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A LOW-COST, OPEN-SOURCE APPROACH FOR SENSOR-BASED LIGHT MANAGEMENT IN PROTECTED CULTIVATION SYSTEMS

Bogdan ILIE[1], Yuxin TONG[2], Ana BUTCARU[1], Tiberiu ION[3], Ionuț Ovidiu JERCA[1]

[1]University of Agronomic Sciences and Veterinary Medicine of Bucharest,
59 Mărăști Blvd, District 1, Bucharest, Romania
[2]Institute of Environment and Sustainable Development in Agriculture,
Chinese Academy of Agricultural Sciences, China
[3]SC Skip Monday Studio SRL, 10 Triumfului Street, Ploiesti, Prahova County, Romania

Corresponding author email: ovidiu.jerca@qlab.usamv.ro

Abstract

Efficient light management represents a key challenge in protected cultivation systems, particularly when cost constraints limit the use of advanced dimmable lighting technologies. This study presents a low-cost, open-source, sensor-based approach for practical light management in protected horticultural environments. A custom-built multi-stage lighting system was combined with a multispectral light sensor used as a control variable, while a reference PAR sensor was employed for calibration under real operating conditions. Light intensity was regulated through automated multi-stage switching with integrated energy monitoring, enabling feedback between illumination targets and electrical power consumption. The control logic was implemented using an open-source automation platform, allowing data acquisition, logging, and system adaptability. The experimental setup was evaluated under greenhouse conditions using Capsicum spp. as experimental plant support. Rather than replacing professional photometric instruments, the proposed approach demonstrates the functional integration of low-cost sensors and open-source tools for scalable and energy-efficient light management applications.

Key words: *artificial lighting; DLI control; Home Assistant; open-source automation; PPFD estimation.*

INTRODUCTION

Protected cultivation systems are increasingly expected to deliver higher productivity, better resource use efficiency, and improved crop quality under variable environmental and economic constraints. In this context, light management has become one of the central technical challenges of greenhouse and other protected horticultural systems. Although natural solar radiation remains the dominant light source in most structures, its quantity and temporal distribution are often insufficient or highly variable, especially during winter, cloudy periods, or in densely developed canopies where self-shading limits light penetration to lower leaf layers. As a result, supplemental lighting is widely regarded as an effective tool for stabilizing photosynthesis, supporting plant development, and improving yield and product quality in protected crops (Moe et al., 2006; Hemming, 2011; Hao et al., 2018).

The physiological importance of light in horticultural systems is not limited to total irradiance. Crop responses depend on several interrelated parameters, including photosynthetic photon flux density (PPFD), daily light integral (DLI), photoperiod, spectral composition, and vertical light distribution within the canopy. For fruiting vegetables and other greenhouse crops, insufficient light reduces assimilate production, affects vegetative–generative balance, and may limit both yield and crop quality. In high-density canopies, most incident radiation is intercepted by the upper leaf layers, leaving the lower canopy under-illuminated. This uneven distribution reduces the contribution of lower leaves to whole-plant photosynthesis and has motivated the development of strategies such as interlighting and spectrum-tailored supplemental illumination (Jokinen et al., 2012; Guo et al., 2016; Hao et al., 2018).

During the last decade, light-emitting diode (LED) technology has become increasingly important in horticultural lighting because it offers several practical advantages over conventional discharge lamps. These include

high photon efficiency, low radiant heat output, long operational lifespan, compact size, and the possibility of spectral tailoring according to plant needs. In addition, LED systems can be integrated more easily into digital control architectures than older lighting technologies. This has enabled not only supplemental and interlighting strategies, but also increasingly precise forms of control based on crop demand and environmental variability (Morrow, 2008; Moe, 2012; Bergstrand et al., 2016; Palmitessa et al., 2021). From the perspective of plant lighting, efficiency should be considered primarily in terms of delivered photosynthetic photons rather than conventional human-centered luminous metrics, because plant responses are driven by photon flux in the photosynthetically active radiation (PAR) region (400-700 nm) (Nelson & Bugbee, 2014). At the same time, there is increasing evidence that lighting strategies should not be treated as simple on/off supplementation. Instead, effective greenhouse lighting must be understood as a dynamic management problem in which light intensity, light quality, timing, and canopy distribution are coordinated with crop requirements and available natural radiation. Reviews and experimental studies have shown that optimized supplemental lighting can improve productivity, accelerate development, and increase the efficiency of canopy light use in crops such as tomato and sweet pepper. This applies not only to northern regions with severe winter limitations, but also to Mediterranean or transitional climates where natural light is often variable rather than consistently limiting (Li et al., 2016; Paucek et al., 2020; Palmitessa et al., 2021). The relationship between PPFD delivery and crop nutrient demand also underlines the importance of precise light quantification in closed growing environments.

Despite these advances, practical implementation in small or medium-scale protected cultivation remains constrained by cost. Professional dimmable lighting systems, quantum sensors, and commercial greenhouse control platforms can be effective, but they are often too expensive for experimental, educational, or low-budget horticultural installations. This creates a technological gap: the biological need for intelligent light management is well established, but affordable systems capable of continuous sensing, automated control, and energy-aware operation are still limited. In practice, many growers and researchers require solutions that are not necessarily perfect substitutes for industrial systems, but are sufficiently robust, transparent, and adaptable for real use under greenhouse conditions.

One of the key barriers to low-cost light management is the measurement of PPFD itself. Professional quantum sensors provide direct and reliable PAR measurements, but their cost may restrict deployment density or routine use in custom automation systems. As a result, low-cost multispectral sensors have attracted increasing interest as potential alternatives for estimating PPFD and related light metrics. However, such sensors do not directly measure PPFD; instead, they provide channel-specific responses that depend on spectral composition, optical geometry, and environmental conditions. Therefore, their use in horticultural applications requires calibration against a reference PAR instrument under relevant operational conditions. The AS7341 is a ten-channel multispectral sensor covering the full PAR range (415-680 nm) plus broadband and NIR channels, at low component cost, making it particularly suitable for integration into custom greenhouse sensing systems. Recent work has demonstrated that compact multi-channel spectral sensors of this type can estimate PAR or PPFD with useful accuracy when appropriately calibrated (Bäumker et al., 2021). The combination of multiple spectral channels for sensor fusion has also been shown to substantially improve estimation accuracy compared to single-channel approaches (Li et al., 2018; Yang et al., 2020). Hyperspectral and multispectral approaches more generally have demonstrated the broader value of spectral sensing in crop monitoring and physiological estimation (Kawasaki et al., 2008; Thorp et al., 2017; Shafaei et al., 2018).

