

LED-infused photoperiod and light intensity regulation on morpho-physiological attributes, productivity, quality and resource use efficiency in french bean (*Phaseolus vulgaris* L.)

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Abstract

Photoperiod and light intensity are critical environmental factors influencing the growth, development of higher plants. To evaluate their effects on french bean, an experiment was conducted at the University of Agricultural Sciences, Bengaluru, Karnataka. The study comprised five infused photoperiod regimes, namely 4 h (8:00 AM–12:00 Noon), 6 h (8:00 AM–2:00 PM), 8 h (8:00 AM–4:00 PM), 10 h (8:00 AM–6:00 PM), and 12 h (8:00 AM–8:00 PM), along with ambient light as the control. In each photoperiod treatment, ambient sunlight was supplemented with LED illumination at a constant light intensity. The results revealed that french bean plants grown under infused photoperiod exhibited significantly greater leafiness than those grown under ambient light alone (33–41% at 20 DAS and 19–70% at 40 DAS). Enhanced leaf development resulted in substantial improvements in photosynthetic rate (65–87% and 47–97%) and instantaneous water use efficiency (77–102% and 43–116%). Consequently, dry matter accumulation increased by 5–30% under the infused photoperiod regimes compared with the control. The improved physiological performance translated into remarkable enhancements in yield-attributing traits and seed yield (29–100%) over ambient light-grown plants. Furthermore, exposure to elevated photoperiods at a constant light intensity improved seed quality by increasing protein and fat contents, while also enhancing nitrogen, phosphorus, and potassium uptake by plant. These findings demonstrate the potential of photoperiod manipulation through supplemental lighting to improve productivity, quality, and resource use efficiency in french bean cultivation.

Keywords: Artificial Lighting, Electricity Use Efficiency, Photosynthesis, Transpiration, Yield

1. Introduction

Light, an important growth regulating factor in higher plants. It plays a key role in multiple metabolic processes, most importantly it plays a vital role in mediating fundamental plant production process called photosynthesis (Landi *et al.*, 2020; Amirshakari and Fakhroleslam, 2025; Wu *et al.*, 2025). The plants usually obtain light energy from the visible range of sun's electromagnetic spectrum (400-750 nm). According to Liang *et al.* (2021) visible range of electromagnetic spectrum provides varied range of light intensity, which perform specific role in mediating different biochemical process in plants. Notably, the blue light (400-500 nm) is crucial

for chlorophyll development, red light (600-700 nm) stimulates flowering, far-red light (700-800 nm) influences germination, green light (500-600 nm) imparts stomatal regulation, and UV light (300-400 nm) mediates plant defensive mechanisms.

Light as an imperative environmental signal influence plant growth, its intensity and the duration significantly regulate the plants growth and development. Especially, enhanced light intensity triggers plants growth and development till saturation point, over and above it adversely impacts on normal plant production. From the study conducted by Qin et al. (2024) showed that, the plant stature and above ground biomass was enhanced with higher light intensity. Similarly, the reviews summarised by Wu et al. (2025) also highlighted the differential response of plants to varied light intensity. Infact, life cycle of plants directed by light quality. The study conducted by Wei et al. (2023); Wang et al. (2024); Wu et al. (2024) clarified that, light intensity governs the agro-morphological development, yield formation, nutrient composition in multiple crop plants with distinct physiology. According to them plants devises their growth and development process by sensing light intensity and photoperiod available in their proximity. Especially, seed germination, flowering, and maturity subjected to the variation in photoperiod, therefore crops plants respond differently to the seasonal changes under identical management practices (Shibaeva et al., 2024).

Likewise, photoperiod also controls key developmental stages such as germination, dormancy, flowering, reproduction, nutrient allocation, maturity, and survival of plants (Liu and Iersel, 2021; Roeber *et al.*, 2022). Several studies conducted earlier showed that, photoperiod manipulation have substantial implication on plant growth and productivity. For instance, a study conducted by Sun and Lu (2009) showed that longer photoperiod enhanced growth, yield, and nutrient uptake in maize. Subsequently, Reddy and Gowda (2020) also found that reduced light caused by cloudiness at reproductive stage causes substantial yield loss (up to 55.7%) in finger millet. Furthermore, several controlled plant factories experiment undertaken at various part of the world also emphasized the remarkable implication of photoperiods on plant growth, photosynthesis, and chlorophyll content, nutrient composition, resource use efficiency, and economics in different crops (Wu *et al.*, 2024, Wu *et al.*, 2025, Collado *et al.*, 2024).

Knowing these facts, a need was felt to investigate the effects of light intensity and photoperiod on the physio-morphological development and productivity of French bean

(*Phaseolus vulgaris* L.). French bean is an important vegetable crop valued for its tender, succulent, nutritious, and flavourful pods. Being a C₃ plant, its growth and productivity are highly influenced by environmental factors, particularly light intensity and photoperiod. Variations in these factors have been reported to affect photosynthetic rate, flowering behaviour, and pod set, resulting in considerable yield fluctuations across different growing seasons (Kakon et al., 2018; Whankate et al., 2020). Furthermore, studies on leguminous crops have demonstrated diverse responses to altered light intensity and photoperiod, influencing their physiological processes, growth, and reproductive development (Shafiq et al., 2021; Landi et al., 2020; Mitache et al., 2024; Lanoue et al., 2024; Rahman et al., 2025). Therefore, understanding the response of French bean to varying light environments is essential for optimizing its growth and productivity under changing cultivation conditions.

Therefore, a need was felt to investigate the effects of photoperiod and light intensity on the growth, productivity, and resource use efficiency of French bean. The study was based on the hypothesis that exposure of french bean plants to an extended photoperiod at a constant light intensity would enhance their growth, yield, quality, and resource use efficiency. Accordingly, the objective of the study was to evaluate the influence of varying photoperiods and light intensities on the physio-morphological characteristics, productivity, quality, and resource use efficiency of French bean. The findings of this study are expected to aid in identifying the optimum photoperiod and light environment required for maximizing productivity and improving resource use efficiency in French bean production systems.

2. Material and method

Experimental unit and treatment detail

The experiment was carried out in the cage house top covered with a transparent polyethylene roof at the Zonal Agricultural Research Station, Gandhi Krishi Vigyan Kendra, University of Agricultural Sciences, Bangalore, Karnataka, India. The experiment comprised of 6 treatments *Viz.*, 4 h (8:00 AM–12:00 Noon), 6 h (8:00 AM–2:00 PM), 8 h (8:00 AM–4:00 PM), 10 h (8:00 AM–6:00 PM), and 12 h (8:00 AM–8:00 PM), along with ambient light as the control. The conceptual diagram of experimental unit is presented in the Figure 1. The treatment was arranged in the complete block design with four replications. French bean variety ‘Arka Suvidha’ was raised in 10-kilogram capacity grow bags containing 45 cm radius. Each grow bags were filled with 8 kg

soil amended with 250 grams of well decomposed farmyard manure. In each bag three points were marked at equal distance from each other, and were applied with recommended rate of fertilizer (75-125-90 kg N-P₂O₅-K₂O ha⁻¹) followed by two bold and healthy seeds treated with a *Rhizobium* were sown each spot. The grow bags were soaked daily to ensure good germination. Ten days after sowing three healthy plants one from each spot were allowed to grow and remains were removed. Subsequently, each grow bags were irrigated once in two days with 500 mL water.

