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Growth and Floral Induction in Okra (*Abelmoschus esculentus* L.) Under Blue and Red LED Light and Their Alternation

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Abstract: Okra (*Abelmoschus esculentus*) is a tropical vegetable with high nutritional and economic value. Rich in fiber, vitamins (C, K, and B9), and minerals (magnesium, potassium, calcium, and iron), it contributes to food security in many tropical regions. Global production is estimated at 11.5 million tons in 2023, 62% of which will come from India. Nigeria, Mali, Sudan, Pakistan, and Côte d'Ivoire are also among the major producers. Given its economic importance, optimizing its growth through controlled methods such as greenhouse cultivation and light-emitting diode (LED) lighting is a strategic challenge. Energy-efficient LED horticultural lighting offers promising prospects, but each plant variety reacts differently depending on the light spectrum, intensity, and duration of exposure (photoperiod). This study evaluated the effects of different LED spectra on okra's flowering after 30 days of growth using B (blue, 445 nm) and R (red, 660 nm) LED lights and red-blue alternating in a three-day cycle (R3B3) by alternating the photoperiod from 14 to 10 h. Outdoor and greenhouse conditions served as controls. The results show that the R3B3 treatment improves germination in terms of both speed and percentage. However, plant growth (height, stem diameter, and leaf area) remains higher in the control group. R3B3 and red light stimulate leaf and node development. Flowering occurs earlier in the control group (51 days) and later under LED, particularly blue (73 days). Fruit diameter after petal fall was also larger in the control group. These results confirm the sensitivity of okra to photoperiod and light quality, and highlight the potential of spectral and photoperiod manipulation to regulate flowering in controlled-environment agriculture.

Keywords: horticultural LED lighting; germination; okra growth; photoperiodic flowering; alternating red-blue LED light; Zigbee protocol; Domoticz

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1. Introduction

Okra (*A. esculentus* L.) is an annual plant in the Malvaceae family. It is mainly grown in the open field or under cover in many African and Asian countries, and to a lesser extent in southern Europe and America [1]. In 2023, according to the FAOSTAT database [2], 11.52 million tons of okra fruit were produced worldwide on a surface area of 2.95 million hectares. India produced 7.15 million tons, making it the world's leading producer, followed in order of production by Nigeria, Mali, Sudan, Pakistan, Egypt, Côte d'Ivoire, Benin, Bangladesh, and Cameroon [2]. Okra has enormous nutritional potential (minerals,

proteins, fiber, antioxidants, and vitamins), particularly in the young fruit and leaves, as reported by numerous researchers [3–5]. It is important to highlight that in West Africa, okra ranks as the second most consumed vegetable after tomatoes [6]. It is grown mostly for its fresh fruits, which can be eaten as a sauce. These fresh fruits are a vital source of vitamin C and calcium, while the dried ones stand out for their richness in protein and lipid [7].

Nonetheless, climate change, pests and disease attacks are limiting field production of okra [8,9], which led to the use of insecticides and pesticides as a solution. However, some adverse effects on health and the environment were witnessed with this approach. Moreover, herbicides have been reported to reduce plant growth, pod weight, and nutritional quality of okra [8]. Indoor cultivation could be a solution in this case, despite the fact that it is limited by the lack of light required for photosynthesis and morphogenetic processes mainly regulated by light [10,11]. More precisely, it is monitored by photons with wavelengths between 400 nm and 700 nm. This wavelength band is known as photosynthetically active radiation (PAR) [12]. Moreover, the main difference between these artificial systems and their traditional counterparts is the complete absence of natural light, and the main source of energy for photosynthesis will be LED lamps [13]. The development of LED technology is a solution for their use as an artificial light energy source in plant factories and in controlled environment plant production systems [14–16]. The wavelength of red and blue lights, their different ratios with other wavelengths and their Photosynthetic Photon Flux Density (PPFD) expressed in $\mu mol \cdot m^{-2} \cdot s^{-1}$ has drawn great attention of current research recently, thanks to its regulatory effect on plant development and flowering [17–19].

In fact, red light (600–7000 nm) is more efficiently absorbed by photosynthetic pigments in plants (chlorophyll and carotenoids) and stimulates phytochrome photoreceptors. However, blue light (400–500 nm) plays various important photomorphogenic roles in plants, including stomata opening, stem elongation, and phototropism [20]. However, monochromatic R or B light alone is unsuitable for plant production compared with simultaneous R + B (RB) light or white light (W) [21]. R light alone decreases photosynthetic rate and biomass and leads to an abnormal shape [22]. Nevertheless, B light alone decreases stem length, leaf area and photosynthetic rate, due to the chloroplast avoidance response [23,24]. However, it is widely recognized that simultaneous irradiation of RB lights is a promising procedure for vegetables and plants such as artichoke, lettuce (*Lactuca sativa* L.), tomato (*Solanum lycopersicum*), cucumber (*Cucumis sativus* L.), Indonesian Chili Pepper (*Capsicum annuum*), okra (*A. esculentus*), and upland cotton (*Gossypium hirsutum*) [21,25–30]. In the same vein, recent studies on lettuce have shown that the alternating use of red light and blue light develops favorable anatomical characteristics, such as greater leaf thickness and higher mesophyll cell density compared with white light or simultaneous RB with the same daily light integrals [31,32]. Though simultaneous red and blue light ratios are effective for okra growth, alternating use has not been the subject of studies on its growth and flowering, which could reveal some cross-sectional information as in the case of lettuce [31,32]. This light spectrum was therefore incorporated into our study in order to assess the distinctive effect of the red and blue spectra on the growth and flowering of okra.