A second major barrier is control architecture. In recent years, smart greenhouse research has increasingly moved toward sensor networks, IoT-based monitoring, cloud-connected platforms, and data-driven automation. These systems can improve environmental control, reduce labor, and increase resource efficiency

by linking sensors, actuators, and supervisory logic in a single platform (Rath & Kawollek, 2009; Sagheer et al., 2021). However, many published systems remain relatively complex or infrastructure-heavy and are not always directly transferable to simple protected cultivation structures or researcher-built installations. Open-source platforms represent an attractive alternative because they allow custom hardware integration, real-time logging, flexible control logic, and direct transparency of algorithms and thresholds.

For lighting control specifically, the combination of instantaneous PPFD estimation with daily light integral (DLI) tracking is especially promising. PPFD enables rapid decisions in response to transient changes in natural radiation, while DLI provides an integrative measure of total daily photosynthetic light received by the crop. Together, these variables support a biologically meaningful control strategy: supplemental lighting can be activated when natural light is insufficient and limited when the daily light target has already been reached. Such an approach is well aligned with commercial greenhouse principles, yet it can also be implemented in simplified form using discrete lighting stages and open-source automation (Kim et al., 2006; Hao et al., 2018).

Therefore, the novelty of the present study does not lie in proposing a new photometric standard or replacing professional horticultural instrumentation. Instead, it lies in demonstrating that a practical light management system for protected cultivation can be built from low-cost components and open-source tools, provided that calibration, control logic, and energy monitoring are treated rigorously. The system presented here combines a custom-built multi-stage LED lighting fixture, a multispectral AS7341 sensor used as a control variable, a reference quantum sensor for calibration, and a Home Assistant-based automation framework for PPFD estimation, DLI integration, and stage-based lighting control under real greenhouse conditions.

The objective of this study was to develop and evaluate a low-cost, open-source, sensor-based lighting management approach suitable for protected horticultural environments. More specifically, the study aimed to: (i) calibrate a multispectral AS7341 sensor against a reference quantum sensor for estimating canopy-level PPFD under real greenhouse conditions; (ii) implement an adaptive, multi-stage supplemental lighting strategy based on estimated PPFD and DLI; and (iii) integrate lighting control with energy monitoring through an open-source automation platform in order to demonstrate a scalable and practically useful alternative for protected cultivation systems, using *Capsicum* spp. as experimental plant support.

MATERIALS AND METHODS

AS7341 Sensor Calibration for PPFD Estimation

In modern protected cultivation systems, accurate light management is essential for both optimizing photosynthesis and minimizing the energy costs associated with supplemental lighting. Professional quantum sensors, which directly measure photosynthetic photon flux density (PPFD, $\mu mol \cdot m^{-2} \cdot s^{-1}$), serve as reference instruments but are costly and impractical for multi-point deployment in experimental or commercial greenhouses (Hemming, 2011; Nelson and-Bugbee, 2014).

In this context, the AS7341 multispectral sensor represents an attractive low-cost alternative, providing separate measurements across ten spectral bands in the visible and NIR range (415-680 nm, Clear, NIR). However, the AS7341 does not measure PPFD directly; instead, it outputs raw digital counts that depend on the spectral composition of the light source, the angle of incidence, and local optical conditions. Consequently, the use of this sensor in horticultural applications requires rigorous calibration under conditions as close as possible to real-world operation (Bäumker et al., 2021).

The objective of this calibration step was to establish a mathematical relationship (regression model) between the raw channel outputs of the AS7341 and the actual PPFD values measured by a reference quantum sensor, enabling the AS7341 to subsequently estimate canopy-level PPFD, compute the Daily Light Integral (DLI), and support automated supplemental lighting control.

The AS7341 breakout board was soldered with a four-wire I²C cable (SDA, SCL, VCC, GND) and mounted inside a custom 3D-printed

enclosure designed specifically for this experiment (Figure 1). The enclosure provides mechanical protection and ensures a fixed, reproducible optical geometry for the sensor. An opal diffuser dome was positioned above the optical capsule of the sensor. The dome serves a dual purpose: (1) uniformizing the angle of incidence, thereby reducing sensitivity to the sun's position (sunrise vs. sunset), and (2) approximating the angular response of a cosine-corrected quantum sensor, which integrates photon flux across a full hemisphere. The enclosure was sealed and weatherproofed, enabling permanent installation in the greenhouse environment.



Figure 1. AS7341 sensor assembly components. Left: multispectral breakout board in the custom 3D-printed enclosure with I²C wiring. Centre: opal diffuser dome above the AS7341 optical capsule prior to assembly. Right: sensor mounted upward-facing on the greenhouse support post

A LightScout Quantum Light Meter (Spectrum Technologies, USA) was used as the reference instrument, capable of directly measuring PPFD in the 400-700 nm range, expressed in $\mu mol \cdot m^{-2} \cdot s^{-1}$. This sensor served as the calibration standard throughout the entire measurement campaign. It was positioned at canopy level, in a fixed upward-facing orientation, without adjusting the angle of incidence during measurements.

It is important to note that the sensor angle was not adjusted toward the sun to maximize PPFD readings, even under strong direct irradiance. Although orienting the sensor toward the sun could have produced values exceeding 1000 $\mu mol \cdot m^{-2} \cdot s^{-1}$, this approach would have introduced an additional source of geometric error and compromised the comparability of measurements across different times of day.

The AS7341 sensor was mounted in a fixed position on a dedicated steel support post inside the greenhouse, approximately 3 m from the reference quantum sensor. Although this separation introduces the possibility that one sensor may occasionally be partially shaded by the greenhouse structure or covering film, this was not systematic and was considered acceptable for calibration under real operating conditions.

Calibration was performed exclusively under natural light, with all supplemental LED lighting switched off, over multiple days (12-13 January 2025), across different times of day covering a broad range of PPFD values from approximately 1-10 $\mu mol \cdot m^{-2} \cdot s^{-1}$ up to approximately 700 $\mu mol \cdot m^{-2} \cdot s^{-1}$. This approach ensured that the calibration dataset included a wide variety of illumination conditions: overcast sky, diffuse light, direct sunlight at different solar angles, and spectral variations caused by solar position and greenhouse film transmittance.

