IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 2 (2026) 155-166
https://publisher.uthm.edu.my/ojs/index.php/ijie

Effects of Photoperiod Fragmentation on Lettuce Yield and Specific Energy Consumption in Indoor Farming Systems

Mohd Faiz Othman[1,2], Muhammad Ikhram A. Wahid[2], Mohd Faizal Mohideen Batcha[1], Suzairin Md Seri[3]*

[1] *Integrated PDP Sdn. Bhd., Level 33 Ilham Tower, 8, Lorong Binjai, 50450 Kuala Lumpur, MALAYSIA*
[2] *Centre for Energy and Industrial Environment Studies (CEIES), Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Batu Pahat, Johor, MALAYSIA*
[3] *Flow Analysis, Simulation and Turbulence Research Group, Faculty of Mechanical Engineering and Manufacturing, Universiti Tun Hussein Onn Malaysia, 86400, Parit Raja, Batu Pahat, Johor, MALAYSIA*

*Corresponding Author: suzairin@uthm.edu.my
DOI: https://doi.org/10.30880/ijie.2026.18.02.013

Article Info

Received: 15 November 2025
Accepted: 20 March 2026
Available online: 28 April 2026

Keywords

Indoor farming, Specific Energy Consumption (SEC), photoperiod fragmentation, hydroponics, LED lighting, vertical farming

Abstract

Energy efficiency remains a critical aspect for indoor farming, where electricity via artificial lighting dominates operational costs. Among the viable strategies for energy efficiency is photoperiod fragmentation. This study investigates the effects of four photoperiod configurations (continuous, intermittent, and segmented) on the yield and energy efficiency of *Lactuca sativa* (butterhead and green coral varieties). Experiments were carried on a 4-tier, multi-rack hydroponic system with wide-spectrum artificial lighting. An identical 14-hour daily photoperiod is provided, ensuring comparable light energy input, but varied the light/dark frequency (e.g., single 14h block vs. multiple short cycles). Results indicate that photoperiod structure significantly alters biomass accumulation and SEC, though outcomes are cultivar- and system-dependent. For butterhead lettuce, a segmented schedule (P3: 5h/4h/5h ON blocks) maximized rooted fresh mass (0.088 kg/plant) and minimized facility-level SEC to 52.2 kWh kg^{-1}, whereas highly frequent cycling (P4) resulted in a twofold increase in energy intensity (102.0 kWh kg^{-1}) due to severe yield penalties. Conversely, for green coral in a container system, the high-frequency schedule (P4) produced the highest yield and lowest lighting-only SEC (29.0 kWh kg^{-1}). These findings demonstrate that equal daily light duration does not guarantee comparable productivity. Furthermore, the study highlights the importance of energy boundaries; including HVAC loads significantly elevates SEC, confirming that non-lighting subsystems often define the ceiling for energy performance. Optimization of light/dark fragmentation offers a viable, zero-cost control strategy to enhance energy productivity in controlled environment agriculture.

1. Introduction

Indoor farming, particularly through vertical farms and plant factories with artificial lighting, offers significant advantages for the year-round production of leafy greens like lettuce. These systems provide precise control over growth conditions, which can lead to optimized yields and quality. One example of it is the Controlled Environment Agriculture (CEA) can reduce electricity consumption by up to 75% through improvements in facility design, such as better HVAC systems, lighting, and the use of distributed generation technology [1]. Plant factories, which are a type of CEA, can produce vegetables two to four times faster than traditional outdoor cultivation, optimizing yields per unit of floor area [2].

The choice of lighting, including light intensity, photoperiod, and light quality, significantly affects the growth and energy efficiency of lettuce. For instance, a photosynthetic photon flux density (PPFD) of 250 $\mu mol/m^2 \cdot s$ with a 16-hour photoperiod under LED lighting with a red to blue ratio of 2.2 is optimal for lettuce growth and quality [3]. Recent benchmarking and review work emphasizes that energy performance is best assessed using yield-normalized metrics (e.g., kWh per kg of lettuce) because facility designs and operating strategies can shift energy use substantially even when the crop and growing area are similar [4,5].

The growth of plants under LED lighting is significantly influenced by the dose and timing of photosynthetically active radiation (PAR), which is quantified as photosynthetic photon flux density (PPFD). This parameter is crucial in controlled environments where light intensity and spectrum can be precisely managed to optimize plant growth and photosynthesis. Previous research highlights the importance of specific light wavelengths and their combinations in enhancing plant growth, with red and blue lights being particularly effective due to their high quantum efficiency [6]. Cumulative daily photon dose is quantified as the daily light integral (DLI).

For constant PPFD, DLI can be computed directly from PPFD and photoperiod, using the standard conversion factor that accounts for seconds per hour and µmol-to-mol conversion [7,8]. For lettuce specifically, multiple controlled-environment studies and reviews report that DLI strongly influences leaf expansion, fresh mass, and quality, and that many production regimes operate within a moderate DLI band. For example, higher DLI levels are associated with increased leaf expansion and biomass production. High light intensities can lead to higher energy consumption, which may not be sustainable in all production systems. Therefore, balancing DLI with energy efficiency is crucial for optimizing lettuce production in controlled environments.