Photoperiod imposition

The experiment was conducted in a cage house to assist precise regulation of photoperiod. The grow bags corresponding to each photoperiod treatment unit were placed on a concrete slab, maintaining a spacing of 100 cm between adjacent units. Within the unit four grow bags representing replications were placed 20 cm apart from each other to avoid mutual shading and to ensure uniform exposure conditions. Subsequently, each photoperiod units were separated by using non-transparent tarpaulin sheet light barrier to avoid transmission of light from the adjacent unit. Each photoperiod units marked to provide different photoperiod exposure were artificially illuminated by using 100-watt light emitting diode (LED) as per the assumption that, they provide photosynthetically active spectrum of lighting as per the suggestion of Darko *et al.* (2015); Gómez and Izzo (2018) and Rahman *et al.* (2021). The wires supplying power to each LEDs were connected to electrical panel having 5 regulating switches in tern connected to an uninterrupted AC electricity supply. The treatments consisted of different durations of supplemental illumination, which were imposed daily according to the respective treatment schedules, commencing at 08:00 h. The artificial illumination was terminated at the predetermined time for each treatment to achieve the desired photoperiod. Thus, the duration of supplemental lighting varied among treatments while maintaining the prescribed photoperiod regime throughout the experimental period. The conceptual diagram showing details of treatment is given in the Figure 1.

Growth measurement

The growth and physiological performance of French bean were evaluated using standard procedures at the early vegetative stage (20 DAS), active canopy development stage (40 DAS), and crop maturity stage (70 DAS). At 20 DAS, five plants were randomly selected and tagged in each treatment for recording non-destructive observations, whereas destructive sampling was

employed for parameters involving biomass estimation and root analysis. Plant height was measured from the base of the plant to the terminal growing point and expressed in centimetres (cm). The number of branches per plant was determined by counting all branches arising from the main stem, and the mean value was calculated from the sampled plants. The total number of leaves per plant was recorded from the tagged plants at each growth stage, and the average leaf number was computed accordingly. Leaf area was determined using a leaf area meter (LI-COR, Nebraska, USA) from destructively sampled plants and expressed as dm² plant⁻¹. Dry matter accumulation in different plant parts was estimated through destructive sampling of five randomly selected plants from each treatment. The sampled plants were carefully uprooted and separated into leaves, stems, roots, and pods. The separated plant components were initially shade-dried and subsequently oven-dried at 65 ± 5°C until a constant weight was attained. The dry weights of individual plant parts were recorded separately, and the total dry matter production was expressed as g plant⁻¹. Based on the data obtained on leaf area and dry matter production, leaf area ratio (LAR) and leaf weight ratio (LWR) were computed according to the methodology described by Kvet et al. (1971) using the following formulae.

$$LAR = \frac{\text{Leaf area (cm}^2\text{)}}{\text{Total dry matter production (g)}}$$

$$LWR = \frac{\text{Dry matter accumulation in leaf (g)}}{\text{Total dry matter production (g)}}$$

Biophysical parameters measurement

The Chlorophyll status was assessed through SPAD meter readings. The SPAD observations were recorded from the fully expanded topmost functional leaves using a SPAD meter, and the averaged to indicate SPAD values. The physiological functions such as vapor pressure deficit (VPD), photosynthetic rate (PR), transpiration rate (TR), and instantaneous water use efficiency (IWUE), were measured using a portable Infrared Gas Analyzer (IRGA). Observations were recorded at vegetative and reproductive stages using healthy and fully expanded upper canopy leaves selected randomly from each treatment. Measurements were taken between 09:00 and 11:00 AM under clear sunny conditions to minimize diurnal variation. During the observation the leaf was enclosed within the IRGA chamber until the readings stabilized, followed by observation on VPD, PR, TR and IWUE was recorded.

174 *Root measurement*

175 The root growth parameters were studied from the plants sampled for destructive analysis.
176 Plants were uprooted carefully with intact root systems and immersed in water to facilitate gentle
177 removal of soil particles without detaching nodules. Nodules were then separated manually and
178 counted to obtain the mean number of nodules per plant. the root length was determined by
179 measuring root from the collar region to the tip of the longest root using a measuring scale. The
180 root volume was measured by using water displacement using a graduated measuring cylinder. A
181 known quantity of water was poured into a measuring cylinder, and the initial water level was
182 recorded. The cleaned root sample was then completely immersed in the water without trapping
183 air bubbles. The rise in water level after immersion was noted as the final volume. The difference
184 between the final and initial water levels represented the root volume and was expressed in cubic
185 centimeters per plant. Next, Root biomass was estimated by oven drying the cleaned roots at
186 $65\pm 5^{\circ}\text{C}$ for 72 h and recording dry weight using an electronic balance.

187 *Yield measurement*

188 The yield and yield-attributing parameters were recorded at harvest. The number of pods
189 per plant was counted and averaged. The pod length was measured from the base to the tip using
190 a measuring scale and expressed in centimeter. The pod weight per plant was recorded by
191 measuring weight 25 mature pods in each treatment, average was worked out and expressed as
192 gram per pod. Similarly, the beans harvested at harvesting maturity were collected pods and were
193 dried in the sun to reduce moisture, followed by seeds were separated manually and cleaned. The
194 dried seeds were weighed using a digital balance and seed weight per plant was calculated and
195 expressed in grams per plant. Haulm yield per plant was estimated after complete pod harvest by
196 drying the residual plant biomass and recording its weight. Finally, harvest index was computed
197 as the ratio of economic yield to total biological yield multiplied by 100.

198 *Quality assessment*

199 The seeds samples collected were used for estimation of various quality parameters. The
200 samples were dried at $65\pm 5^{\circ}\text{C}$ in hot air oven, powdered (6 mm sieve) and preserved. The
201 carbohydrate content of french bean seeds were estimated from preserved powdered sample. The
202 finely samples were assessed for their total carbohydrate content using Anthrone Reagent Method
203 and amount of carbohydrate in the sample was estimated using following formula.

$$\text{Carbohydrate (\%)} = \frac{\text{Weight of glucose (Mg)}}{\text{Volume of test sample (ml)}} \times 100$$

The protein content of french bean seeds were estimated from the oven-dried sample via its nitrogen content estimation by Kjeldahl's method (Jackson, 1973). Subsequently crude protein content was computed by multiplying the per cent nitrogen with factor 6.25. Similarly, the fat content was determined by the Soxhlet extraction method and the amount of fat in the sample was estimated using following formula.

$$\text{Fat content (\%)} = \frac{\text{Weight of extracted fat (Mg)}}{\text{Weight of sample (Mg)}} \times 100$$

The total ash content was determined by igniting a known weight of oven-dried sample in a muffle furnace at $550 \pm 25^\circ\text{C}$ for four to six hours until it turned white or grey, indicating complete combustion of organic matter. The residue was weighed and per cent ash content was worked out by using following formula.

$$\text{Ash content (\%)} = \frac{\text{Dry weight of ash (Mg)}}{\text{Weight of sample (Mg)}} \times 100$$