Attempts were made under red and blue monochromatic light, subjecting okra to long-day (LD) and night interruption (NI) conditions. The study examined the reproductive response of two okra cultivars (*A. esculentus*): 'Clemson Spinless' and 'Emerald'. A native roselle cultivar (*A. moschatus* ssp. *tuberosus*) was also studied. These three plants, belonging to the Malvaceae family, are considered short-day (SD) plants. The plants were subjected to LD and NI with red, blue, and green LED lights. Similar effects were observed in all three cultivars. Daylengthening with red or blue LEDs inhibited flower bud formation and flower opening. The effect was particularly marked with the red light. On one hand, the NI

treatment with red LEDs also delayed the appearance of flower buds. On the other hand, the NI treatment with blue LEDs did not produce any clearly observable effect. Green light also delayed flowering to a greater extent than blue light, but slightly less than red light [33]. However, red light caused Kalanchoe, a qualitative SD plant, to flower earlier than blue light under SD conditions [34]. It therefore appears that plant responses to light depend on the plant species, cultivars and photoperiod. A study on the okra variety (*A. esculentus* cv GB1230) was carried out under monochromatic red, green, and blue LED light with a photoperiod of 18 h and a PPFD of 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for 60 days, and showed an inhibition of flower bud formation and flowering [35]. These results show that many phenomena linked to the light quality and photoperiod during the induction of flowering are still unexplained

Flowering responses to photoperiod fall into three broad categories: LD, SD, and neutral plants, depending on their response to daylength. In okra (*A. esculentus*), several studies have shown quantitative SD behavior, with flower induction favored when daylength is less than 12 h [35,36]. However, sensitivity seems to vary from one cultivar to another, suggesting a certain photoperiodic plasticity. These observations allow us to consider okra as an SD plant with quantitative behavior in our study. In contrast, longer photoperiods have been observed to accelerate growth and biomass accumulation in SD plants, but inhibit flowering [18]. Thus, longer photoperiods during the juvenile phase make it possible to accelerate plant growth before flowering. The 10 h photoperiod has been shown to be effective in inducing flowering, anthesis and fruit quality in okra [35,37].

Although the growth of okra indoors has been extensively studied, less is known about its flowering under SD conditions, which is essential for optimizing indoor cultivation. Understanding the effects of red and blue light, and their alternating, on okra flowering in these controlled environments, is therefore crucial. The aim of this study is to determine whether switching from an (LD, 14 h) photoperiod to an (SD, 10 h) photoperiod at a specific developmental stage can induce flowering under different light spectra. Moreover, Nwoke [37] reported that the number of flower buds per plant remained unchanged when (SD, 10 h) treatment was initiated either at 30 days after sowing or immediately after cotyledon emergence. Based on these results, the authors suggested that photoperiod sensitivity in okra should be evaluated in plants that are at least 10 days old. To investigate this sensitivity, okra plants will be exposed to a 14 h photoperiod for 30 days, followed by a 10 h photoperiod to induce flowering under artificial light. Observations will be compared to control plants grown in greenhouses and outdoors under natural sunlight conditions.

2. Materials and Methods

2.1. Plant Material and Soil Properties

The experiment was carried out at the Félix Houphouët Boigny National Polytechnic Institute, located in Yamoussoukro, Ivory Coast (6°52.9650′ N, 5°13.7340′ W; altitude 250 m), and ran from 10 August to 23 October 2024. The okra variety *A. esculentus* cultivar GB1230, from ORSTOM-France (Office de la Recherche Scientifique et Technique Outre-Mer) and supplied by the CNRA (Centre National de Recherche Agronomique) of Ivory Coast, was used in this study. This cultivar was selected due to its widespread use in local production programs and its availability at experimental stations in the region. It is also an early variety, which opens its first flowers between 60 and 70 days after sowing (DAS) and the length of the crop cycle is 110 to 120 DAS [38]. However, studies carried out indoors, under monochromatic light, with a photoperiod of 18 h for 60 days inhibited flowering in this cultivar [39]. Before sowing, the soil was mixed and analyzed according to the methods reported in the study of Kjeldahl [40], Walkley and Black [41], and Thomas [42]. Soil nutrient composition (nitrogen, carbon, and phosphorus in %) was as follows: N 0.13, C 1.17, and

P 0.17. Exchangeable cations and cation exchange capacity (EC) are also determined in (cmol.kg^{-1}): Ca^{2+} 3.76, Mg^{2+} 1.26, Na^{2+} 0.1, K^{+} 1.6, and EC 10. The initial pH was 6.2. Then, 31 kg of soil were introduced into 18 pots with dimensions (width × length × height = 22 × 22 × 40 cm). Two weeks before sowing, 5 g of N 12-P 22-K 22 fertilizer was incorporated into each container, and 50 days after sowing, in accordance with CNRA okra growing conditions. Then, 30 days after sowing, a dose of 2 g of urea was administered under each okra plant. Water was added every third day, according to the recommendation of Al-Ubaydi et al. [43] For the best irrigation of okra, a quantity of 375 mL of water per pot was added every three days for the first 30 DAS. Thereafter, the water was modified to a dose of 200 mL per pot, every 48 h, for all plants.