Most indoor farms apply long, continuous photoperiods (e.g., 14–18 h) to deliver the desired DLI. There is increasing interest in intermittent or segmented photoperiods, where the same daily lighting hours are delivered in multiple light/dark blocks. The scientific motivation is that plant carbon gain is not only a function of total photons; it also depends on temporal dynamics such as photosynthetic induction, stomatal responses, and potential circadian alignment. This is supported by research on intermittent irradiation regimes, including red/blue LED cycling, which have been shown to enhance lettuce fresh weight and improve certain quality attributes compared to continuous lighting under similar daily exposure [9], [10]. More recent work explicitly frames adjustable light/dark cycles in plant factories as a control dimension that can influence photosynthetic performance, biomass accumulation, and energy-use efficiency in lettuce cultivars [11].

From an engineering standpoint, segmented lighting schedules may also interact with facility energy use, as changes in heat release timing from LEDs, transpiration dynamics, and humidity profiles can shift HVAC and dehumidification loads. Because climate control can dominate facility electricity consumption in vertical farming, even "lighting-only" schedule changes may translate into meaningful differences in total SEC when evaluated at the facility boundary.

In indoor lettuce production, the occurrence of tip burn, a physiological disorder, significantly affects marketability due to its impact on the quality of the produce. Tip burn is primarily associated with localized calcium deficiency in rapidly expanding inner leaves, exacerbated by conditions that limit transpiration and calcium transport, such as high humidity and insufficient airflow [12]. Controlled-environment studies show that increasing airflow can reduce leaf temperature, increase transpiration, enhance calcium transport, and thereby reduce tip burn incidence [13]. Therefore, any photoperiod optimization that accelerates growth must be evaluated alongside microclimate conditions that govern transpiration and nutrient transport, especially in enclosed racks and container-type systems.

Despite progress in indoor lighting research, indoor farms still face three practical problems. The first is that energy productivity remains a bottleneck. Even when photoperiod hours are fixed, differences in realized yield can strongly change kWh/kg outcomes, which is the operational metric that ultimately matters for cost and sustainability [14]. Secondly, DLI does not uniquely determine yield and quality. Facilities can deliver similar DLI while achieving different biomass and disorder outcomes due to cultivar sensitivity, induction/cycle effects, and microclimate differences. Finally, quality constraints (e.g., tip burn) can negate yield gains. Increased growth rate and unfavorable humidity or airflow can increase tip burn risk, reducing marketable yield.

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 155-166

Hence, the first objective of this study is to quantify PPFD and DLI for each photoperiod of butterhead and green coral lettuce growth. Next, is to evaluate the butterhead and green coral crop performance in terms of tip burn and harvest yield under each photoperiod and finally to assess the energy productivity using SEC (kWh/kg) under two energy-accounting boundaries (lighting-schedule comparison under fixed light-hours; and facility-level energy use with subsystem contributions).

2. Materials and Methods

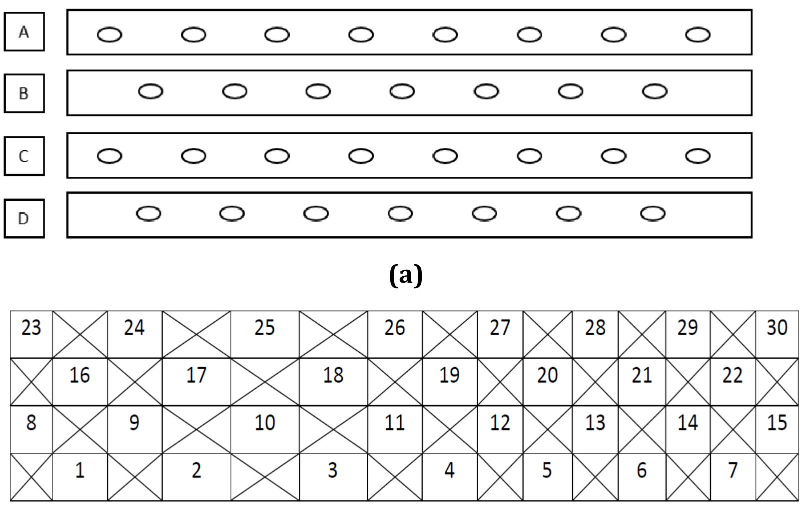
This study integrates two controlled-environment experiments conducted in the same indoor farming system using two lettuce types, namely butterhead lettuce and green coral lettuce (measured primarily with lux-based light monitoring and growth traits). Both experiments tested four photoperiod configurations implemented via programmable timers, while maintaining a comparable total daily "light-on" duration (14 h light per 24 h), but with different light/dark fragmentation patterns (continuous vs intermittent). The photoperiod approach was chosen because plant responses depend not only on total light received (DLI) but also on the temporal structure of light exposure (photosynthesis induction/relaxation, carbohydrate turnover, and respiration recovery), which can alter growth and energy-use outcomes under indoor LEDs. Each experiments are repeated twice, to ensure reproducibility of results.