Nutrient uptake

The N content was determined by micro Kjeldahl's method (Jackson, 1973) using 0.5 g powdered seed and haulm samples digested with concentrated H_2SO_4 and a digestion mixture ($\text{K}_2\text{SO}_4:\text{CuSO}_4 \cdot 5\text{H}_2\text{O}:\text{Se}$, 100:20:1) and distilled under alkaline conditions. The liberated NH_3 was trapped in H_3BO_3 with an indicator and titrated against standard H_2SO_4 , expressed as a percentage. Further, P and K was estimated from 0.5 g samples pre-digested with 5 ml concentrated HNO_3 and further digested with a di-acid mixture ($\text{HNO}_3:\text{HClO}_4$, 9:4), then diluted to 100 ml. Total P was measured by the Vanado-molybdate yellow color method, and K by flame photometry of the diluted digest, both following Jackson (1973). Nutrient uptake by the French bean crop was calculated by multiplying nutrient content by dry matter yield.

$$\text{Nutrient uptake (g plant}^{-1}\text{)} = \frac{\% \text{ Nutrient content} \times \text{Biomass yield (g plant}^{-1}\text{)}}{100}$$

Resource use efficiency

The electricity use efficiency was assessed by dividing the biomass yield at harvest by total electricity consumed (kWh) using following formula.

$$\text{Electricity Use Efficiency (g kW}^{-1} \text{ h}^{-1}) = \frac{\text{Fresh weight of plant (g)}}{\text{Electricity consumed in lighting (kW}^{-1} \text{ h}^{-1})}$$

The water use efficiency was calculated to determine the efficiency of the crop in utilizing water to produce yield. It was computed using the formula:

$$\text{Water Use Efficiency (g FW L}^{-1}) = \frac{\text{Fresh weight of plant (g)}}{\text{Water utilized (L}^{-1})}$$

The nitrogen use efficiency was calculated by dividing plant biomass at harvest by total nitrogen applied as per the following formula:

$$\text{Nitrogen Use Efficiency (g DW g}^{-1}) = \frac{\text{Dry weight of plant (g)}}{\text{Nitrogen absorbed (g)}}$$

The phosphorous use efficiency was calculated by dividing plant biomass at harvest by total nitrogen applied as per the following formula:

$$\text{Phosphorus Use Efficiency (g DW g}^{-1}) = \frac{\text{Dry weight of plant (g)}}{\text{Phosphorous absorbed (g)}}$$

The potassium use efficiency was calculated by dividing plant biomass at harvest by total nitrogen applied as per the following formula:

$$\text{Potassium Use Efficiency (g DW g}^{-1}) = \frac{\text{Dry weight of plant (g)}}{\text{Potassium absorbed (g)}}$$

Statistical analysis

The experimental data collected on growth, yield, quality parameters, physiological function, nutrients uptake and resources use efficiency of plant were subjected to Fisher's method of "Analysis of Variance" (ANOVA) as outlined by Gomez and Gomez (1984). Wherever, F-test was significant, for comparison among the treatment means, an appropriate value of critical difference (LSD) was worked out. If F-test found non-significant, against LSD. values NS (Non-significant) was indicated.

3. Results

Growth attributes

Table 1 presents the influence of photoperiod and light intensity on growth attributes of french bean. The plant height of french bean increased successively as the length of the

photoperiod increased. Specifically, taller plants were observed with the plants exposed to 12 h photoperiod in a day (69.0 cm), and were statistically comparable with the plants grown under 6-10 h photoperiod. The number of leaves did not differ significantly at 20 DAS, while at 40 DAS plants grown under infused photoperiod regimes produced significantly higher number of leaves (22.3-28.8 plant⁻¹) over when compared to plant grown under ambient light (18.4 plant⁻¹). The number of branches per plant more or less followed the similar trends as that of leaves number (Table 1). The variation in photoperiod showed profound influence on the leaf area per plant both at 20 and 40 DAS. The leaf area per plant was gradually increased over the photoperiod regimes. Notably, the plants grown under 10-12 h infused photoperiod registered significantly more leaf area over rest of the treatment. On account of higher leaf area per plant LAI was also significantly higher with the plants grown under infused photoperiods over lower regimes both during 20 and 40 DAS. Conversely, LAR showed reverse trend to leaf area and LAI (Table 1). Wherein, plants grown under every additional photoperiod exhibited consistent decline in LAR till 20 DAS. Surprisingly, the trend was reverse at 40 DAS (Table 1). Subsequently, LWR showed similar trend as that of LAR both at 20 and 40 DAS.

The photoperiod has beneficial impact on dry matter production. The dry matter production in french bean plant increased with successive increase in photoperiod exposure. Significantly highest dry matter production was recorded in the plants grown under 12 h photoperiod in a day (2.06, 22.07, and 65.78 g plant⁻¹, respective at 20, 40 DAS and at harvest). However, it was statistically comparable with those plants grown under 10 h photoperiod in a day (Table 2). Furthermore, analysis of dry matter distribution revealed that, french bean leaf and roots showed progressive gain in dry matter accumulation up to 40 DAS, after that there was a clear withdrawal of dry matter in leaf and root, while the dry weight of stem was consistently increased as the plant ages till harvest (Figure 2).

Physiological functions

The physiological functions are the dynamic processes that sustain growth, and development of plants. Importantly, the chlorophyll content in the leaves consistently increased with infused photoperiod from 4-12 h both at vegetative and reproductive phase (Table 2). Significantly, higher chlorophyll content was observed with the plants grown under 12 h photoperiod in a day (33.4 and 38.5, respectively at 20 and 40 DAS). However, it was statistically

comparable with that of 8-10 h photoperiod during vegetative stage and 6-10 h photoperiod during reproductive phase of french bean. The VPD, photosynthetic rate, transpiration rate, and instantaneous WUE was significantly varied due to variation in photoperiod at vegetative and reproductive phases in french bean. The VPD consistently declined with increasing photoperiod from 4-12 h, while plants grown under ambient light recorded the highest VPD at both vegetative (1.18 kPa) and reproductive stages (2.39 kPa). Conversely, the photosynthetic rate increased progressively with increase in photoperiod from 4-12 h in a day (4.36 - 4.94 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). Particularly, the plants exposed to 12 h photoperiod recorded the significantly highest photosynthetic rate at both vegetative and reproductive phases (4.94 and 7.43 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, respectively), whereas the plants grown under ambient light registered the lowest photosynthetic rate at 20 and 40 DAS (2.64 and 3.77 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$). The transpiration rate was highest in the plants raised under ambient light (7.02 and 1.11 $\text{mmol m}^{-2} \text{ s}^{-1}$, respectively at 20 and 40 DAS) and decreased with successive the successive longer photoperiods and was reached minimum with the plants grown under 12 h photoperiod (5.96 and 0.68 $\text{mmol m}^{-2} \text{ s}^{-1}$, respectively at 20 and 40 DAS). Consequently, instantaneous WUE was significantly greater with the plants grown under 10-12 h photoperiods and lowest under ambient light (Table 2).

Yield attributes and yield

Table 3 present the data on yield attributes and yield of french bean. The data indicated that, almost all the yield attributing traits significantly influenced due to variation in photoperiod. Specifically, plants raised under elevated photoperiod showed substantial improvement in yield attributing traits. Importantly, a greater number of pods per plant (48.3), longer pods (14.5 cm), higher pod weight (12.7 g), more seed in the pod (7.59), higher seed weight per plant (273 g) and haulm yields (200 g) were significantly higher in the plants grown under 12 h photoperiod in a day. However, most of the aforementioned traits were remained statistically comparable with that of plant grown under 8-10 h photoperiod condition. On the contrary, all the yield attributing traits of french bean was significantly inferior in the plants grown under ambient light (Table 3).