2.2. Experimental Design and Lighting Treatments

As part of the experiment, three growth boxes for LED artificial lighting were built (width × length × height = 1.5 × 1.5 × 2.5 m) and covered with black plastic to isolate the plants from ambient light. Two further controls experiments were carried out: the first outdoors, with no cover, and the second in a greenhouse (width × length × height = 1.5 × 1 × 2 m) covered with white plastic to let in the sunlight, (Figure 1) shows the experimental design and the okra plants 30 DAS.

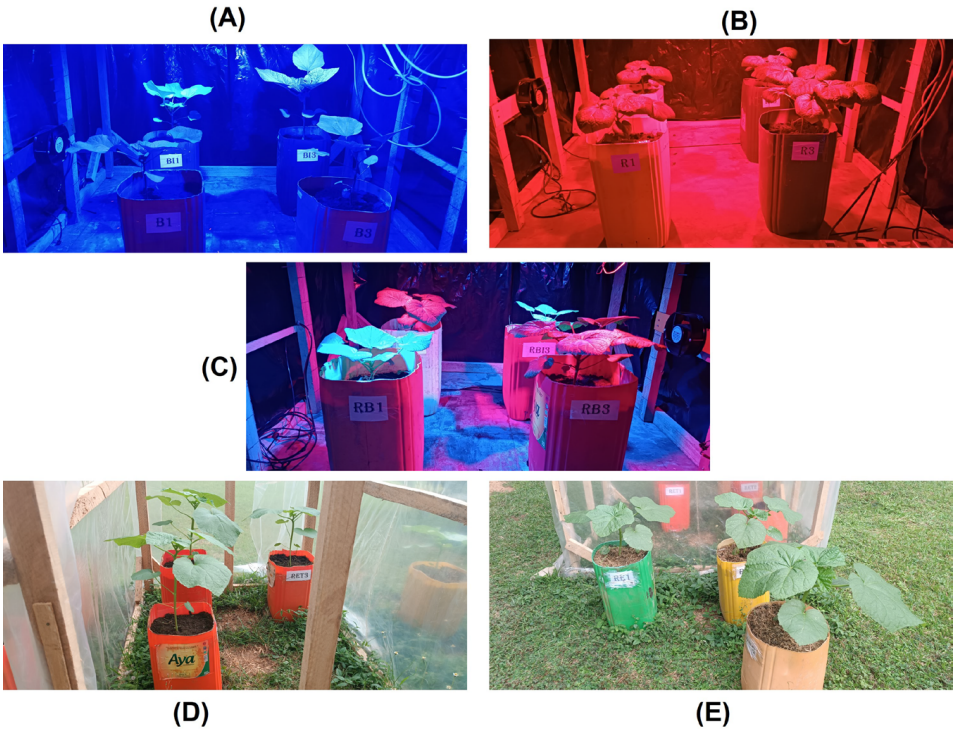


Figure 1. Okra (*A. esculentus* L.) plant 30 days after sowing. (**A**) Blue LED light treatment; (**B**) red LED light; (**C**) red-blue alternating in a three-day cycle; (**D**) greenhouse, natural light; (**E**) outdoor, with natural sunlight.

During the experiment, five okra seeds were placed at a depth of between 1 and 3 cm in the pots, with four pots placed in each LED growth box and a further three pots in each control group. The LED modules selected from Intelligent Led Solutions Oslon® (Thatcham City, UK) 150 16+ color power cluster emit wavelengths of 445 nm blue and 660 nm deep red. The light treatment protocol developed for this study involved growing four okra plants under B, R, and R3B3 LED lighting. The germination period, essential for plant growth, lasted fifteen days, with a photoperiod of 14h and a PPFD light intensity of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$. Indeed, previous studies on the germination of okra

seeds at different light intensities have shown that more efficient germination was obtained at a PPFD of 100 $\mu mol \cdot m^{-2} \cdot s^{-1}$ [44]. Plant growth began 15 DAS, with photoperiod maintained at 14 h and PPFD at 200 $\mu mol \cdot m^{-2} \cdot s^{-1}$. This choice is due to the fact that photoperiods higher than the critical photoperiod for SD plants accelerate their growth [18]. Additionally, increasing PPFD helps increase the photosynthesis rate [45]. At 30 DAS, photoperiod was reduced to 10 h, to induce photoperiodic flowering according to the study of Nwoke [37]. The PPFD of each plant was measured using a LightScout 3415FXSE (Bristol, U.K.) quantum counter, and the position of the LED lights was adjusted daily to maintain an equivalent PPFD between treatments and allow only differences in spectrum to be taken into account. The daily light integral (DLI) for the different plant life stages was 5.05, 10.08, and 7.2 $mol \cdot m^{-2} \cdot d^{-1}$ at germination, growth, and flowering induction, respectively. Figure 2 shows a description of R3B3 light treatment, the photoperiod, and the spectrum of the LEDs used.