For each calibration point, the following procedure was applied: (1) the PPFD value was read from the quantum sensor ($\mu mol \cdot m^{-2} \cdot s^{-1}$); (2) the exact time was recorded (hh:mm); (3) a screenshot of the raw channel counts of the AS7341, as displayed in the Home Assistant platform, was captured; and (4) values were subsequently entered manually into a centralized data table. Approximately 100 individual measurements were collected in total, distributed across the full PPFD range of interest (Figure 2).



Figure 2. Calibration data collection procedure

The LightScout quantum sensor (reading 148 $\mu mol \cdot m^{-2} \cdot s^{-1}$) is positioned at canopy level alongside *Capsicum* spp. experimental plants. The data recording sheet on the clipboard is visible in the foreground, illustrating the parallel manual logging of quantum sensor values and timestamps.

Raw unprocessed channel values were used for regression, without internal normalization, in order to preserve the direct relationship between the received optical signal and the electronic response of the sensor. The Clear and NIR channels were analyzed separately; however, the final model was built primarily on channels within the PAR range (415–680 nm), as these are directly relevant to photosynthesis (Kim et al., 2004; Nelson & Bugbee, 2014).

The relationship between PPFD and AS7341 signals is not perfectly linear across the full measurement range, particularly at very low light levels where the ratio of diffuse to direct light varies substantially and the contribution of non-PAR spectral components becomes relatively larger. For this reason, calibration was approached using multiple linear regression, followed by a critical analysis of its domain of validity. The resulting model expresses estimated PPFD as a weighted sum of the AS7341 spectral channels:

$$PPFDest = a_0 + a_1 \cdot Ch415 + a_2 \cdot Ch445 + \ldots + a_n \cdot Ch680$$

Coefficients were determined by the least-squares method using the complete collected dataset. Subsequently, the use of a piecewise model was found necessary, separating the low-light domain from the medium–high illuminance domain, in order to improve accuracy under reduced illumination conditions (Bäumker et al., 2021). The combination of multiple spectral channels substantially improves estimation accuracy compared to single-channel broadband approaches (Li et al., 2018; Yang et al., 2020).

The final calibration model allows: (1) PPFD estimation with satisfactory accuracy across the horticultural range of interest; (2) real-time integration into Home Assistant; and (3) use for DLI computation and supplemental lighting control. The objective of this calibration was not to replace a laboratory-grade quantum sensor, but to obtain a robust, reproducible, and sufficiently accurate instrument for practical greenhouse control applications (Figure 3).

The dashed line represents perfect agreement (1:1); the shaded band indicates ±RMSE. Right: MLR regression coefficients per spectral channel. Channels at 445 nm and 480 nm show the strongest positive contributions; the 590 nm channel shows the largest negative coefficient.

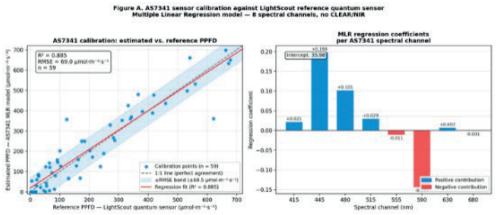


Figure 3. AS7341 calibration against the LightScout reference quantum sensor. Left: scatter plot of AS7341-estimated PPFD vs. reference PPFD (n = 59; $R^2 = 0.896$; RMSE = 69.5 µmol·m^{-2}·s^{-1}).

Lighting System Configuration

The supplemental lighting fixture was custom-built from 20 full-spectrum LED bulbs (2.5 W real consumption each), mounted on a 3 m aluminium rail suspended horizontally above the crop canopy. The bulbs were arranged in three independently controlled circuits of 7, 7, and 6 lamps respectively, connected in parallel within each circuit (Figure 4 and Figure 5).

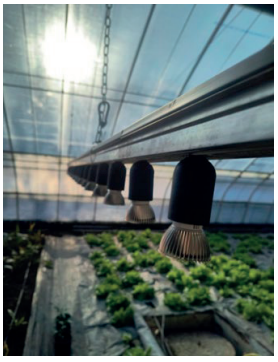


Figure 4. Custom-built supplemental lighting fixture consisting of 20 full-spectrum LED bulbs mounted on an aluminium rail, photographed under natural daylight conditions with lamps switched off. The three independently controlled circuits are arranged along the rail

The three circuits define three cumulative lighting stages, activated in succession:

- Stage 1 (circuit 1 only, 7 lamps): approximately 30 µmol·m^{-2}·s^{-1}
- Stage 2 (circuits 1+2, 14 lamps): approximately 70 µmol·m^{-2}·s^{-1}
- Stage 3 (circuits 1+2+3, all 20 lamps): approximately 150 µmol·m^{-2}·s^{-1}.

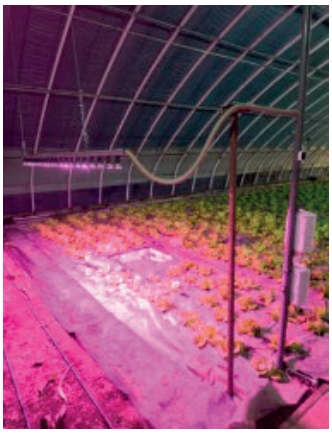


Figure 5. Supplemental lighting fixture operating at full output (Stage 3, all 20 lamps) during nighttime, illuminating the crop canopy with characteristic pink-magenta spectrum

The smart plug control box is visible on the support post (right). The AS7341 sensor post is positioned in the background.

PPFD values associated with each stage were determined experimentally at canopy level using the reference quantum sensor, under nighttime conditions with natural light fully excluded. Given the directional nature of the LED sources and the spatial variability inherent to a DIY fixture (particularly the disproportionate contribution of the six overhead lamps in stage 3, which illuminate the plant canopy perpendicularly), measured values ranged approximately 20-30% around the mean at each stage. The representative values of 30, 70, and 150 $\mu mol \cdot m^{-2} \cdot s^{-1}$ were adopted as operational parameters and maintained consistently throughout the experiment. All three stages operate exclusively in ON/OFF mode; no dimming is applied (Figure 6).

The hardware architecture was built around the AS7341 multispectral sensor, connected via the I²C bus (SDA/SCL, GPIO21/GPIO22) to an ESP32 microcontroller running ESPHome firmware, powered at 5 V DC. The ESP32 transmitted raw spectral channel values wirelessly (Wi-Fi, 2.4 GHz) to a local Home Assistant server, where PPFD estimation and control logic were implemented.

Supplemental lighting was delivered by the custom three-stage LED fixture described above. Each stage was powered independently at 230 V AC through a dedicated smart power outlet with integrated energy metering (Zigbee protocol), enabling discrete control of photon flux and real-time monitoring of electrical energy consumption per stage. This architecture allows full separation between the sensing/decision layer and the energy delivery layer, improving system robustness and scalability (Figure 7).