Quality parameters

The quality attributes of french bean seed indicated that, the carbohydrate content in the grain did not show any remarkable variation across the photoperiod (Table 3). However, there was a marginal improvement over increased photoperiod exposure. Surprisingly, the seeds harvested

from the plants grown under 8 h photoperiod recorded the significantly higher protein content (25.6%), however, it was remained at par with carbohydrate content of the seeds harvested from the plants grown under 12 h (25.3%) and 10 h photoperiod in a day (25.0%), were but superior to 4 h photoperiod (24.4%) and 6 h photoperiod (24.3%). Similarly, the fat content consistently increased over the photoperiod regimes, and was ranging between 11.9-12.7%. Again, the ash content did not vary significantly due to variation in photoperiod. As like other growth and yield attributing parameters french bean plants grown under ambient light condition consistently recorded lower values of quality attributes of seed (Table 3).

Nutrient uptake

The nutrient uptake by french bean exhibited significant variation due to photoperiods. The N uptake increased with increasing photoperiod (Table 4). Significantly highest N uptake was recorded with the plants grown under 12 h photoperiod in day (33 mg plant⁻¹) which was significantly higher than rest of the treatments. Likewise, P and K uptake were also showed similar trend as that of N uptake across the photoperiod regimes (Table 4). The lowest uptake was recorded by the plants grown under ambient light (24.8, 5.4 and 15.8, mg plant⁻¹, N, P and K, respectively) which was markedly inferior to all other treatments.

Resource use efficiency

The use efficiency of important resource used in the experimentation such as electricity, water and nutrients were worked out and presented in the Table 4. The result revealed that, EUE exhibited a clear declining trend with increasing duration of infused photoperiods. The highest EUE was recorded under 4 h photoperiod in a day (3.75 g FW kW⁻¹ plant⁻¹), which progressively decreased to 2.50 g FW kW⁻¹ plant⁻¹ at 10 h. Conversely, the WUE increased consistently increased with photoperiod. The WUE was highest with plants grown under 12 h photoperiod in day (10.7 g FW L⁻¹) and was consistently declined with reduced photoperiod and was lowest with the plants grown under ambient light (Table 4). Likewise, N-use efficiency showed a variable trend across photoperiod. Among the photoperiod, plants grown under 4 and 6 h infused light in a day recorded lower NUE (274 and 246 g DW g⁻¹, respectively), while plants grown more than 6 h photoperiod showed a gradual increase in NUE and it reached peak at 12 h photoperiod in a day (293 g DW g⁻¹). Interestingly, the highest NUE was observed under ambient conditions (303 g DW g⁻¹). The PUE followed a declining trend from 4-8 h exposure, but was gradually picked up

at 10-12 h photoperiod in a day. The KUE demonstrated an increasing trend with longer photoperiods. Nevertheless, plants grown in the ambient light recorded higher values of nutrient use efficiency (N, P and K).

4. Discussion

Growth attributes

Light is the primary driver of plant growth (Wu et al., 2025), serving as the fundamental energy source for photosynthesis. Through photosynthesis, plants synthesize the assimilates required for various metabolic processes, which collectively regulate growth, development, and productivity in higher plants. This study assessed the impact of photoperiod and light intensity on growth and biomass accumulation in french bean. Firstly, plant height was progressively increased with the extended duration of photoperiod (Table 1). The taller plants under longer photoperiod could be attributed to increased duration of photosynthetically active radiation interception, which improved photosynthetic efficiency and assimilate production. Greater availability of assimilates under extended light exposure might have promoted cell elongation and internodal growth through enhanced hormonal activity, especially gibberellin-mediated stem elongation. The result aligns with the findings of Hwang et al. (2017), who observed vegetative growth and developmental progression in french bean strongly regulated by environmental conditions, particularly light availability. Similarly, leaves count per plant showed remarkable variation from 40 DAS. Increased leaf production under longer photoperiod might be due to additional photosynthetic activity, delayed senescence and enhanced meristematic activity. Similarly, extended photoperiod enhanced branches in french bean, it could be due to improved vegetative proliferation due to greater carbohydrate availability and favorable hormonal balance. Noor et al. (2017) also reported increased vegetative growth and branching in french bean under enhanced photosynthetic rate in pulses. Likewise, leaf area and LAI were also markedly influenced by photoperiod. The plants exposed to 10- and 12-hour photoperiods recorded significantly higher leaf area and LAI compared to their corresponding lower photoperiod regimes and also ambient light (Table 1). Increased leaf area under prolonged photoperiod could be attributed to enhanced cell division, cell enlargement and greater photosynthate availability under extended duration of light exposure. Infact, leaf area directly determines photosynthetic surface and radiation interception efficiency, the increased LAI under longer photoperiod indicates improved canopy development. In common bean Hwang et al.

(2017) observed direct implication of photoperiod on leaf area development. In contrast to leaf area and LAI, LAR and LWR showed declining trends with increasing photoperiod at 20 DAS. The reduction in LAR under prolonged photoperiod suggests that plants accumulated relatively higher biomass in non-leaf organs compared to leaf area expansion, indicating improved efficiency of assimilate utilization. Lower LAR values under extended photoperiod may therefore reflect increased structural growth and biomass accumulation in stem tissues. Interestingly, the trend was reversed at 40 DAS, possibly due to ontogenic changes in assimilate partitioning during crop development. As the crop progressed towards reproductive stages, assimilates might have diverted towards developing sinks, thereby altering the relative contribution of leaf tissue to total plant biomass. Similar variations in assimilate partitioning patterns during crop ontogeny have been reported in common bean under varying environmental conditions by Singh et al. (2017).

Dry matter production is the product of plant height, leafiness and branching potential. In this study the dry matter production in french bean progressively increased with increase in photoperiod duration at all stages (Table 2). It indicates the beneficial role of prolonged light exposure in enhancing biomass accumulation. Increased dry matter accumulation under extended photoperiod may primarily be due to prolonged photosynthetic duration. The prolonged photoperiod exposure enables plants to synthesize and accumulate greater quantities of carbohydrates in different plant part. Further, an analysis of dry matter partitioning also suggested that, every additional photoperiod exposure showed incremental dry matter accumulation in leaves, stem, root and beans. For instance, Noor et al. (2017) observed enhanced dry matter production and growth performance in french bean owing to improved physiological efficiency and assimilate production. Similarly, Ruark et al. (2017) also reported that increased canopy development and efficient radiation utilization significantly improved biomass accumulation in snap bean with enhanced photoperiod regime. Further, the comparatively lower dry matter production observed under ambient light conditions in the present study could therefore be associated with reduced photosynthetic duration and limited assimilate availability. The dry matter distribution among plant organs further indicated dynamic assimilate partitioning during crop growth. Leaf and root dry matter accumulation increased progressively up to 40 DAS, suggesting active vegetative growth and root establishment during the early stages of crop development. Thereafter, decline in leaf and root dry matter towards harvest indicated remobilization of stored assimilates from vegetative tissues towards developing reproductive sinks. Such remobilization of

assimilates from source organs to reproductive structures is a common physiological phenomenon in legumes during reproductive growth. In contrast, stem dry matter continuously increased up to harvest, indicating sustained structural growth and active assimilate translocation through stem tissues. Hwang et al. (2017) also highlighted that environmental conditions significantly influence biomass partitioning and reproductive development in common bean. The present findings therefore suggest that prolonged photoperiod not only enhanced total biomass production but also improved assimilate partitioning efficiency in french bean.