Table 1 *Photoperiod configurations used in the integrated study (all deliver 14 h light/day)*

Photoperiod code	Light–dark schedule (On/Off, hours)	Pattern type	Total light per 24 h
P1	14 h On / 10 h Off	Continuous (single block)	14 h
P2	7 h On / 5 h Off, repeated twice per day	Intermittent (two blocks)	14 h
P3	5 h On / 3.5 h Off / 4 h On / 3 h Off / 5 h On / 3.5 h Off	Segmented (multi-block)	14 h
P4	3.5 h On/ 2.5 h Off, repeated four times per day	Highly intermittent (frequent cycling)	14 h

3. Cultivation System and Crop Area Layout

The grow bed systems are designed to hold and guide plants while managing the flow of nutrient solutions. This setup is essential for hydroponic systems, where soil is not used, and nutrients are delivered directly to the plant roots through water. The grow bed used in this study is the multilayer system, which facilitate the movement and treatment of plants across different layers



(b)

Fig. 1 *(a) Growing area location arrangement on grow bed; (b) crop area designation*

4. Lighting System and Photoperiod Control

LEDs are the dominant lighting technology in indoor/vertical farms because they permit spectral and temporal control (photoperiod shaping) with high efficacy, enabling experiments that isolate temporal structure effects under otherwise controlled conditions. Artificial lighting was supplied using LED fixtures, and photoperiod timing was controlled using automatic timers (to implement P1–P4) as shown in Table 2.

Table 2 *LED electrical specification and operating parameters used for photoperiod treatments*

Rated Power (W)	Power Factor (PF)	Product Voltage (V)	Current (I)
25	0.9	240	0.29

4.1 Nutrient Solution Monitoring and Light Measurement Protocol

Nutrient solution strength and acidity were monitored using handheld meters. Electrical Conductivity (EC) is widely used to characterize field variability, which is essential for precision agriculture. It helps in understanding soil texture, salinity, moisture content, and organic matter, which are critical for making informed decisions about agricultural inputs like irrigation and fertilization [15]. In hydroponic systems, EC is used to monitor the concentration of nutrients available to plants. It helps in maintaining the optimal nutrient balance necessary for plant growth and yield [16].

Canopy-level light was characterized by using spatial sampling to reduce bias from local intensity hot spots and edge fall-off across the cultivation bed. In the multi-level rack system, photosynthetic photon flux density (PPFD/PAR) was measured at canopy height using a PAR meter, and the mean canopy intensity was estimated using a nine-point sampling grid distributed across the bed. The nine-point pattern used to compute representative mean canopy PPFD is shown in Fig. 2.

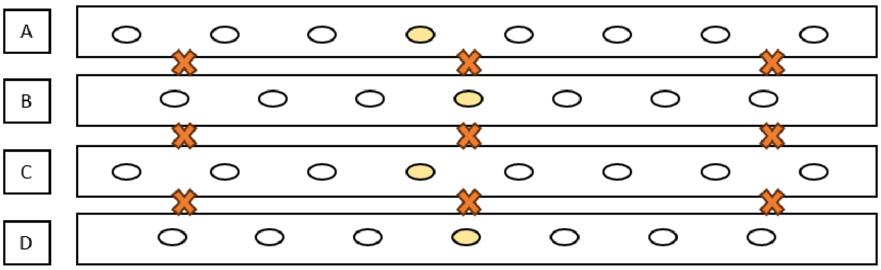


Fig. 2 *Butterhead lettuce and green coral lettuce*

In the container-type system, canopy light was monitored at canopy height using a lux meter and likewise summarized using a nine-point spatial sampling approach across the growth bed. The crop-area physical layout is shown in Fig. 3. Light monitoring was repeated throughout cultivation following the system-specific monitoring intervals described for each experimental setup (two-day interval in the multi-level rack system; three-day interval in the container-type system).

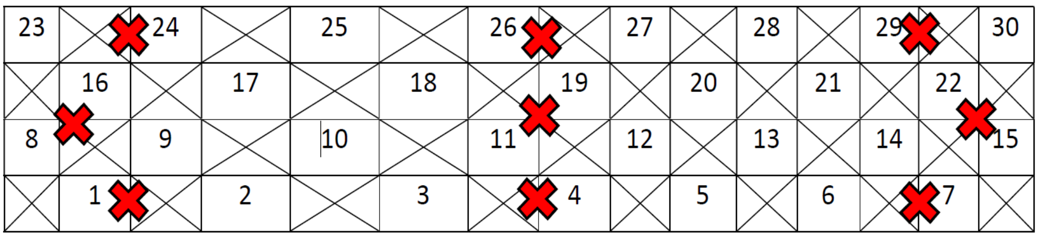


Fig. 3 *Butterhead lettuce and green coral lettuce*

Daily photon delivery was summarized using the Daily Light Integral (DLI). DLI was computed from measured PPFD and photoperiod duration using the standard time-integration relationship as in the following equation (1). This formulation was used to report DLI for each photoperiod schedule, enabling consistent comparison of daily light dose across continuous and intermittent light delivery patterns.

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 155-166

$$DLI(mol\ m^{-2}d^{-1}) = 0.0036 \times PPFD\ (\mu mol\ m^{-2}s^{-1}) \times photoperiod\ (h) \quad (1)$$

4.2 Plant Growth and Harvest Yield

Plant responses to photoperiod scheduling were tracked using non-destructive morphological indicators measured consistently within each cultivation system. In the container-type system, plant height, leaf number, and plant width were recorded using a standardized procedure in which height was measured from the plant base to the highest leaf tip, leaf number excluded detached or damaged leaves, and width was measured across the widest canopy span. In the multi-level rack system, morphological measurement included leaf width, leaf length, and plant height. These metrics provide a consistent basis for tracking canopy development and morphological differences between photoperiod schedules.

