \pm 5^{c}$ | Low | Low |
| L2–W2–A2 | $165 \pm 10^{b}$ | $320 \pm 25^{a}$ | $62 \pm 7^{a}$ | Best | Most suitable |
| L3–W3–A3 | $180 \pm 12^{a}$ | $260 \pm 30^{b}$ | $45 \pm 6^{b}$ | Moderate | Moderate |

**Note:** Different superscript letters (a, b, c) in the same column indicate statistically significant differences ($p < 0.05$). Fiber quality was categorized based on the uniformity and strength of the extracted bast fibers.

The physical properties of hemp fibers, including tensile strength and fiber density, were qualitatively evaluated based on visual inspection and the consistency of manual fiber extraction. Fiber quality was classified into three categories, Low (L1–W1–A1), Moderate (L3–W3–A3), and Best/High Quality (L2–W2–A2).

## Discussion

Inferential statistical analysis confirmed that the L2–W2–A2 treatment was significantly superior in promoting leaf expansion and seed production. Although L3–W3–A3 produced the greatest stem height, the significant reduction in seed yield ($p < 0.05$) indicates that excessive environmental inputs induce physiological stress and unbalanced growth. These findings support the transition from time-based control to a balanced, precision-controlled system for optimizing hemp productivity. The smart greenhouse system demonstrated that coordinated regulation of light, water, and air directly influences plant growth, uniformity, and yield potential (Jansote et al., 2024; Proietti et al., 2021). Optimal lighting at 8 hours per day with an intensity of 5,000 to 7,000 lux supported stable morphology and fiber quality, whereas insufficient or excessive light reduced performance.

An irrigation duration of 20 minutes per day maintained optimal root-zone moisture, promoting efficient nutrient uptake. Lower irrigation levels caused water stress (Osakabe et al., 2014), while excessive irrigation increased the risk of oxygen deficiency and soil-borne diseases (Yang et al., 2021). Similarly, ventilation at 8 hours per day maintained temperature and relative humidity within optimal ranges (Proietti et al., 2021). Insufficient ventilation led to heat and humidity accumulation (Nguanhom et al., 2025), whereas excessive ventilation increased plant water loss (Suphan et al., 2024). Overall, the L2–W2–A2 treatment produced the best performance, with optimal stem height (165 ± 10 centimeters), maximum leaf area (320 ± 25 square centimeters per leaf), and the highest seed yield (62 ± 7 grams per plant). These results highlight that balanced environmental control is essential for maximizing hemp growth, yield, and quality. (Jansote et al., 2024).

## Conclusion and suggestions

### Conclusion

The experimental results, supported by statistical analysis, demonstrate that the L2–W2–A2 configuration—comprising 8 hours per day of lighting at an intensity of 5,000 to 7,000 lux, 20 minutes per day of irrigation, and 8 hours per day of air control—represents the statistically optimal condition for hemp cultivation. Under this treatment, plants exhibited enhanced photosynthetic performance and reproductive success, achieving the highest seed yield of 62 ± 7 grams per plant, which was significantly greater than those observed under both low-level and excessive control conditions.

In contrast, low-level environmental control (L1–W1–A1) induced plant stress due to insufficient light, water, and ventilation, resulting in reduced growth, smaller leaf area, limited root development, and low seed yield. Excessive control (L3–W3–A3), although promoting greater stem elongation, led to imbalanced growth characterized by etiolation, increased water loss, and no proportional improvement in seed yield, thereby potentially compromising stem strength and fiber quality over the long term.

### Suggestions

1. Future studies should evaluate the performance of different lighting technologies, such as full-spectrum light-emitting diode systems compared with wavelength-specific light sources, to improve energy use efficiency.

2. Further research should investigate the combined effects of environmental control, planting density, spacing, and fertilizer management on fiber quality and seed yield in hemp cultivation systems.

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