Physiological functions

The physiological performance of french bean was markedly influenced due to variation in photoperiod. Notably, chlorophyll content in leaves increased progressively with increase in photoperiod from 4 to 12 h during both vegetative and reproductive phases. It suggested that prolonged light exposure enhanced chlorophyll biosynthesis and chloroplast development (Table 2). Increased chlorophyll accumulation under extended photoperiod may also be associated with enhanced nitrogen assimilation and delayed chlorophyll degradation under favorable light environments. The comparatively lower chlorophyll content observed under ambient light and shorter photoperiods could be due to limited light interception and reduced photosynthetic pigment synthesis. These findings align with the earlier reports of Hernández and Kubota (2016) who observed increased chlorophyll under supplemental lighting and extended photoperiod in vegetable crops under controlled environments. On the contrary, the VPD showed a declining trend with increase in photoperiod duration, whereas plants grown under ambient light recorded significantly higher VPD both at vegetative and reproductive phases. Higher VPD generally increases atmospheric evaporative demand, resulting in excessive water loss and partial stomatal closure, which ultimately reduces photosynthetic efficiency. In the present study, reduced VPD under prolonged photoperiod might have created a more favorable microclimate for stomatal functioning and leaf water balance, thereby supporting higher physiological activity. Conversely, the higher VPD observed under ambient light conditions may have induced greater transpirational demand and physiological stress, resulting in reduced photosynthetic performance (Shamshiri et al., 2018). Further, the photosynthetic rate increased progressively with increase in photoperiod from 4 to 12 h, with maximum photosynthetic activity recorded under 12 h photoperiod during both vegetative and reproductive stages. Increased photosynthetic rate under prolonged photoperiod may primarily be attributed to enhanced chlorophyll content, greater light interception

and improved stomatal functioning under favorable microclimatic conditions. The significantly lower photosynthetic rate observed under ambient light conditions indicates that limited light duration and comparatively higher VPD restricted photosynthetic carbon fixation in french bean.

Transpiration rate showed an inverse trend compared to photosynthetic rate, wherein plants grown under ambient light conditions recorded the highest transpiration during both vegetative and reproductive phases, while minimum transpiration was observed under 12 h photoperiod. The higher transpiration under ambient light conditions could be attributed to elevated VPD, which increased atmospheric evaporative demand and promoted greater water loss through stomata. In contrast, reduced transpiration under extended photoperiod may be due to moderated VPD and improved stomatal regulation, enabling plants to conserve water while maintaining efficient photosynthetic activity. Lower transpiration under prolonged photoperiod suggests improved water balance and greater physiological adaptation to extended light environments. Similar findings were reported by Shamshiri et al. (2018), who emphasized that maintenance of favorable microclimatic conditions, particularly moderate VPD, significantly reduces transpirational water loss while sustaining higher photosynthetic activity in crops grown under protected conditions. Consequently, instantaneous WUE was significantly greater under 10-12 h photoperiods, whereas the lowest WUE was recorded under ambient light conditions. Increased WUE under prolonged photoperiod indicates superior physiological efficiency, wherein plants were able to assimilate greater quantities of carbon dioxide per unit of water transpired. Higher WUE under extended photoperiod resulted from the combined effect of enhanced photosynthetic rate and moderated transpiration loss. Again, the lower WUE observed under ambient light conditions may therefore be associated with restricted photosynthesis and excessive transpirational loss resulting from higher VPD. Similarly, in tomato Zhang et al. (2018) observed enhanced photosynthetic water use efficiency under elevated photoperiod through better stomatal regulation and carbon assimilation.

Yield attributes and yield

The yield attributes and yield of french bean were significantly influenced by variation in photoperiod, which highlighted role of photoperiod in enhancing reproductive growth and productivity. In the present study, elevated photoperiod (8-12 h) substantially improved all major yield attributing traits including number of pods per plant, pod length, pod weight, number of seeds per pod, seed yield per plant and haulm yield (Table 3). The increased number of pods per plant under prolonged photoperiod could be attributed to enhanced vegetative growth, greater leaf area

development and increased photosynthetic efficiency observed under extended light exposure (Table 1 and 2). Higher chlorophyll content, leaf area index and photosynthetic rate under longer photoperiod likely improved assimilate production and source strength, thereby supporting better flower retention, pod setting and reproductive sink development. In legumes, pod initiation and retention are highly dependent on continuous assimilate supply during reproductive growth (Wu et al., 2025). Similar observations were reported by Upadhyay et al. (2017), who noted the improved physiological efficiency and assimilate production significantly enhanced reproductive growth and pod yield in french bean under favorable environmental conditions. Subsequently, on account of higher yield attributes, the seed yield per plant was observed under elevated photoperiod condition when compared to their corresponding lower photoperiod regimes. Similarly, improvement in haulm yield could be due to combined effect of improved vegetative growth, higher dry matter accumulation, enhanced photosynthetic activity. Similar relationships between improved light environment, biomass accumulation and eventually higher seed and haulm yield were earlier reported in french bean and other leguminous crops by Kalsi et al. (2019). In contrast, plants grown under ambient light conditions recorded significantly lower yield attributes and yield, indicating that insufficient effective photoperiod adversely affected reproductive efficiency and assimilate accumulation in french bean (Reddy and Gowda, 2020).

Quality attributes

The quality attributes of french bean seeds were moderately influenced by variation in photoperiod. According to Rouphael et al. (2018) variation in light intensity and photoperiod influences biochemical composition and nutrient accumulation in higher plants. In the present study, carbohydrate content did not vary significantly among photoperiod treatments, while the protein content of french bean seeds showed significant variation due to photoperiod treatments. Interestingly, plants exposed to 8 h photoperiod recorded the highest protein content, which remained statistically comparable with 10-12 h photoperiod treatments, but significantly superior to 4-6 h photoperiod regimes (Table 3). Increased protein accumulation under moderate to prolonged photoperiod may be associated with enhanced nitrogen assimilation and improved metabolic activity resulting from greater photosynthetic efficiency. Higher chlorophyll content and biomass accumulation under extended photoperiod likely improved nitrogen uptake (Table 4). Enhanced nitrogen uptake might have optimally complimented amino acid synthesis, which might have eventually contributed to greater protein deposition in seeds (Sehrawat et al. 2019).

Subsequently data on fat content in french bean seeds influenced by photoperiod duration showed that, increased fat content under longer photoperiod ascribed to enhanced carbon assimilation and improved translocation of assimilates towards developing seeds during reproductive growth. Extended photoperiod likely prolonged the duration of active photosynthesis, thereby increasing availability of precursors required for lipid synthesis. For instances the study conducted by Hernández and Kubota (2016) also reported that supplemental lighting and prolonged light exposure improved physiological efficiency and assimilate production, ultimately enhancing quality attributes in vegetable crops.