Harvest yield was quantified as fresh mass at the end of the cultivation cycle. In the multi-level rack system, yield was reported using both rooted fresh mass (roots retained) and unrooted fresh mass (roots removed). This dual reporting reduces ambiguity when comparing yield across treatments and is particularly important when normalizing energy by harvested mass. In the container-type system, harvested fresh weight was recorded by grow bed/sample and compiled as the yield basis for energy normalization.

4.3 Electrical Monitoring and Specific Energy Consumption (SEC)

Operational electricity use was quantified using non-invasive current measurement and device-level energy accounting. Current draw was monitored using clamp meters, enabling load measurement without modification of wiring.

To ensure transparency and comparability across the integrated study, the operational-energy boundary was defined as the electricity consumption directly attributable to crop cultivation during the experimental period. This boundary includes electricity for LED lighting under the photoperiod schedules and, where accounted, electricity for climate control and essential auxiliaries (e.g., pumping). Within this boundary, the multi-level rack system provides explicit device-level contributions (including air conditioning and lighting), enabling subsystem interpretation of SEC sensitivity to non-lighting loads.

Energy productivity was quantified using Specific Energy Consumption (SEC), defined as operational energy use per unit harvested fresh mass:

$$SEC = \frac{E_{op}}{Y} \quad (2)$$

where E_{op} is total operational electricity (kWh) within the defined boundary and Y is harvested fresh mass (kg). In the present setup, SEC was computed explicitly by normalizing operational energy by harvested yield for each photoperiod schedule, producing a direct ranking of schedules under the fixed daily lighting duration design. In the multi-level rack system, facility energy totals and photoperiod-specific yield reporting provide the corresponding basis for SEC evaluation under a facility-wide operational boundary.

5. Results & Discussion

Across both crops, the lighting treatments were designed to provide the same nominal daily lighting duration (14 h light per 24 h), while varying the temporal distribution of light/dark cycles. For butterhead, the measured average PPFD and DLI differed by photoperiod, with Photoperiod 1 (14 h ON/10 h OFF) achieving an average PPFD of 274.31 μmol m^{-2} s^{-1} and an average DLI of 13.82 mol m^{-2} d^{-1} as shown in Table 3.

Table 3 *Data of butterhead for PPFD and daily light integral for 14 hours ON / 10 hours OFF*

Photoperiod 1 (14 hours on 10 Hours Off)				
Day	mol m^{-2} h^{-1}	PPFD ($\mu mol^{-2} s^{-1}$)	LED Switch On (Hours)	DLI (butterhead) ($mol\ m^{-2}\ d^{-1}$)
3	0.0036	273.38	14	13.78
5	0.0036	269.38	14	13.58
7	0.0036	267.31	14	13.47
9	0.0036	271.03	14	13.66
11	0.0036	268.13	14	13.51
13	0.0036	272.69	14	13.74
15	0.0036	276.00	14	13.91
17	0.0036	276.14	14	13.92
19	0.0036	287.18	14	14.47
21	0.0036	282.21	14	14.22
23	0.0036	267.72	14	13.49
25	0.0036	276.14	14	13.92
27	0.0036	278.76	14	14.05
Total		3566.06		179.73
Average		274.31		13.82

Photoperiod 2 (7 h ON/5 h OFF, repeated to make 14 h total ON-time) produced a lower average PPFD of 249.11 μmol m^{-2} s^{-1} and average DLI of 12.56 mol m^{-2} d^{-1} as shown in Table 4.

Table 4 *Data of butterhead for PPFD and daily light integral for 7 hours ON 5 hours OFF*

Photoperiod 2 (7 hours On 5 hours Off)				
Day	mol m^{-2} h^{-1}	PPFD ($\mu mol^{-2} s^{-1}$)	LED Switch On (Hours)	DLI (butterhead) ($mol\ m^{-2}\ d^{-1}$)
3	0.0036	245.36	14	12.37
5	0.0036	240.40	14	12.12
7	0.0036	239.98	14	12.10
9	0.0036	243.29	14	12.26
11	0.0036	247.57	14	12.48
13	0.0036	243.02	14	12.25
15	0.0036	243.71	14	12.28
17	0.0036	255.16	14	12.86
19	0.0036	260.82	14	13.15
21	0.0036	257.51	14	12.98
23	0.0036	247.16	14	12.46
25	0.0036	257.65	14	12.99
27	0.0036	256.82	14	12.94
Total		3238.45		163.22
Average		249.11		12.56

For Photoperiod 3, the recorded DLI values reported in the DLI table include values in the ~14–15 mol m^{-2} d^{-1} range early in the table sequence, consistent with the statement that Photoperiod 3 yields the highest DLI among the tested configurations as shown in Table 5.