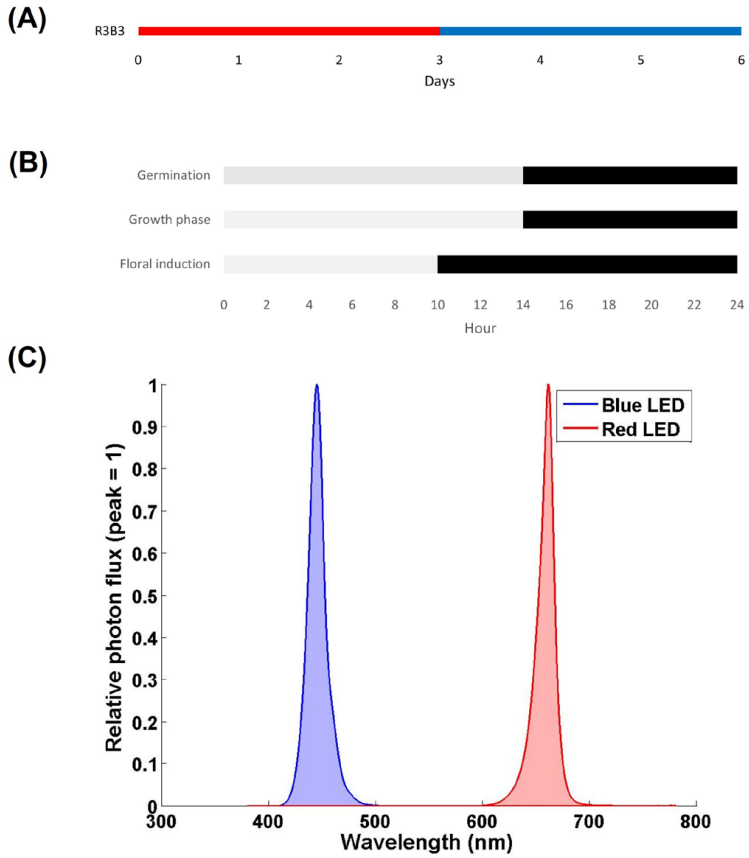


Figure 2. (**A**) R3B3 treatment methodology (Red lighting during 3 days followed by blue lighting during 3 days); (**B**) daily photoperiods (white zones) and period of darkness (black zone); (**C**) relative photon fluxes (peak = 1) blue and red light-emitting diodes used in this study. Spectral distribution scans were taken from wavelengths of 380 to 800 nm with a spectroradiometer (MINOLTA CS-1000, Co., Ltd., Osaka, Japan).

2.3. Outdoor Light Conditions

In order to capture outdoor growing conditions, it is necessary to determine the properties of light that are relevant to plant growth. The properties in question include photoperiod duration, intensity, PPFD, and DLI. These calculations are based on publicly available meteorological and geographical data from NASA's Prediction of Worldwide Energy Resource (POWER) [46] program. Global solar irradiance (I, $MJ \cdot m^{-2} \cdot d^{-1}$) was collected using the geographical coordinates of our experimental site. Sensors such as the pyranometer used at these stations, which quantifies the energy of shortwave radiation

(SW_i), cannot be used to calculate PPFD. In fact, the PPFD of solar radiation, which corresponds to the quantity of photons between 400 nm and 700 nm (PAR), can be obtained by applying Equation (1) [47].

$$PPFD_{sun} = I(\frac{PAR}{SW_i})(\frac{1}{E_{PAR}}) \quad (1)$$

A study of the proportion of PAR revealed that, assuming a PAR/SW_i constant equal to 0.45 and an E_{PAR} set at 0.223 $J \cdot \mu mol^{-1}$ (corresponding to the average of the various skies observed), the calculated $PPFD_{sun}$ shows a variation of less than 5% compared with the measured $PPFD_{sun}$ [47,48]. Using these constants, DLI values are shown in (Figure 3B), obtained by converting I measurements into $Jm^{-2} \cdot s^{-1}$ and using photoperiod data shown in (Figure 3A) [49]. The white tarpaulin used for the greenhouse had a light transmission of around 98%, allowing the DLI to be considered as outdoor, and the mean DLI in both treatments was 14.41 $mol \cdot m^{-2} \cdot d^{-1}$.

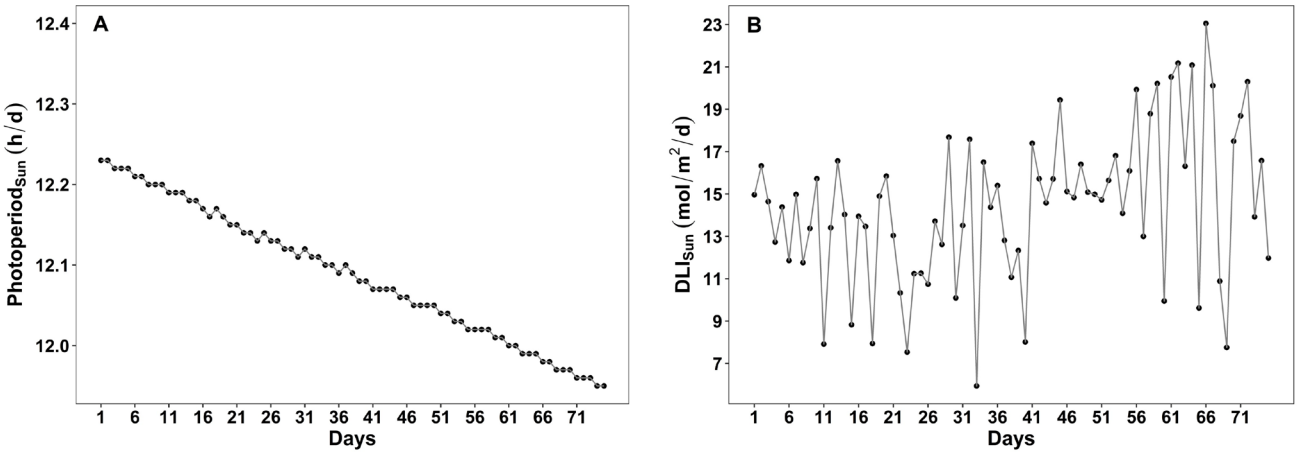


Figure 3. (**A**) Variation in photoperiod and (**B**) Daily Light Integral (DLI) in greenhouse and outdoors.