Nutrient uptake

French bean showed significant variation for nutrient uptake due to variation in photoperiod. Nitrogen uptake increased progressively with increase in photoperiod duration. Precisely, nitrogen uptake was higher under 12 h photoperiod compared to all other treatments. Similar trends were even observed for phosphorus and potassium uptake. The enhanced uptake of nitrogen under prolonged photoperiod may be attributed to enhanced nutrient content and higher biomass production under elevated photoperiod regimes and were significantly higher with higher photoperiod regimes when compared to their corresponding lower photoperiod levels. Infact higher rate of nutrient uptake under longer photoperiod was earlier reported by Singh et al. (2018), Kiferle et al. (2019), Elkins and Van Iersel (2020). In contrast, plants grown under ambient light conditions recorded the lowest nutrient uptake, indicating that limited effective photoperiod adversely affected nutrient acquisition and assimilation in french bean. The lowest nutrient uptake observed under ambient light conditions clearly indicates that limited photoperiod reduced nutrient absorption efficiency in french bean attributed by reduced photosynthetic rate, lower chlorophyll content, limited root growth and restricted biomass accumulation. Since nutrient uptake is closely linked with plant growth, photosynthetic efficiency and dry matter production, the inferior nutrient absorption under ambient light further explains the reduced growth and yield performance observed in the present study (Kumar and Hiremath, 2015).

Resource use efficiency

The resource such as electricity, water and nutrient (NPK) use efficiency of french bean was markedly influenced by variation in photoperiod. The EUE exhibited a declining trend with increase in duration of photoperiod. Therefore, the highest EUE recorded under 4 h photoperiod

and it was subsequently declined as the photoperiod enhanced. This decline in EUE under prolonged photoperiod was attributed to increased energy input required for supplemental lighting beyond the optimum efficiency threshold. Similar observations were reported by Kozai et al. (2019) who observed the extended photoperiod improves crop productivity but may reduce energy use efficiency when additional light input exceeds the incremental biomass gain. Conversely, the WUE increased consistently with increase in photoperiod duration, with the highest WUE under 12 h photoperiod and the lowest under ambient light conditions. Improved WUE under prolonged photoperiod may be attributed to enhanced photosynthetic rate, greater carbon fixation and moderated transpiration observed under extended light exposure. Reduced vapor pressure deficit and improved stomatal regulation under prolonged photoperiod likely minimized water loss while maintaining higher assimilatory activity. The lower WUE observed under ambient light conditions may therefore be associated with reduced photosynthetic efficiency coupled with comparatively higher transpiration losses (Table 2). Similar findings were reported by Zhang et al. (2018) who demonstrated that optimized light environments significantly improved photosynthetic water use efficiency through enhanced carbon assimilation and better stomatal regulation in crop plants grown under controlled environments.

Interestingly, the highest NUE observed under ambient light conditions indicates that although total nitrogen uptake and biomass accumulation were comparatively lower, plants utilized the limited absorbed nitrogen more efficiently on a relative basis. This phenomenon may be explained by reduced luxury consumption of nutrients under lower growth conditions, wherein plants produce relatively higher dry matter per unit of absorbed nitrogen despite lower total productivity. Among the infused photoperiod, the NUE increased over photoperiod regimes. The plants exposed to photoperiods beyond 6 h exhibited gradual improvement in NUE, reaching maximum values under 12 h photoperiod. Enhanced NUE under prolonged photoperiod may be associated with increased chlorophyll synthesis, greater photosynthetic efficiency and improved assimilate production, which enabled plants to utilize absorbed nitrogen more effectively for biomass accumulation and reproductive development. Improved light environments significantly enhanced nitrogen assimilation and nutrient utilization efficiency in horticultural crops under controlled cultivation systems (Kiferle et al., 2019). Similarly, PUE initially declined from 4- to 8-hour photoperiods but subsequently improved under 10-12 h photoperiods (Table 4). The improvement in PUE under prolonged photoperiod may be associated with enhanced energy

metabolism, assimilate translocation and reproductive development under greater photosynthetic activity. Since phosphorus is directly involved in ATP synthesis and energy transfer reactions, increased physiological activity under extended photoperiod likely improved phosphorus utilization efficiency. On the other hand, KUE exhibited a consistent increase with increase in photoperiod duration. Improved KUE under prolonged photoperiod may be attributed to enhanced stomatal regulation, photosynthate translocation and maintenance of cellular water balance, all of which are strongly dependent on potassium-mediated physiological processes (Shabala, 2003).

5. Conclusion

This study on impact of light intensity and photoperiod on growth, physiological processes, yield, quality, nutrient uptake, and resource use efficiency of french bean under revealed that, growth attributes of french bean responded positively to increasing photoperiod. The plant height, leafiness, branches, leaf area, LAI as well as TDMP were increased with longer photoperiod. Notably, early growth stages of french bean showed limited response to variation in photoperiod and light intensity, while later growth stages were highly sensitive as it remarkably varied the photosynthesis. Root traits such as root length, volume, biomass, and nodulation improved with increasing photoperiod. The VPD decreased with increasing photoperiod creating a more favourable microclimate under extended light conditions. Photosynthetic rate increased progressively with longer photoperiod reaching maximum under 12 h. Conversely, transpiration rate was higher under ambient and shorter photoperiods due to higher vapor pressure deficit. Instantaneous water use efficiency improved under longer photoperiod. Overall, extended photoperiod improved physiological efficiency and plant performance. The pods number, length of the pod, pod weight, and seeds in a pod were increased significantly with longer photoperiod. Seed yield per plant was also highest under 12 h photoperiod due to cumulative improvement in yield components. The carbohydrate and ash contents showed non-significant but increasing trends with longer photoperiod. The protein content in the seed was more under moderate to longer photoperiods (8–12 h), indicating optimal nitrogen assimilation. Fat content increased with extended photoperiod due to enhanced availability of photosynthates for lipid synthesis. Nutrient uptake (N, P, K) increased significantly with increasing photoperiod. The electricity use efficiency declined with increasing photoperiod due to higher energy input relative to biomass gain. In contrast, water use efficiency increased consistently with longer

photoperiod, reflecting improved physiological efficiency. Overall, while extended photoperiod enhanced growth and yield, moderate conditions balanced resource use efficiency more effectively in french bean.

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740 Table 1: Impact of photoperiod on growth attributes of french bean

Treatment	Plant height (cm)	Number of leaves plant ⁻¹		Number of branches			Leaf area (dm ² plant ⁻¹)		Leaf area index		Leaf area ratio (cm ² g ⁻¹)		Leaf weight ratio (g g ⁻¹)	
		20 DAS	40 DAS	20 DAS	40 DAS	At harvest	20 DAS	40 DAS	20 DAS	40 DAS	20 DAS	40 DAS	20 DAS	40 DAS
4 hours	53.7	10.3	22.3	3.3	5.5	7.2	2.81	4.34	0.94	1.45	173.5	21.7	0.3272	0.1733
6 hours	58.9	10.0	25.8	2.5	5.5	7.8	2.80	5.33	0.93	1.77	163.7	24.2	0.3275	0.1769
8 hours	60.6	11.5	27.3	3.5	8.0	9.6	2.84	5.83	0.93	1.94	156.4	28.8	0.3258	0.1738
10 hours	62.0	11.5	28.1	3.0	9.3	10.3	2.93	6.66	0.98	2.22	149.5	31.2	0.3265	0.1760
12 hours	69.0	11.0	28.8	3.8	9.8	10.8	2.97	7.61	0.99	2.54	144.2	33.0	0.3252	0.1790
Ambient light	51.5	9.0	18.4	2.5	4.3	6.0	2.11	4.46	0.70	1.49	146.5	30.5	0.3264	0.1569
S. Em±	6.8	1.5	3.4	0.5	0.7	0.6	0.13	0.52	0.04	0.17	4.60	1.79	0.0003	0.0033
LSD (<i>p</i> =0.05)	14.2	NS	7.2	NS	1.5	1.3	0.39	1.59	0.13	0.53	14.09	5.49	0.0010	0.0100