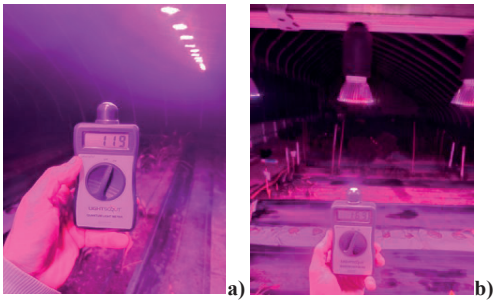


Figure 6. a) LightScout quantum sensor reading 119 $\mu mol \cdot m^{-2} \cdot s^{-1}$ during PPFD characterization of the lighting fixture under Stage 3 operation, measured at a lateral position below the lamp array; b) LightScout quantum sensor reading 169 $\mu mol \cdot m^{-2} \cdot s^{-1}$ measured directly below a Stage 3 lamp in perpendicular orientation, illustrating the elevated PPFD contribution of the overhead bulbs

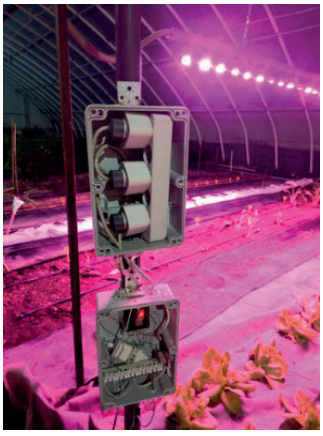


Figure 7. Hardware installation on the greenhouse support post

Upper enclosure: three Zigbee smart plugs with energy metering, one per lighting stage. Lower enclosure: ESP32 microcontroller (red LED visible) and terminal block. The complete sensing and actuation infrastructure is contained within two weatherproof boxes mounted at a single location (Figure 8).

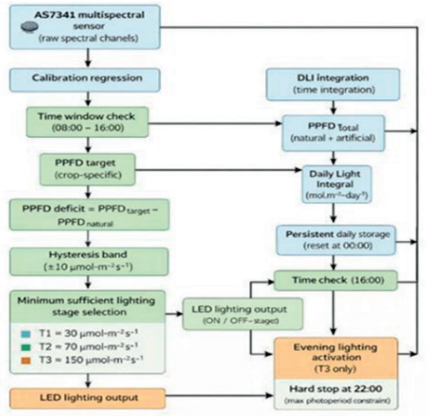


Figure 8. Hardware system overview of the adaptive lighting control system. The AS7341 sensor is connected to an ESP32 microcontroller running ESPHome, which transmits estimated PPFD data over Wi-Fi to Home Assistant. Home Assistant controls three smart plugs powering the three LED lighting stages operating at 230V

Hardware System Overview

To translate the PPFD estimates obtained from the calibrated AS7341 sensor into a practical light management tool, an automated supplemental lighting control strategy was implemented, based on two complementary decision levels: instantaneous PPFD-based control during the daytime, and integrative DLI-based compensation in the evening. This approach was designed to replicate the principles used in modern commercial greenhouses, using low-cost calibrated sensors and an open-source automation platform (Hao et al., 2018; Sagheer et al., 2021).

For the experimental plant support (*Capsicum* spp.), the DLI requirement was defined in the range of 10-12 mol·m^{-2}·d^{-1}, an interval frequently recommended for pepper species grown in protected environments (Jokinen et al., 2012; Hao et al., 2018). In this experiment, a DLI target of 10 mol·m^{-2}·d^{-1} was adopted as the operational setpoint, with a total photoperiod (natural + artificial light) of 14 hours (08:00-22:00). A PPFD control target of 200 µmol·m^{-2}·s^{-1} was used as the instantaneous setpoint for daytime control. This value represents a practical threshold below which supplemental lighting is activated, chosen conservatively to account for natural variability in greenhouse irradiance. It should be noted that for a DLI of 10 mol·m^{-2}·d^{-1} over 14 hours, the equivalent average PPFD would be approximately 198 µmol·m^{-2}·s^{-1}, confirming that the chosen threshold of 200 µmol·m^{-2}·s^{-1} is biologically consistent. The system is designed to be crop-agnostic: both the DLI target and the PPFD threshold are configurable parameters adjustable for any horticultural species without modifying the control logic.

Adaptive Multi-Stage Lighting Control

During the daytime window (08:00-16:00), the system evaluates estimated canopy PPFD every 5 minutes. At each evaluation step, the algorithm determines the light deficit relative to the PPFD target and selects the minimum lighting stage capable of compensating this deficit: if PPFDnatural ≥ 200 µmol·m^{-2}·s^{-1} → all stages OFF; if PPFDnatural + 30 ≥ 200 → Stage 1 ON (7 lamps); if PPFDnatural + 70 ≥ 200 → Stage 2 ON (14 lamps); otherwise → Stage 3 ON (20 lamps).

To prevent frequent switching caused by rapid irradiance fluctuations (e.g., passing clouds), a hysteresis band of ±10 µmol·m^{-2}·s^{-1} was applied: the current stage is maintained as long as the deviation from the target remains within this band. Additionally, daytime control is active only when the accumulated DLI has not yet reached the daily target. Once the DLI target is reached, all stages are immediately switched off and the daytime automation is suppressed for the remainder of the day.

In parallel with instantaneous control, the system continuously computes the daily DLI by integrating total PPFD (natural + artificial) over time. At each 5-minute interval, the DLI increment is calculated as:

$$\Delta DLI = PPFDtotal \times \Delta t / 1{,}000{,}000$$

where: PPFDtotal is the sum of natural and artificial PPFD contributions (µmol·m^{-2}·s^{-1}) and Δt = 300 s (5 minutes).

The DLI accumulator is reset automatically at midnight and integrated throughout the interval 08:00-23:59.

After 16:00, natural PPFD is no longer sufficient to contribute meaningfully to the DLI, and control transitions from instantaneous PPFD regulation to integrative DLI-based compensation. In this mode, the system operates at maximum output (Stage 3, all 20 lamps, 150 µmol·m^{-2}·s^{-1}) and evaluates the accumulated DLI every 5 minutes in a continuous loop: if the

accumulated DLI is below the daily target by more than 0.05 mol·m^{-2}·d^{-1} → Stage 3 remains ON; if the DLI target has been reached → all stages are switched OFF immediately; if the DLI target has not been reached by 22:00 → all stages are switched OFF by a hard-stop automation, regardless of accumulated DLI.