Table 5 *Data of butterhead for PPFD and daily light integral for 5h/3.5h/4h/3h/5h/3.5h ON/OFF*

Photoperiod 3 (5h/3.5h/4h/3h/5h/3.5h On/Off)

Int. Journal of Integrated Engineering Vol. 18 No. 2 (2026) p. 155-166

Day	mol m^{-2} h^{-1}	PPFD ($\mu mol^{-2}s^{-1}$)	LED Switch On (Hours)	DLI (butterhead) ($mol\ m^{-2}\ d^{-1}$)
3	0.0036	279.86	14	14.11
5	0.0036	280.28	14	14.13
7	0.0036	281.11	14	14.17
9	0.0036	281.38	14	14.18
11	0.0036	282.21	14	14.22
13	0.0036	291.73	14	14.70
15	0.0036	286.07	14	14.42
17	0.0036	292.70	14	14.75
19	0.0036	284.28	14	14.33
21	0.0036	283.73	14	14.30
23	0.0036	282.62	14	14.24
25	0.0036	287.18	14	14.47
27	0.0036	286.49	14	14.44
Total		3699.64		186.46
Average		284.59		14.34

For green coral, the measured average DLI was comparatively stable across photoperiod patterns, clustering around ~12.6–12.8 mol m^{-2} d^{-1}. Specifically, Photoperiod 2 (7 h ON/5 h OFF) yielded an average PPFD of 253.52 μmol m^{-2} s^{-1} and average DLI of 12.77 mol m^{-2} d^{-1} as shown in Table 6, while the segmented Photoperiod (5 h/3.5 h/4 h/3 h/5 h/3.5 h ON/OFF) produced an average PPFD of 251.03 μmol m^{-2} s^{-1} and average DLI of 12.65 mol m^{-2} d^{-1} as shown in Table 7.

Table 6 *Data of green coral for PPFD and daily light integral for 7 hours ON 5 hours OFF*

Photoperiod 2 (7 hours On 5 hours Off)				
Day	mol m^{-2} h^{-1}	PPFD ($\mu mol^{-2}s^{-1}$)	LED Switch On (Hours)	DLI (butterhead) ($mol\ m^{-2}\ d^{-1}$)
1	0.0036	257.2	14	12.96
4	0.0036	256.3	14	12.92
7	0.0036	249.6	14	12.58
10	0.0036	243.9	14	12.29
13	0.0036	241.7	14	12.18
16	0.0036	262.7	14	13.24
19	0.0036	261.2	14	13.16
22	0.0036	249.3	14	12.56
25	0.0036	254.9	14	12.85
28	0.0036	253.5	14	12.78
30	0.0036	257.4	14	12.97
Total		2788.7		140.49
Average		253.52		12.77

Table 7 *Data of green coral for PPFD and daily light integral for 5h/3.5h/4h/3h/5h/3.5h ON/OFF*

Photoperiod 1 (5H/3.5H/4H/3H/5H/3.5H On/Off)

Day	mol m^{-2} h^{-1}	PPFD ($\mu mol^{-2} s^{-1}$)	LED Switch On (Hours)	DLI (butterhead) ($mol\ m^{-2}\ d^{-1}$)
1	0.0036	261.5	14	13.18
4	0.0036	248.6	14	12.53
7	0.0036	250.2	14	12.61
10	0.0036	251.6	14	12.68
13	0.0036	255.1	14	12.86
16	0.0036	249.4	14	12.57
19	0.0036	257.4	14	12.97
22	0.0036	240.7	14	12.13
25	0.0036	241.1	14	12.15
28	0.0036	240.7	14	12.13
30	0.0036	265	14	13.36
Total		2761.3	[redacted]	139.17
Average		251.03	[redacted]	12.65

This DLI band (~12–14 mol m^{-2} d^{-1}) sits at the commonly cited lower-to-mid region for lettuce production (often reported around ~12–16 mol m^{-2} d^{-1} depending on cultivar and conditions), supporting that the light supply in these trials was broadly consistent with typical DLI targets rather than being severely light-limiting [17].

5.1 Harvest Quality

Despite broadly comparable daily light durations, harvest biomass differed substantially with the temporal patterning of light/dark exposure. For butterhead, the segmented Photoperiod 3 (5 h ON/3.5 h OFF/4 h ON/3 h OFF/5 h ON/3.5 h OFF) produced the highest average mass at harvest: rooted weight ≈ 0.088 kg and unrooted weight ≈ 0.078 kg, as reported in Fig. 4. Photoperiod 1 (14/10) and Photoperiod 2 (7/5) were intermediate, with rooted weights ≈ 0.076 kg and 0.074 kg, respectively (and unrooted ≈ 0.069 kg and 0.067 kg). Photoperiod 4 (3.5 h ON/2.5 h OFF) resulted in the lowest biomass (rooted ≈ 0.045 kg; unrooted ≈ 0.040 kg).