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763 Table 2: Impact of photoperiod on dry matter production and physiological functions in french bean

Treatment	Total dry matter production (g plant ⁻¹)			SPAD chlorophyll meter values		Vapor pressure deficit (kPa)		Photosynthetic rate ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}$)		Transpiration rate ($\text{mmol m}^{-2} \text{ s}^{-1}$)		Water use efficiency	
	20 DAS	40 DAS	At harvest	20 DAS	40 DAS	25 DAS	55 DAS	25 DAS	55 DAS	25 DAS	55 DAS	25 DAS	55 DAS
4 hours	1.62	19.04	48.11	24.2	33.5	1.08	2.31	4.36	5.54	6.91	0.96	0.71	3.08
6 hours	1.71	20.91	46.14	26.1	35.0	1.06	2.26	4.52	5.70	6.50	0.83	0.70	3.90
8 hours	1.78	19.22	52.88	28.6	36.0	1.05	2.21	4.79	6.25	6.30	0.76	0.69	4.18
10 hours	1.96	20.34	61.90	27.7	36.3	1.02	2.19	4.90	6.98	6.09	0.71	0.80	4.37
12 hours	2.06	22.07	65.78	33.4	38.5	1.01	2.16	4.94	7.43	5.96	0.68	0.81	4.64
Ambient light	1.44	13.64	50.44	27.9	33.3	1.18	2.39	2.64	3.77	7.02	1.11	0.40	2.15
S. Em±	0.28	0.61	2.09	1.8	1.6	0.04	0.07	0.45	0.46	0.28	0.11	0.07	0.38
LSD ($p=0.05$)	0.60	1.30	6.63	3.7	3.4	0.10	0.15	0.99	1.00	0.62	0.24	0.16	0.83

773 Table 3: Impact of photoperiod on yield and quality parameters of french bean

Treatment	No. of pods per plant ⁻¹	Pod length (cm)	Pod weight (g ⁻¹)	No. of seeds pod ⁻¹	100 seed weight (g)	Seed yield per plant (g)	Haulm yield per plant (g plant ⁻¹)	Carbohydrate content (%)	Protein content (%)	Fat content (%)	Ash content (%)
4 hours	31.4	13.0	11.9	6.35	41.5	176	21.5	41.5	24.4	11.9	13.0
6 hours	34.9	13.4	12.2	6.64	41.8	198	24.1	41.8	24.9	12.2	13.4
8 hours	39.6	13.7	12.4	7.16	42.0	222	26.5	42.0	25.6	12.4	13.7
10 hours	43.0	14.1	12.5	7.28	42.2	243	28.4	42.2	25.0	12.5	14.1
12 hours	48.3	14.5	12.7	7.59	42.4	273	30.0	42.4	25.3	12.7	14.5
Ambient light	30.3	10.1	11.5	6.11	41.1	136	16.8	41.1	24.3	11.5	13.1
S. Em±	0.7	0.7	1.8	0.45	0.9	16	2.1	0.9	0.7	0.3	0.7
LSD (<i>p</i> =0.05)	1.6	1.4	3.8	0.94	NS	52	4.5	NS	1.6	1.0	NS

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783 Table 4: Impact of photoperiod on nutrient uptake and resource use efficiency in french bean

Treatment	Nutrient uptake (mg plant ⁻¹)			Electricity use efficiency (g FW k-Watt plant ⁻¹)	Water use efficiency (g FW L ⁻¹)	Nitrogen use efficiency (g DW g ⁻¹)	Phosphorous use efficiency (g DW g ⁻¹)	Potassium use efficiency (g DW g ⁻¹)
	N	P	K					
4 hours	26.1	5.9	18.5	3.75	4.99	274	1221	387
6 hours	27.9	6.8	19.4	2.72	5.45	246	1015	354
8 hours	30.2	8.1	20.3	2.53	6.75	260	969	388
10 hours	32.0	9.0	21.6	2.50	8.34	288	1021	426
12 hours	33.3	9.5	23.0	2.59	10.37	293	1034	426
Ambient light	24.8	5.4	15.8	-	4.23	303	1387	476
S. Em±	0.5	0.2	1.7	-	-	-	-	-
LSD (<i>p</i> =0.05)	1.0	0.5	3.6	-	-	-	-	-