This loop-based approach - rather than a one-shot duration calculation - ensures that the system remains responsive to the actual accumulated DLI at all times and avoids over-illumination in case of any discrepancy between estimated and actual PPFD contributions. The hard stop at 22:00 limits the total photoperiod and prevents circadian disruption of the crop (Figure 9).

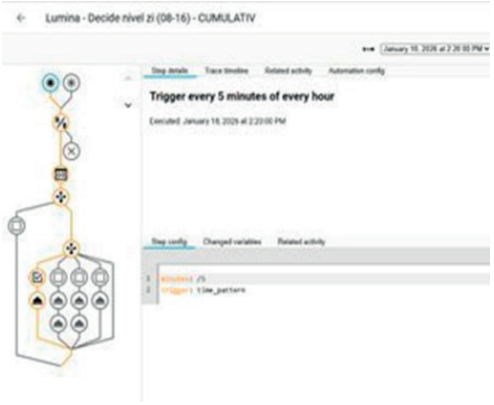


Figure 9. Conceptual diagram of the adaptive lighting control system

Multispectral data acquired from the AS7341 sensor are converted into an estimated PPFD at canopy level using the calibration regression. During daytime (08:00-16:00), the system selects the minimum sufficient lighting stage based on PPFD deficit and a hysteresis band. After 16:00, control switches to a DLI-based compensation mode, activating supplemental lighting only for the duration required to reach the target DLI, with a maximum photoperiod limit at 22:00.

The control logic was implemented within Home Assistant, an open-source home automation platform, using an event-condition-action model (Sagheer et al., 2021). The software architecture comprises four functional components: (1) data acquisition and preprocessing - raw AS7341 channel values are periodically collected via ESPHome and converted into an estimated canopy PPFD value via the regression-based calibration model, implemented as a virtual sensor template; (2) discrete-time lighting control - control decisions are triggered at fixed 5-minute intervals using time-pattern automations; (3) integrative DLI computation - PPFD is integrated over time at each 5-minute step, with the DLI accumulator stored in a persistent input_number helper and reset automatically at midnight; and (4) evening compensation loop - after 16:00, a separate cyclic automation evaluates the DLI deficit every 5 minutes and maintains or switches off Stage 3 accordingly, with a hard-stop limit at 22:00.

The implementation uses exclusively standard platform components (virtual sensor templates, persistent numerical helpers, and declarative YAML automations), without proprietary extensions or external modules. The complete source code of all automations is provided as supplementary material to enable exact replication of the experimental setup (Figure 10).

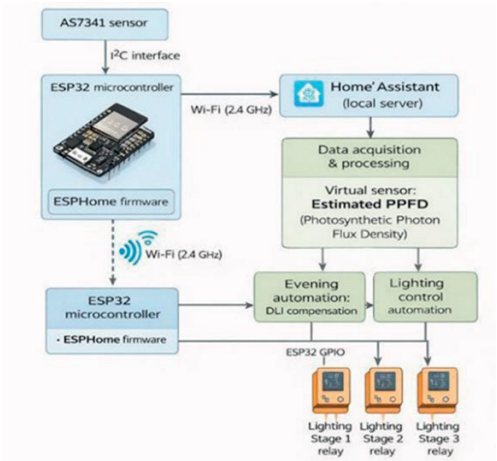


Figure 10. Software stack overview of the control architecture

The ESPHome firmware running on the ESP32 handles sensor interfacing and data transmission. Home Assistant processes the data, implements the PPFD virtual sensor via the calibration regression, and orchestrates two separate control automations: the daytime lighting control (PPFD-based stage selection) and the evening DLI compensation loop.

Software Architecture and Implementation

The complete system - sensor assembly, LED lighting fixture, control hardware, and automation software - was deployed and operated under real greenhouse conditions in a protected cultivation structure. *Capsicum* spp. (hot pepper) plants were used as experimental plant support, positioned directly below the lighting fixture. The greenhouse structure, foil covering, and plant canopy represent the real-world operating environment for which the system was designed and calibrated (Figure 11).

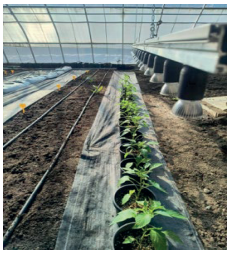


Figure 11. Experimental setup overview: *Capsicum* spp. plants positioned in a row under the custom-built LED lighting fixture inside the greenhouse

The multi-stage supplemental lighting fixture is visible in the upper right. The drip irrigation system and agrotextile ground cover are also visible. Plants were used as experimental support for system evaluation under real growing conditions.

RESULTS AND DISCUSSIONS

AS7341 Sensor Calibration

The AS7341 multispectral sensor was calibrated against the LightScout reference quantum sensor under natural daylight conditions across a broad PPFD range (approximately 1-700 $\mu mol \cdot m^{-2} \cdot s^{-1}$). A total of 59 valid measurement pairs were retained after quality filtering. Multiple linear regression using all ten spectral channels yielded an R^2 of 0.896 and a root-mean-square error (RMSE) of 69.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$, corresponding to a relative estimation error of approximately 20% across the full calibration range. This level of accuracy was considered acceptable for the intended application of discrete-stage supplemental lighting control, where the system operates within defined PPFD thresholds rather than requiring precise absolute measurements.

The calibration model was validated across repeated measurement sessions, confirming its reproducibility under varying natural light conditions. The regression coefficients and performance statistics for the final model are summarised in Table 1. As anticipated for a multi-channel spectral sensor, channels covering the 550-670 nm range contributed most substantially to the regression fit, consistent with the spectral sensitivity of the LED light source and the dominant natural daylight spectrum present during calibration (Bäumker et al., 2021; Yang et al., 2020)

The piecewise domain structure of the calibration was retained in the final model to account for the non-linearity observed at very low PPFD levels (below approximately 10 $\mu mol \cdot m^{-2} \cdot s^{-1}$). Above this threshold, a single linear model was applied across the full horticultural operating range. The scatter plot of estimated versus reference PPFD values is presented in Figure 12.