2.4. Using IoT for Plant Environmental Monitoring Using Home Automation Software

In this section, the objective was to design a wireless sensor system to record temperature and humidity data, and to automatically control the photoperiod of the lighting system in the various growth boxes. Agricultural Internet of Things refers to a type of network technology that applies wireless sensor networks from Internet of Things (IoT) technology to connect with environmental monitoring equipment and agricultural system control equipment.

This connection is made via the protocol chosen by the user for the purpose of monitoring, controlling, and managing agricultural environmental information [50]. Many systems for environmental monitoring or a Smart Home have been implemented on a Raspberry Pi [51,52]. The Raspberry Pi 3 Model B+ (Cambridge, U.K.) was used in this project, communicating via the Zigbee wireless communication protocol. This technology offers a number of advantages: a complex structure, low power consumption, low cost, medium transmission speed, bidirectional communication over short distances, and so on. To be precise, the transmission rate of this technology is between 10 Kb/s and 250 Kb/s, while the optimum transmission distance is around 0 to 75 m [53]. In addition, the device's ability to adjust its operating frequency with a certain selectivity confers notable advantages in terms of stability, low power demand, and crucial importance in network construction [50].

In ZigBee devices, the presence of a coordinator, which can be an FFD (Full Function Device) device, is systematic. The use of the CC2531 USB (Shenzhen, China) key as a coordinator was carried out, with the appropriate firmware flashing, in accordance with

the guidelines provided by the Texas Instrument website [54]. This coordinator operates at a frequency between 2.405 and 2.448 GHz, with a transfer rate of 250 Kbs, and can connect to 20 devices. It has a power consumption of less than 20 mA. As part of the optimal use of the CC2531 USB sniffer as a ZigBee coordinator, the Zigbee2MQTT software (version 1.42.0) developed by Koen Kanters has been installed [55]. This converts messages from ZigBee devices into MQTT (Message Queuing Telemetry Transport), facilitating connectivity and control of new devices, including those from different manufacturers, enabling transmission of sensor measurement data and LED control via switches [56]. In terms of sensors, the use of five SONOFF SNZB-02p (Shenzhen, China) temperature and humidity sensors, which operate with the Zigbee protocol as well, were used. As for the switches, two Smart Plug 16 Ampere Zigbee-compatible switches were chosen. These smart plugs, which connect to a normal power socket, offer the possibility of controlling any other device connected to them.

There is a range of platforms, both free and paid, dedicated to home automation systems. The purpose of these platforms is to provide a common, centralized control interface for collecting data from different types of sensors and controlling various devices. The Domoticz open-source platform offers a richer graphical interface, and user interaction is carried out using HTML markup language via an integrated web server, making it particularly lightweight [57]. It should be noted that the Raspberry Pi must be connected to the internet to enable real-time visualization of data relating to the temperature, humidity, and energy consumption of the lighting system on the platform. The photoperiod is selected in the Domoticz platform by specifying the time at which the lighting system is switched on and off. The data are recorded at five-minute intervals in a CSV file. At the end of the experiment, the CSV files are processed using RStudio software. The mean values for day and night temperatures, as well as the mean values for day and night humidity, are shown in Figure 4.