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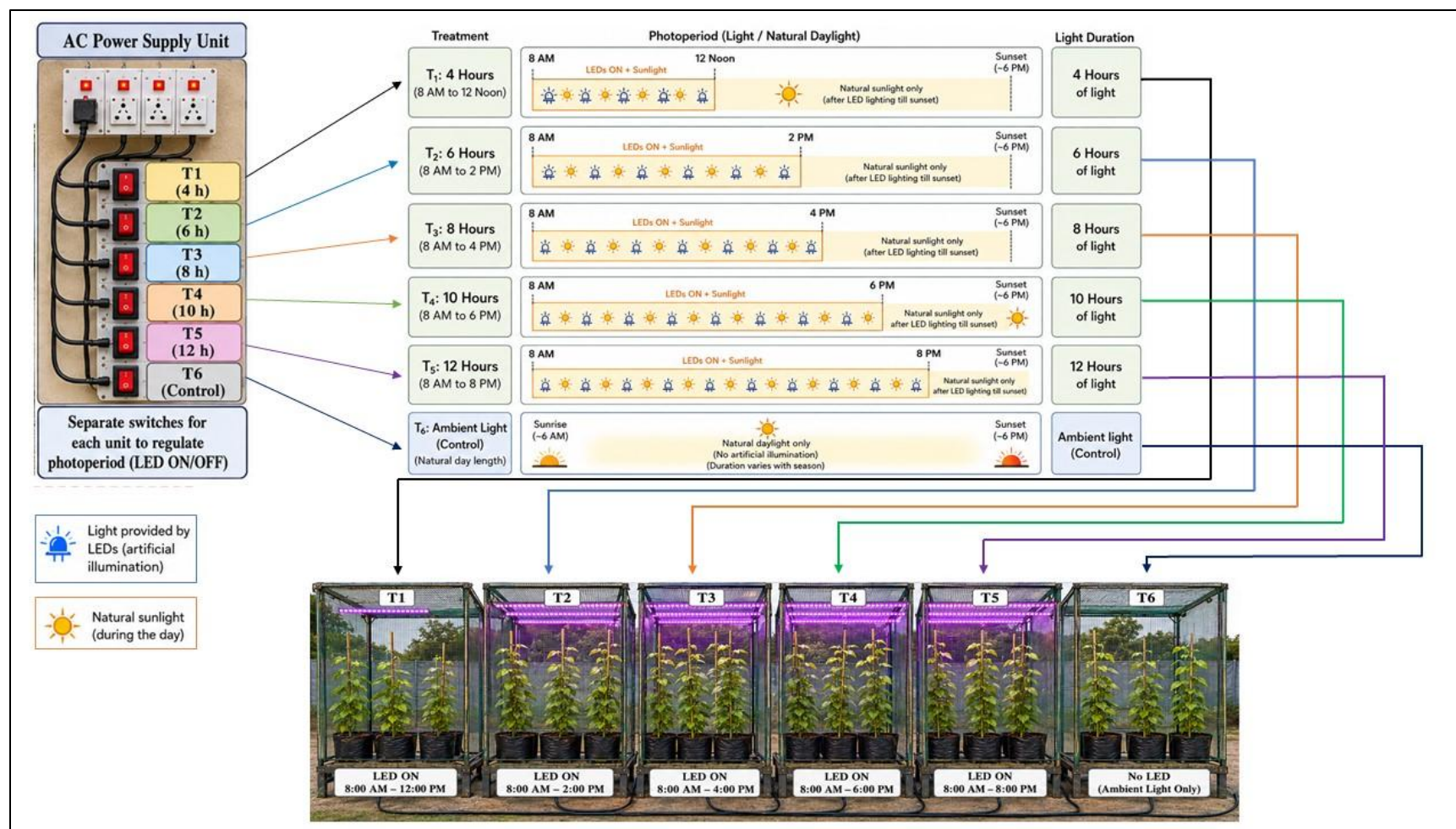
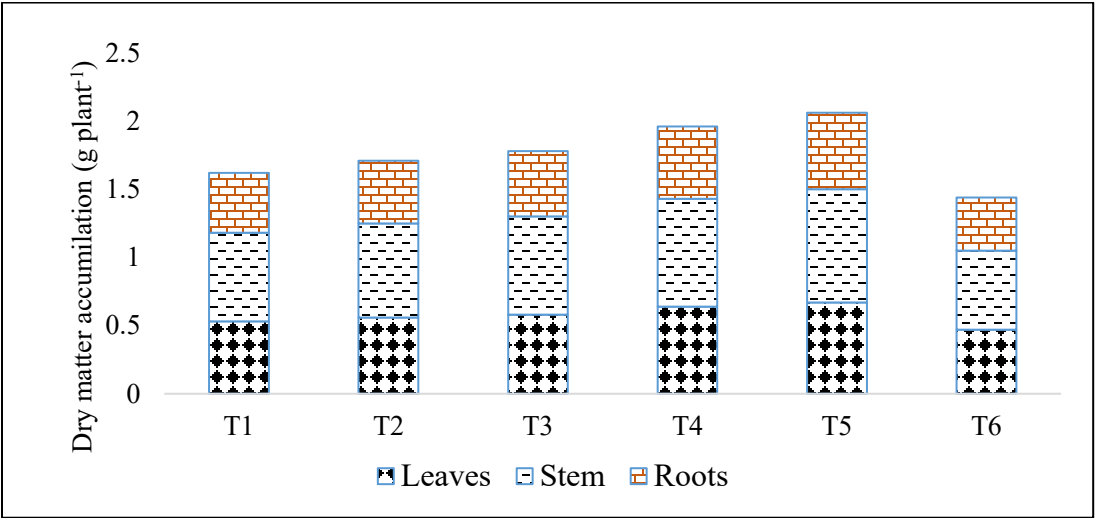
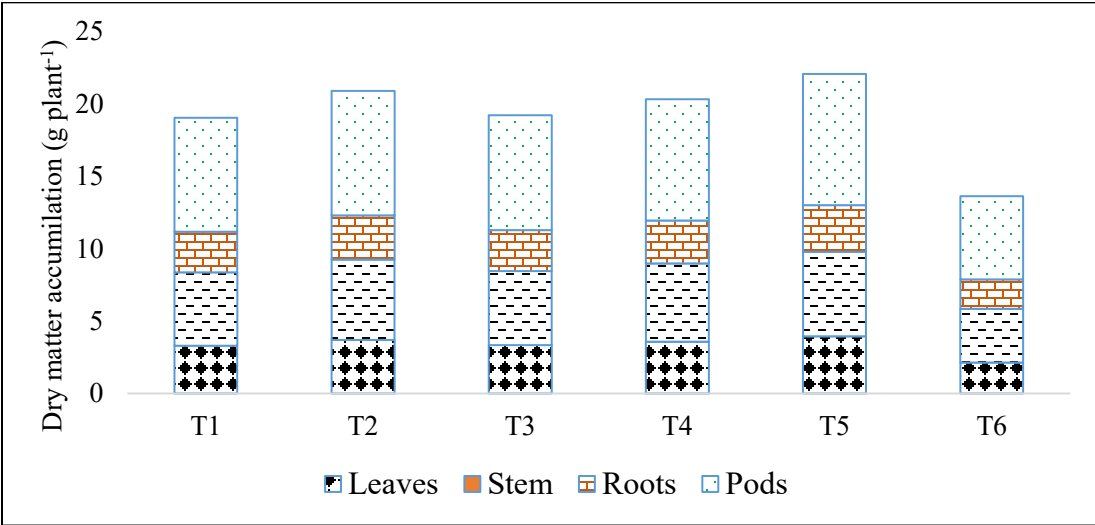


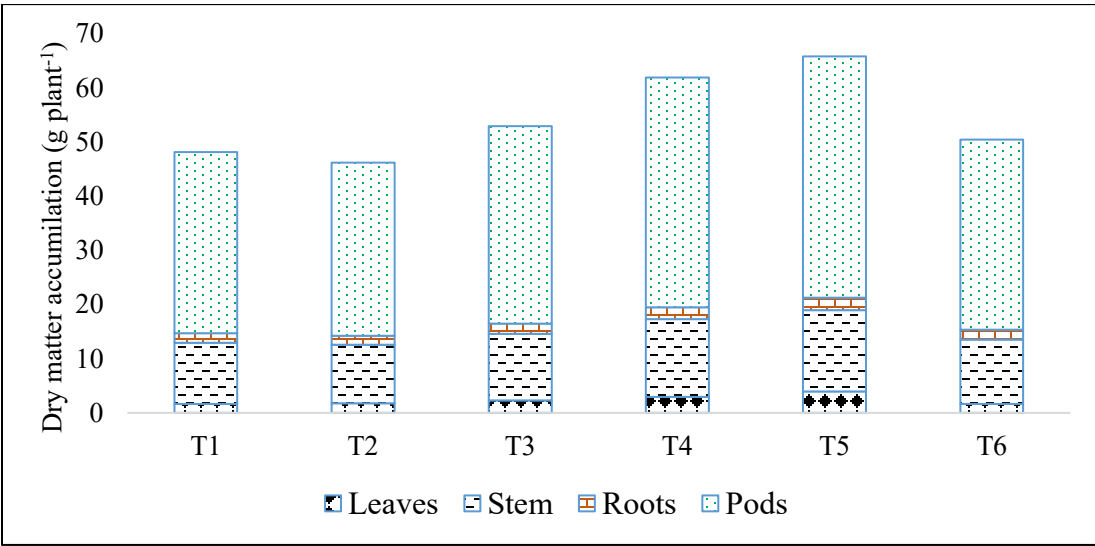
Figure 1: Pictorial representation of treatments and experimental unit



20 Days after sowing (a)



40 Days after sowing (b)



At harvest (c)

803 **Figure 2: Dry matter accumulation in different plant part in french bean at different growth**
804 **stages of french bean**