Table 1. AS7341 MLR calibration model coefficients and performance statistics

Channel	Wavelength (nm)	Coefficient	Contribution
Violet	415	+0.0212	Weak positive
Indigo	445	+0.1977	Strong positive
Blue	480	+0.1011	Moderate positive
Cyan	515	+0.0294	Weak positive
Green	555	−0.0107	Weak negative
Yellow	590	−0.1436	Strong negative (collinearity)
Orange	630	+0.0065	Negligible positive
Red	680	−0.0008	Negligible negative
Intercept	-	35.981	-
R^2	-	0.896	n = 59 measurements
RMSE	-	69.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$	~20% relative error

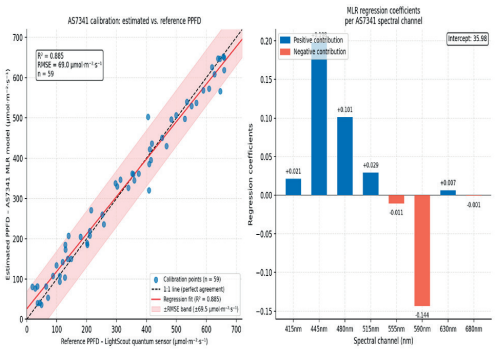


Figure 12. AS7341 calibration against LightScout reference quantum sensor (n = 59). Left: estimated vs. reference PPFD ($R^2 = 0.896$; RMSE = 69.5 µmol·m^{-2}·s^{-1}). Right: MLR regression coefficients per spectral channel

System Performance - DLI Achievement

The automated supplemental lighting system was operated continuously over a 41-day experimental period from 20 January to 1 March 2026. Daily Light Integral values achieved at canopy level are presented in Figure 13. Over the full experimental period, the system maintained a mean DLI of 9.88 ± 1.28 mol·m^{-2}·d^{-1}, closely corresponding to the programmed target of 10 mol·m^{-2}·d^{-1}. The observed DLI ranged from a minimum of 7.67 mol·m^{-2}·d^{-1} on days with sustained cloud cover to a maximum of 13.50 mol·m^{-2}·d^{-1} on days with strong natural irradiance supplemented by evening compensation (Figure 13).

On 12 of the 41 days (29%), the DLI target was met or exceeded. On the remaining 29 days (71%), DLI values remained below the nominal target but above 7.67 mol·m^{-2}·d^{-1}. The period under evaluation (late January through early March) corresponds to the lowest irradiance months of the year at the study location (Bucharest, Romania, 44°N). The mean DLI of 9.88 mol·m^{-2}·d^{-1} across the full 41-day period demonstrates that the system maintained near-target light accumulation even under these challenging seasonal conditions.

For the 14-day sub-period (16 February-1 March 2026) during which complete per-stage activation data were available, a quantitative comparison of actual energy consumption against a full-time reference was performed. The reference scenario represents a conventional supplemental lighting approach in which all three stages operate simultaneously at maximum output (58 W total) throughout the entire 14-hour photoperiod, regardless of prevailing natural light conditions. This corresponds to an energy demand of 0.812 kWh per day.

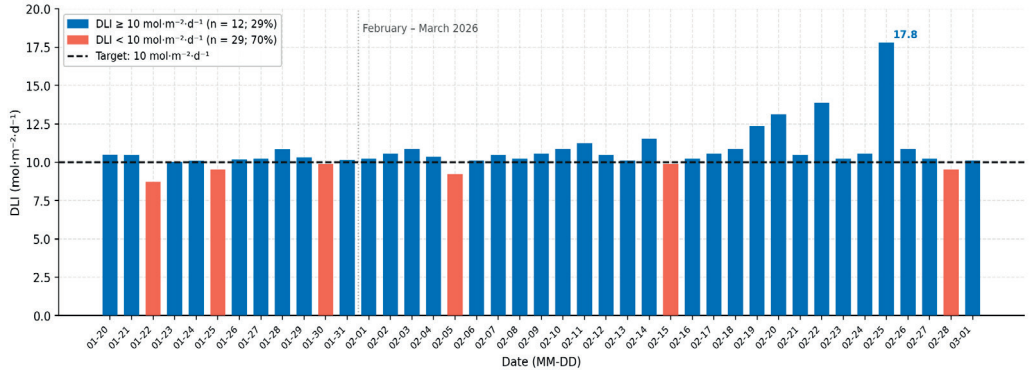


Figure 13. Daily Light Integral (DLI) achieved over the 41-day experimental period (20 January – 1 March 2026). Blue bars: DLI ≥ target (n = 12; 29%); red bars: below target. Dashed line: target = 10 mol·m^{-2}·d^{-1}. Mean DLI = 9.88 ± 1.28 mol·m^{-2}·d^{-1}.

Energy Efficiency

Over the 14-day analysis period, the AS7341-controlled system consumed a mean of 0.417 kWh per day, corresponding to an energy saving of 48.7% relative to the full-time reference. The daily energy saving varied substantially according to prevailing sky conditions. On days with high natural irradiance, the system consumed as little as 0.039–0.042 kWh per day, achieving savings of up to 95%. Conversely, on

overcast days, the system operated in near-continuous mode at maximum stage, consuming approximately 0.775-0.804 kWh per day, with savings below 5%.

The distribution of energy savings across day types was as follows: 8 of 14 days were classified as high-irradiance days (saving exceeding 50%), with a mean saving of 80.1%; 2 days were classified as mixed conditions (saving 10-50%), with a mean saving of 14.4%; and 4 days were classified as overcast (saving below 10%), with a mean saving of 3.1%. This distribution confirms that the system functions as intended: it minimises consumption when natural light is abundant, while operating identically to a conventional system when natural irradiance is insufficient to approach the DLI target (Table 2 and Figure 14).

Table 2. Daily energy consumption of the AS7341-controlled system vs. full-time reference, by sky condition (16 February-1 March 2026)

Sky condition	n days	Actual (kWh·day⁻¹)	Reference (kWh·day⁻¹)	Energy saving (%)
Overcast (saving <10%)	4	0.789	0.812	3.1
Mixed (saving 10-50%)	2	0.519	0.812	14.4
High irradiance (saving > 50%)	8	0.230	0.812	80.1
All days - period mean	14	0.417	0.812	48.7