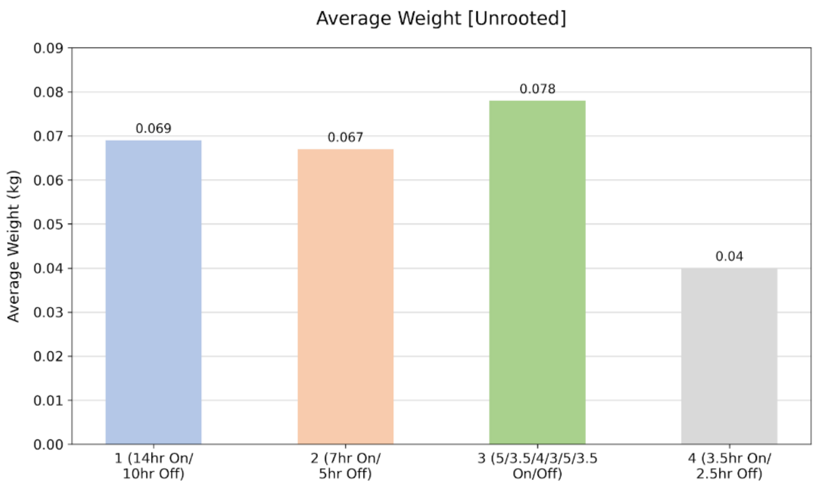


Fig. 4 *Average weight (unrooted) after harvesting for butterhead*

For green coral, the mass response differed in direction and magnitude. Photoperiod 1 (14/10) and Photoperiod 2 (7/5) produced relatively low mean rooted masses of 0.0459 kg and 0.043467 kg, respectively (with unrooted 0.03197 kg and 0.0269 kg).

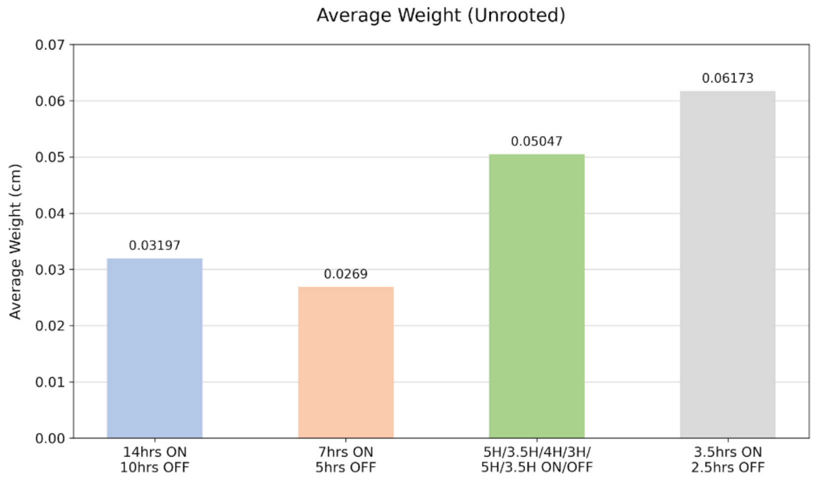


Fig. 5 *Average weight (unrooted) after harvesting for green coral*

In contrast, the segmented photoperiod (5/3.5/4/3/5/3.5) increased mean rooted/unrooted mass to 0.07563/0.05047 kg, while Photoperiod 4 (3.5/2.5) produced the highest mean rooted/unrooted mass of 0.0907/0.06173 kg.

A plausible physiological interpretation for why "pattern" can matter even when total daily light hours are held constant is that photosynthesis under intermittent illumination can be limited by induction and relaxation dynamics (e.g., stomatal opening, Rubisco activation, and non-photochemical quenching), and the net carbon gain may depend on the frequency and duration of transitions. In some regimes, frequent interruptions reduce effective assimilation due to repeated induction penalties; in other regimes, strategically spaced dark periods can reduce excess excitation and improve overall efficiency depending on intensity and cultivar sensitivity [18].

5.2 Harvest Quality

Two operational boundaries were therefore reported in this integrated study. In the container-type system, electricity accounting was treated as lighting-only because all photoperiods provide the same daily lighting duration (14 h day^{-1}) across the cultivation period; consequently, energy input is effectively held constant and SEC differences arise predominantly from yield differences. In the multi-level rack system, electricity accounting followed a facility boundary including lighting, pumping, and air-conditioning; this boundary is consistent with facility-relevant benchmarking where HVAC frequently dominates total electricity demand in plant factories [19], [20]. Operational lighting energy over the cultivation period was treated as constant across photoperiods, $E_{Op} = 78.9264\ kWh$. Under this constant-energy design, SEC differences directly reflect yield differences among photoperiod schedules as in Table 8.

Table 8 *Photoperiod, total yield and SEC for operational energy, yield, and SEC (lighting boundary). Operational lighting energy was treated as constant across photoperiods:* $\boldsymbol{E_{Op} = 78.9264kWh}$

Photoperiod	Yield basis	Total yield, (Y) (kg)	SEC (kWh/kg)
P1	Rooted	1.378	57.2761
P2	Rooted	1.304	60.5264
P3	Rooted	2.269	34.7847
P4	Rooted	2.721	29.0064

P4 achieved the lowest SEC (29.0064 kWh/kg) and P2 the highest (60.5264 kWh/kg), corresponding to a ~2.1× spread in energy intensity under fixed lighting energy input. This result illustrates a central operational principle for indoor farms: when energy is constrained or fixed (e.g., fixed lighting hours), existing studies similarly emphasize that SEC variability across facilities is often driven as much by productivity differences as by equipment efficiency, particularly when comparing operations with similar lighting durations.

Total facility operational electricity over the cultivation period was $E_{Op} = 551.05kWh$, with air-conditioning contributing 423.55 kWh, LED lighting 102.88 kWh, and pumping 24.62 kWh. The dominance of cooling/air-conditioning is consistent with broader PFAL literature indicating that HVAC (cooling and/or dehumidification) can account for a large share of total electricity use and often sets the ceiling for achievable energy intensity when evaluated [21].