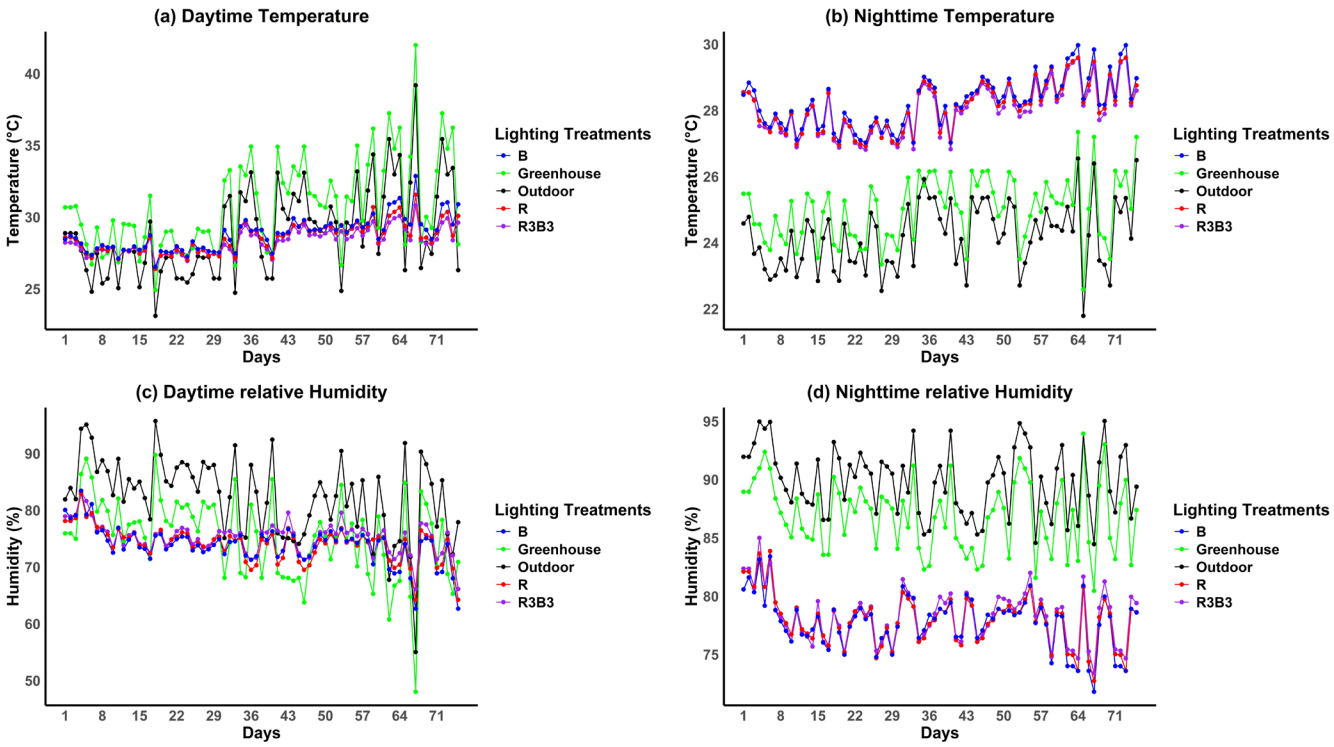


Figure 4. Temperature and relative humidity day and night in growth boxes B, blue LED light treatment; greenhouse, natural sunlight; outdoor, natural sunlight; R, red LED light; R3B3, red-blue alternating in a three-day cycle.

Average temperatures and relative humidity were virtually the same in the LED lighting boxes, both day and night. The average daytime temperature ranged from 28.31 to 28.81 °C compared with 28.01 to 28.25 °C at night. Relative humidity ranged from 73.89% to 75.20% during the day and 77.75% to 78.25% at night. The highest daytime temperature values were in the greenhouse: temperatures ranged from 30.80 °C during the day to 25 °C at night, and relative humidity from 75.29% during the day to 86.98% at night. The highest relative humidity values day and night were outdoors: 82.2% during the day and 89.88% at night. The temperature ranged from 28.87 °C during the day to 24.21 °C at night.

2.5. Germination Observations

Seed germination was recorded daily from sowing to 15 days after sowing. These data were used to calculate various germination indices such as germination percentage and mean germination time (MGT), which respectively represent the percentage of seeds completing the germination process and the index of germination speed [58,59].

2.6. Flowering Observations

Plants were observed daily to record the number of days until the flower bud was visible (first flower bud) and anthesis (first fully open flower). In addition, fruit diameter was measured one day after petal fall, using a caliper.

2.7. Growth and Morphology Observations

In this study, okra plants were grown for a period of 76 days, under different light regimes, namely B, R, and R3B3, in greenhouse and field conditions. During this period, morphological parameters were recorded every 7 days, starting on 20 DAS. Main plant height (cm), measured from the top of the soil to the shoot apex, was determined using a tape measure. The total number of leaves and nodes number per plant were counted manually. Furthermore, stem diameter (mm) was also collected using a caliper. The length and width of each leaf per plant were measured using a graduated ruler, and the resulting leaf area (LA) was calculated using the method of Hoyt and Brandfield [60]: LA = leaf length × leaf width × 0.75. The leaf area index (LAI) was also calculated as the quotient of the total leaf area by the soil area occupied by the plant. The soil area occupied by each plant was 0.09 m^2. At 76 DAS, all specimens were destructively removed in order to determine the fresh and dry weight of the main stem, using a digital balance. The internodes and roots were also measured.

2.8. Statistical Design and Analysis

Three okra plants were used for each treatment, for statistical analysis to assess their respective statistical significance and identify significant differences between treatment means. Note that all statistical analyses were performed using R software, version 4.4.2, RStudio version 2024.12.0.467. For each type of measurement, a one-way analysis of variance (ANOVA) was performed, followed by a separation of means according to Tukey's Honest Significant Difference (HSD) test at ($p < 0.05$).

3. Results

3.1. Germination Parameters

The average day/night temperatures and the average day/night relative humidity over the 75 days of the experiment were as follows: B (28.81/28.25 °C; 73.89/77.75%), R3B3 (28.31/28.01 °C; 75.2/78.25%), R (28.55/28.10 °C; 74.07/77.96%), greenhouse (30.80/25 °C; 75.29/86.98%), and outdoor (28.87/24.21 °C; 82.2/89.88%).

The germination percentage (Figure 5A) showed no significant difference between treatments. The highest germination rate under LED lighting was observed with the R3B3 treatment (87 ± 12%), followed closely by treatment B (73 ± 23%), while the lowest was recorded with treatment R (67 ± 12%). In the control groups, germination rates ranged from 53 ± 12% (outdoor) to 63 ± 5.8% (greenhouse). These results reveal that okra seeds respond more favorably to artificial LED lighting conditions, especially those associated with a prolonged photoperiod and higher, more stable night temperatures.