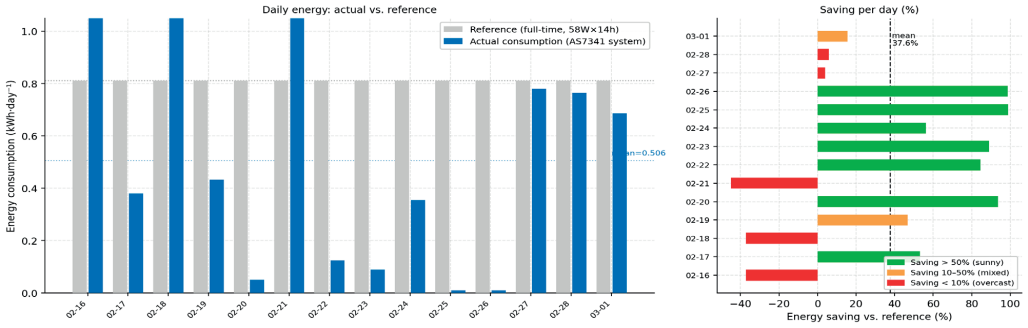


Figure 14. Daily energy consumption: AS7341-controlled system (blue) vs. full-time reference (grey; 58 W × 14 h = 0.812 kWh·day⁻¹). Mean saving: 48.7%

Contribution of Supplemental Lighting to Total DLI

For the 14-day sub-period with complete activation records, the total daily DLI was decomposed into its natural and artificial components, as illustrated in Figure 15. The estimated mean natural DLI over this period was 6.71 mol·m⁻²·d⁻¹ (64% of total), while the supplemental lighting system contributed a mean of 3.81 mol·m⁻²·d⁻¹ (36% of total). Without supplemental lighting, the mean DLI available to the crop would have been 6.71 mol·m⁻²·d⁻¹ - a 33% deficit relative to the target. The supplemental system added a mean of +57% relative to the natural baseline, effectively bridging the light deficit characteristic of the late-winter season.

Considerable variability was observed in the natural–artificial partition across individual days. On overcast days (e.g., 17-18 and 21 February 2026), the artificial component reached 91-92% of total DLI. On high-irradiance days (e.g., 19-20 and 25-27 February 2026), the natural component represented over 95% of total DLI. This adaptive partitioning demonstrates the fundamental advantage of feedback-based control over open-loop timer-based systems: light is added only where and when the natural supply is insufficient.

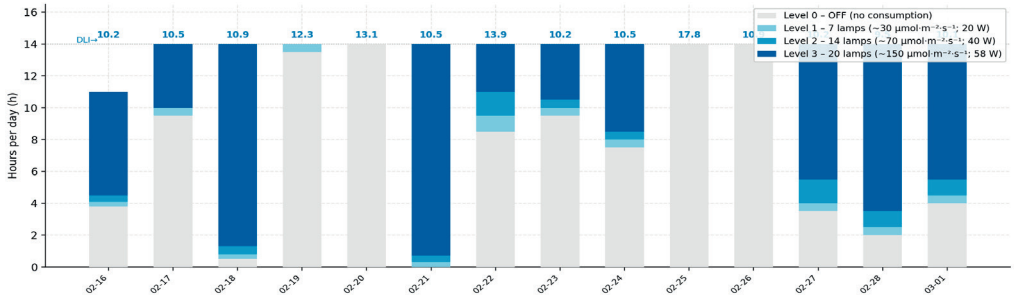


Figure 15. Decomposition of daily DLI into natural (yellow) and artificial (blue) components (16 February-1 March 2026). Mean natural DLI = 6.71 mol·m^{-2}·d^{-1} (64%); mean artificial = 3.81 mol·m^{-2}·d^{-1} (36%).

Stage Activation Distribution

The daily distribution of supplemental lighting stages over the 14-day sub-period is illustrated in Figure 16.

A strong dependence on sky conditions was evident: overcast days were characterised by extended Level 3 activation (13-14 hours per day), while sunny days showed predominantly Level 0 (system off) with brief periods of Level 1 or Level 2 activation.

The multi-stage architecture is functionally justified: on partially overcast days, intermediate stages played a transitional role, minimising energy use while maintaining adequate instantaneous PPFD at canopy level.

This graduated response would not be achievable with a conventional single-stage on/off system, which would either overshoot the required PPFD at full power or provide no supplementation at all.

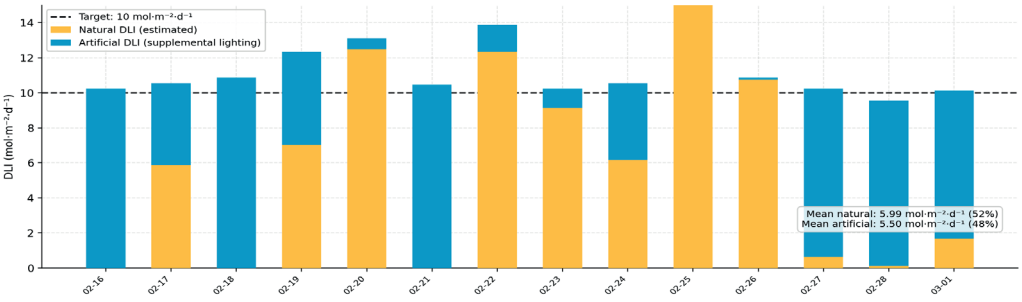


Figure 16. Daily distribution of supplemental lighting activation levels (16 February-1 March 2026). Stacked bars: hours per day at each stage

Calibration Accuracy and Practical Adequacy

The AS7341 multispectral sensor achieved an R^2 of 0.896 and an RMSE of 69.5 µmol·m^{-2}·s^{-1} when calibrated against a reference quantum sensor under natural greenhouse conditions. This level of accuracy is appropriate for the intended application: the control logic operates on discrete PPFD thresholds with a ±10 µmol·m^{-2}·s^{-1} hysteresis band, within which a 20% estimation error is fully acceptable. The DLI achievement results confirm this: the system maintained a mean accumulated light integral of 9.88 mol·m^{-2}·d^{-1} across a 41-day winter period, closely tracking the target of 10 mol·m^{-2}·d^{-1}. This outcome confirms that the calibration accuracy, although moderate by photometric standards, is adequate for practical DLI-based greenhouse light management (Bäumker et al., 2021; Palmitessa et al., 2021). The multi-channel architecture of the AS7341 proved advantageous, as it captures spectral variation and allows the regression model to partially compensate for changes in spectral composition between natural and artificial light conditions (Li et al., 2018; Yang et al., 2020).

Negative regression coefficients at 555 nm, 590 nm and 680 nm reflect inter-channel collinearity, which is characteristic of multiple

linear regression applied to spectrally overlapping sensors. These coefficients do not indicate a negative physical relationship between irradiance and sensor response; rather, they represent compensatory terms that improve model fit across the full PPFD range when all channels are considered jointly (Li et al., 2018; Yang et al., 2020).