To express SEC by photoperiod under this facility boundary (one photoperiod per level), facility energy was allocated evenly across the four levels, $E_{level} = 551.05/4 = 137.7625kWh$ per level. Yield per level was computed using 30 plants per level and the reported mean harvested mass per plant (rooted and unrooted).

Table 9 *Total yield and SEC for different photoperiods*

Photoperiod	Yield basis	Total yield, (Y) (kg)	SEC (kWh/kg)
P1	Rooted	2.28	60.4221
P2	Rooted	2.22	62.0552
P3	Rooted	2.64	52.1828
P4	Rooted	1.35	102.04631
P3	Rooted	2.34	58.8729
P4	Rooted	1.20	114.8021

Facility-wide SEC aggregated across all four levels was 64.9058 kWh/kg on a rooted basis (total rooted yield 8.49 kg) and 72.3163 kWh/kg on an unrooted basis (total unrooted yield 7.62 kg). Within this facility boundary, P3 delivered the lowest SEC (best energy productivity) and P4 the highest SEC (worst energy productivity), with the worst case exceeding the best case by approximately a factor of two. This large spread is consistent with theory and prior measurements: when HVAC electricity is a dominant fixed (or weakly yield-dependent) load, yield is low.

The absolute SEC values should be interpreted in light of boundary differences. Under the lighting-only boundary (container-type system), SEC quantifies the yield response to photoperiod patterning under fixed lighting energy input. Under the facility boundary (multi-level rack system), SEC represents facility-relevant electricity intensity inclusive of HVAC, which is expected to be higher when cooling is a major component. A recent dedicated benchmarking analysis of vertical farming reports a literature-derived SEC of approximately 10–18 kWh kg^{-1} for lettuce under current systems and proposes lower technical benchmarks under improved equipment and controls.

In addition, facility-level optimization studies show that substantial reductions can be achieved when dominant factors (often HVAC-related) are optimized, with some analyses reporting minimum achievable SEC values in the low single digits under favorable assumptions and optimized control strategies. Accordingly, the present facility-boundary SEC values underscore that (i) HVAC dominance can raise electricity intensity substantially when evaluated at the facility boundary, and (ii) photoperiod schedules that reduce yield (e.g., P4 in the multi-level rack system) can be disproportionately costly because they convert largely “fixed” facility energy expenditure into fewer kilograms of product. This boundary-aware framing is consistent with the controlled-environment energy literature, which highlights the necessity of reporting both subsystem contributions and the precise accounting boundary when interpreting kWh/kg results.

6. Conclusion

Across two indoor lettuce cultivation configurations using identical 14 h day^{-1} lighting duration but different light–dark fragmentation patterns (P1–P4), the results show that photoperiod structure materially altered yield-normalized energy performance, with outcomes depending on crop/system context and the operational energy boundary. In the present indoor farming system, the operational lighting energy was constant across photoperiods (78.9264 kWh), yet SEC varied more than two-fold because harvested yield differed substantially, with the lowest SEC under P4 (29.0064 kWh kg^{-1}) and the highest under P2 (60.5264 kWh kg^{-1}). The total operational electricity was 551.05 kWh and was dominated by air-conditioning (423.55 kWh), indicating that facility SEC is strongly influenced by non-lighting loads; under this boundary, the segmented schedule P3 produced the best energy productivity (lowest SEC based on the highest mean harvested mass), while the most frequently interrupted schedule P4 produced the poorest energy productivity due to a pronounced yield penalty. Collectively, these findings demonstrate that equal daily light-on time (and broadly comparable DLI within a system) does not guarantee comparable biomass outcomes. At the same time, boundary transparency (lighting-only vs facility electricity) is essential for interpreting kWh kg^{-1}. Finally, photoperiod fragmentation can either improve or degrade SEC depending on cultivar/system coupling, motivating future work that repeats treatments with statistical replication while co-monitoring microclimate and HVAC response to determine whether intermittent schedules can deliver simultaneous yield gains and facility-level energy reductions.

Acknowledgement

This research was supported by Ministry of Higher Education (MOHE) through Fundamental Research Grant Scheme (FRGS) (vot K487).

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors are responsible for the study conception, research design, data collection, data analysis, result interpretation and manuscript drafting.

References

[1] A. van Zyl and H. Smuts, "An Indoor Farming Framework for Decision Support Towards Food Security in Society 5.0," 2021, pp. 116–128. doi: 10.1007/978-3-030-86761-4_10.

[2] S. Valle de Souza, K. C. Shasteen, J. Seong, C. Kubota, M. Kacira, and H. C. Peterson, "Production planning in an indoor farm: Using time and space requirements to define an efficient production schedule and farm size," *International Food and Agribusiness Management Review*, vol. 27, no. 2, pp. 237–255, Feb. 2024, doi: 10.22434/ifamr2023.0038.

[3] M. Kreuger, L. Meeuws, and G. Meeuws, "Total Indoor Farming Concepts for Large-Scale Production," in *Smart Plant Factory*, Singapore: Springer Singapore, 2018, pp. 125–135. doi: 10.1007/978-981-13-1065-2_8.

[4] M. Acosta-Coll, D. Anaya, L. Ojeda-Field, and R. Zamora-Musa, "Low-Cost Smart Indoor Greenhouse for Urban Farming," 2021, pp. 120–132. doi: 10.1007/978-3-030-86973-1_9.