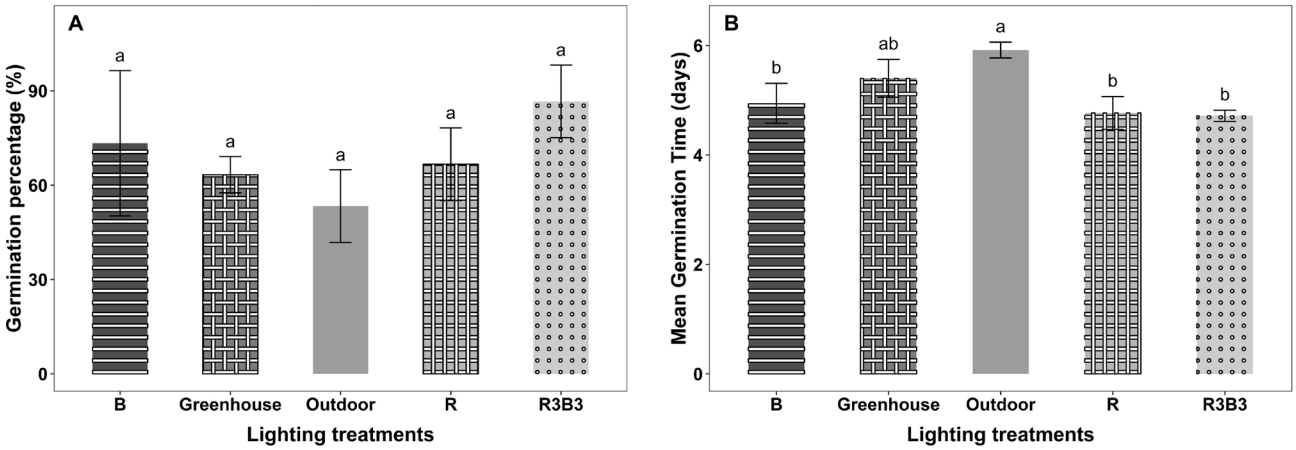


Figure 5. Germination percentage (**A**) and mean germination time (**B**) of okra (*A. esculentus* L.) plants grown in different LED light treatments: blue (B), red (R), and red-blue alternating in a three-day cycle (R3B3) and controls, greenhouse, and outdoor. Vertical bars represent mean ± Standard Deviation (S.D.) (n = 3). Different letters above the bars indicate significant difference at $p < 0.05$ according to Tukey's HSD test.

The mean germination time (Figure 5B) was noticeably shorter under LED light treatments compared with the controls exposed to natural sunlight. On average, seeds germinated in about five days under LED conditions, with the shortest time recorded for the R3B3 treatment (4.7 days), followed by R and B treatments (4.9 days), which represented the longest germination times among the LED groups. In contrast, the outdoor control exhibited the longest germination time (6 days), while the greenhouse control showed an intermediate duration. No significant differences were observed among the LED treatments.

3.2. Flowering and Fruiting

The light treatments had a significant impact on the average number of days required for flower bud initiation (see Figure 6). The earliest initiation occurred in the control groups, with both showing flower buds at 36 DAS. Among the LED treatments, there were significant differences: treatment R resulted in the earliest flower bud initiation at 51 DAS (15 days later than the controls), followed by R3B3 at 53 DAS (17 days later). Treatment B showed the latest initiation, occurring 20 days after the control group at 56 DAS (Figure 6A).

The average number of days to first flower opening followed a similar trend to that of flower bud initiation, with significant differences observed between treatments (Figure 6B). Flowering occurred earliest in the outdoor control group (51 DAS), followed by the greenhouse treatment (56 DAS). Among the LED light treatments, treatment R led to the earliest flower opening at 68 DAS, followed by R3B3 at 70 DAS, which showed an intermediate response. Treatment B recorded the longest time to first flower opening at 73 DAS. All plants successfully flowered under all treatments. Figure 7 presents okra plants with flower buds and open flowers across the various LED treatments and control conditions.