Adaptive Control and Energy Efficiency

The central finding of this study is the demonstration that a feedback-based, multi-stage supplemental lighting system can adapt its energy consumption dynamically to prevailing natural light conditions, without compromising DLI target achievement. Over the 14-day sub-period, the AS7341-controlled system consumed 48.7% less energy than the full-time reference scenario, while achieving a mean DLI of 10.52 $mol \cdot m^{-2} \cdot d^{-1}$. The energy savings ranged from below 5% on fully overcast days to above 90% on high-irradiance days. This variable saving structure is precisely what distinguishes a feedback-controlled system from a conventional open-loop timer: on sunny days, the system effectively switches itself off, whereas on overcast days, it provides full supplementation indistinguishably from a fixed schedule.

The reference scenario used in this study - a timer-based system with a fixed 14-hour photoperiod at maximum output - represents a common practice in low-technology greenhouse operations (Morrow, 2008; Bergstrand, 2016). Compared to this baseline, the 48.7% mean saving is substantial and directly attributable to the sensor-based control logic. Even in the winter months of this study, high-irradiance days accounted for 8 of 14 days (57%), demonstrating that the feedback system finds frequent opportunities for saving that a fixed timer cannot exploit. The graduated multi-stage architecture further enhances this: intermediate stages allow partial supplementation matched to partial natural deficits, which a single-stage on/off system cannot provide.

Natural vs. Artificial DLI Contribution

The decomposition of total DLI into natural and artificial components revealed that natural light accounted for 64% of total accumulated DLI, with supplemental lighting contributing 36% over the 14-day sub-period. Without supplemental lighting, the mean natural DLI of 6.71 $mol \cdot m^{-2} \cdot d^{-1}$ would have represented a sustained 33% deficit relative to the target. For Capsicum spp., which requires a DLI of at least 10–15 $mol \cdot m^{-2} \cdot d^{-1}$ for productive growth during the winter season (Kim et al., 2004; Guo et al., 2016), this deficit would be expected to result in reduced photosynthetic rates and lower marketable yield. The supplemental system effectively bridged this deficit, maintaining total DLI close to the target across the full experimental period.

The extreme variability in the natural–artificial partition (from 3% to 92% artificial contribution on individual days) underlines the importance of real-time sensor feedback. A fixed-schedule system would have delivered identical maximum supplementation on all day types, unnecessarily consuming full energy on sunny days and potentially delivering DLI values well above the target, which may induce photosaturation in sensitive species (Moe et al., 2012; Nelson & Bugbee, 2014). The DLI hard-stop mechanism implemented in this system prevents this outcome by halting supplementation as soon as the daily target is reached.

Open-Source Platform Suitability

The Home Assistant platform provided the necessary functional infrastructure for all aspects of the control system: sensor data acquisition via ESPHome, regression-based virtual sensor computation, time-triggered automation logic, persistent state management, and long-term data logging via InfluxDB. The system operated continuously for 41 days without requiring manual intervention, demonstrating adequate reliability for a research-grade greenhouse application. The open-source approach facilitates reproducibility and adaptability: the complete system can be replicated with commercially available components at a total hardware cost well below that of proprietary horticultural control systems, positioning it as a practical option for small and medium-scale operations and research facilities where budget constraints are significant (Hemming et al., 2011; Sagheer et al., 2021).

Limitations and Future Work

Several limitations of the present study should be acknowledged. First, the AS7341 sensor and

the reference quantum sensor were mounted approximately 3 m apart within the greenhouse, introducing the possibility of positional bias in the calibration. Future work should investigate co-located calibration protocols. Second, calibration was performed exclusively under natural daylight, with supplemental LED lighting switched off; the spectral composition of the LED source differs from natural daylight, and dedicated calibration under mixed-spectrum conditions is recommended. Third, the per-stage energy analysis was limited to the 14-day sub-period for which complete activation logs were available in InfluxDB; extending the logging configuration from the start of the experimental period would enable more complete long-term analysis. Finally, the study was conducted in a single greenhouse at one geographic location; transferability of the calibration model and control parameters to different structures and latitudes should be validated in future work.

This study demonstrated the feasibility of a low-cost, open-source, sensor-based approach for supplemental light management in protected horticulture. A multispectral AS7341 sensor, calibrated against a reference quantum sensor under real greenhouse conditions, was integrated into a multi-stage supplemental lighting system controlled through the Home Assistant open-source automation platform. The system was evaluated over a 41-day winter period (20 January-1 March 2026) in a passive solar greenhouse located in Romania.

CONCLUSIONS

This study demonstrated the feasibility of a low-cost, open-source, sensor-based approach for supplemental light management in protected horticulture. A multispectral AS7341 sensor, calibrated against a reference quantum sensor under real greenhouse conditions, was integrated into a multi-stage supplemental lighting system controlled through the Home Assistant open-source automation platform. The system was evaluated over a 41-day winter period (20 January-1 March 2026) in a passive solar greenhouse located in Romania.

The key findings of this study can be summarised as follows. (i) The AS7341 sensor calibration yielded an R^2 of 0.896 and an RMSE of 69.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$, corresponding to approximately 20% relative estimation error, demonstrated to be adequate for discrete-stage lighting control with DLI integration. (ii) Over the full 41-day period, the system maintained a mean DLI of 9.88 ± 1.28 $mol \cdot m^{-2} \cdot d^{-1}$, closely tracking the programmed target of 10 $mol \cdot m^{-2} \cdot d^{-1}$ despite challenging late-winter irradiance conditions. (iii) Over a 14-day sub-period, the AS7341-controlled system achieved a mean energy saving of 48.7% relative to a conventional full-time supplemental lighting reference (58 W, 14 h day^{-1}). On high-irradiance days, savings exceeded 90%; on overcast days, the system operated identically to a conventional fixed-schedule system. (iv) Without supplemental lighting, the mean natural DLI would have been 6.71 $mol \cdot m^{-2} \cdot d^{-1}$ - 33% below the target - confirming the agronomic necessity of supplemental light at this latitude and season. (v) The open-source software stack (ESPHome, Home Assistant, InfluxDB) provided a reliable and fully functional control infrastructure operating continuously without interruption.

These results confirm that the integration of low-cost multispectral sensing, multi-stage LED fixtures, and open-source automation can deliver adaptive, energy-efficient supplemental light management for protected cultivation at a fraction of the cost of commercial solutions. The approach is scalable to larger greenhouse structures and is readily adaptable to other crops and DLI targets. Future work should address mixed-spectrum calibration, multi-zone deployment, and long-season validation under variable irradiance conditions.

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