[5] D. Papadimitriou *et al.*, "Photoperiod and Light Intensity Impact on Wild Edible Vegetables Performance: From Controlled Environment Agriculture to Crop Resilience," Mar. 18, 2025. doi: 10.5194/egusphere-egu25-19862.

[6] J. Li, Y. Zhang, R. Cheng, and T. Li, "Light Spectrum, Intensity, and Photoperiod Are Key for Production as Well as Speed Breeding of Spring Wheat in Indoor Farming," *Plant-Environment Interactions*, vol. 6, no. 5, Oct. 2025, doi: 10.1002/pei3.70085.

[7] M. A. C. Griffith *et al.*, "A Comparative Study Analyzing Light Durations for the Growth of 'Rex Butterhead' Lettuce Lactuca sativa Utilizing GREENBOX Technology," *J. Environ. Hortic.*, vol. 43, no. 2, pp. 74–82, Jun. 2025, doi: 10.24266/0738-2898-43.2.74.

[8] Z. Iqbal, M. Munir, and M. N. Sattar, "Morphological, Biochemical, and Physiological Response of Butterhead Lettuce to Photo-Thermal Environments," *Horticulturae*, vol. 8, no. 6, p. 515, Jun. 2022, doi: 10.3390/horticulturae8060515.

[9] S. Palmer and M. W. van Iersel, "Increasing Growth of Lettuce and Mizuna under Sole-Source LED Lighting Using Longer Photoperiods with the Same Daily Light Integral," *Agronomy*, vol. 10, no. 11, p. 1659, Oct. 2020, doi: 10.3390/agronomy10111659.

[10] K. Y. Choi, K. Y. Paek, and Y. B. Lee, "Effect of Air Temperature on Tipburn Incidence of Butterhead and Leaf Lettuce in a Plant Factory," in *Transplant Production in the 21st Century*, Dordrecht: Springer Netherlands, 2000, pp. 166–171. doi: 10.1007/978-94-015-9371-7_27.

[11] N. Engler and M. Krarti, "Review of energy efficiency in controlled environment agriculture," *Renewable and Sustainable Energy Reviews*, vol. 141, p. 110786, May 2021, doi: 10.1016/j.rser.2021.110786.

[12] L. Morgan, "Plant factories - closed plant production systems (CPPS).," Jan. 28, 2021. doi: 10.1079/HC.77820789.20219903102.

[13] X. Zhang, D. He, G. Niu, Z. Yan, and J. Song, "Effects of environment lighting on the growth, photosynthesis, and quality of hydroponic lettuce in a plant factory," *International Journal of Agricultural and Biological Engineering*, vol. 11, no. 2, pp. 33–40, 2018, doi: 10.25165/IJABE.V11I2.3420.

[14] A. Franco and L. Miserocchi, "Measuring Energy Use in Controlled Environment Agriculture," in *2023 IEEE International Workshop on Metrology for Agriculture and Forestry (MetroAgriFor)*, IEEE, Nov. 2023, pp. 721–726. doi: 10.1109/MetroAgriFor58484.2023.10424330.

[15] M. Paz, P. R. Fisher, and C. Gómez, "Minimum Light Requirements for Indoor Gardening of Lettuce," *Urban Agriculture & Regional Food Systems*, vol. 4, no. 1, pp. 1–10, Jan. 2019, doi: 10.2134/urbanag2019.03.0001.

[16] N. Ohtake, M. Ishikura, H. Suzuki, W. Yamori, and E. Goto, "Continuous Irradiation with Alternating Red and Blue Light Enhances Plant Growth While Keeping Nutritional Quality in Lettuce," *HortScience*, vol. 53, no. 12, pp. 1804–1809, Dec. 2018, doi: 10.21273/HORTSCI13469-18.

[17] K. P. Gavhane, M. Hasan, D. K. Singh, S. N. Kumar, R. N. Sahoo, and W. Alam, "Determination of optimal daily light integral (DLI) for indoor cultivation of iceberg lettuce in an indigenous vertical hydroponic system," *Sci. Rep.*, vol. 13, no. 1, p. 10923, Jul. 2023, doi: 10.1038/s41598-023-36997-2.

[18] Y. Wang, "Improving photosynthetic efficiency in fluctuating light to enhance yield of C3 and C4 crops," *Crop and Environment*, vol. 3, no. 4, pp. 184–193, Dec. 2024, doi: 10.1016/j.crope.2024.06.003.

[19] L. Miserocchi and A. Franco, "Benchmarking energy efficiency in vertical farming: Status and prospects," *Thermal Science and Engineering Progress*, vol. 58, p. 103165, Feb. 2025, doi: 10.1016/j.tsep.2024.103165.

[20] K. Bu, Z. Yu, D. Lai, and H. Bao, "Energy-saving effect assessment of various factors in container plant factories: A data-driven random forest approach," *Cleaner Energy Systems*, vol. 8, p. 100122, Aug. 2024, doi: 10.1016/j.cles.2024.100122.

[21] W. Cai, K. Bu, L. Zha, J. Zhang, D. Lai, and H. Bao, "Energy consumption of plant factory with artificial light: Challenges and opportunities," *Renewable and Sustainable Energy Reviews*, vol. 210, p. 115235, Mar. 2025, doi: 10.1016/j.rser.2024.115235.