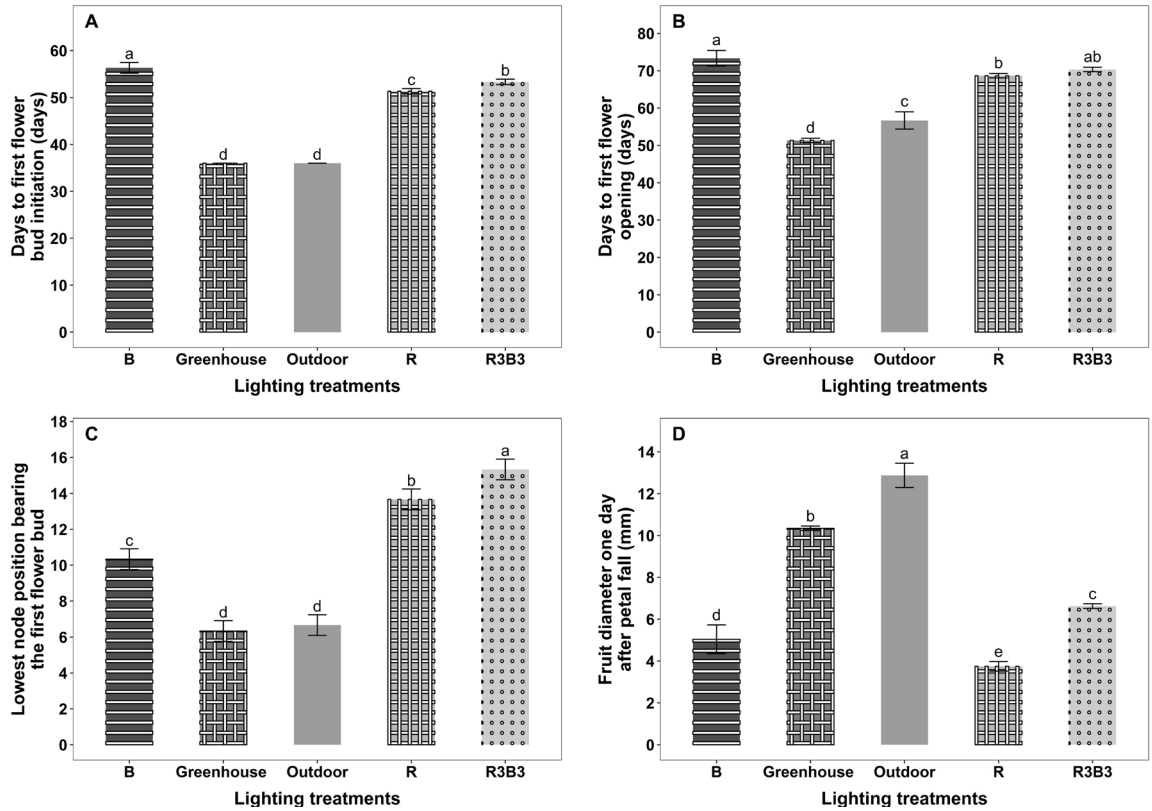


Figure 6. Days to first flower bud initiation (**A**); days to first flower opening (**B**); lowest node position bearing the first flower bud (**C**) and fruit diameter one day after petal fall (**D**) of okra (*A. esculentus*) plants grown in different LED light treatments blue (B), red (R), and red-blue alternating in a three-day cycle (R3B3) and controls, greenhouse, and outdoor Vertical bars represent mean ± Standard Deviation (S.D.) (n = 3). Different letters above the bars indicate significant difference at $p < 0.05$ according to Tukey's HSD test.

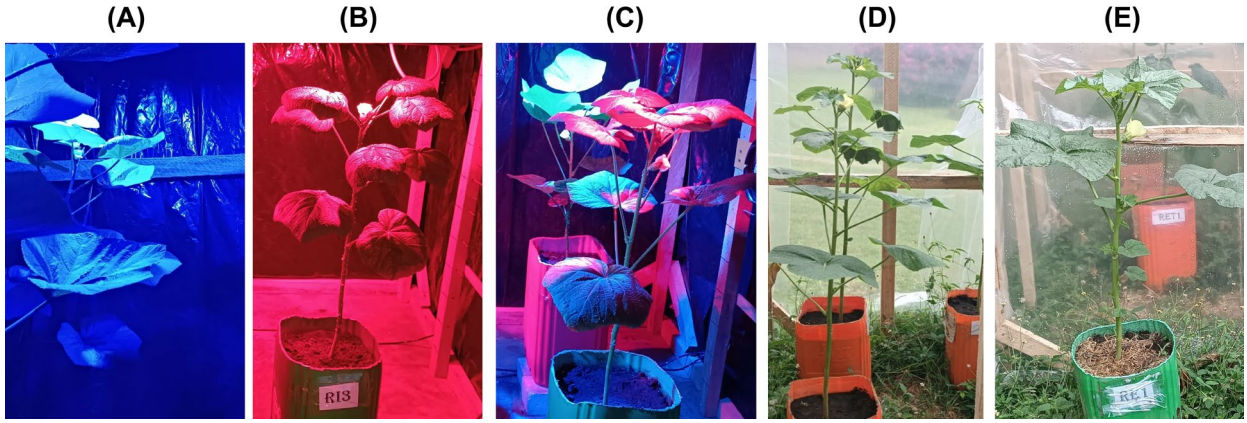


Figure 7. Okra plants (*A. esculentus*) showing the appearance of flower buds and flowers under different light conditions: (**A**) blue LED light; (**B**) red LED light; (**C**) alternating red-blue light in a three-day cycle; (**D**) greenhouse with natural sunlight; (**E**) outdoor with natural sunlight.

The lowest mean nodal position under treatments B, R, and R3B3 was considerably higher than that of the control treatments (Figure 6C). Among the LED treatments, R3B3 resulted in a significantly higher mean nodal position (15.3), followed by the red treatment (13.7), with the blue treatment producing the lowest nodal position (10.3). However, no significant differences were observed between the control treatments, which showed similar effects, with the first floral bud appearing around node 7.

These results indicate that under LED light treatments with long photoperiods, okra plants produce a greater number of nodes before floral bud initiation compared with those grown under sunlight with natural photoperiods.

Both greenhouse and outdoor treatments significantly increased fruit diameter one day after petal fall compared to LED treatments (Figure 6D). The highest value in the control group was for the outdoor treatment (12.9 mm, Figure 8A), followed by the greenhouse control treatment (10.3 mm). Under LED lighting, the average fruit diameter was highest in the R3B3 treatment (6.6 mm), followed by the B treatment. The lowest diameter was recorded under the R treatment (3.8 mm). A significant difference was found between the different LED treatments, as illustrated by the highest diameter in Figure 8B. Figure 8 shows okra plants outdoors and under R3B3 treatment, with pods appearing after petal fall.



Figure 8. Okra plants grown outdoors (**A**) and under R3B3 treatment (**B**), showing pod development one day after petal fall.

3.3. Growth Parameters

Some Temporal Growth Parameters

Table 1 shows the growth parameters 30 days after sowing, before the change in photoperiod, for the LED B, R and R3B3 treatments compared with the greenhouse and outdoor control treatments.

Table 1. Okra (*A. esculentus* L.) plant growth parameters in different LED lighting treatments and control greenhouse and outdoor 30 DAS.

	Growth Parameters Under Different Light Treatments					
Lighting Treatments	**Plant Height (cm)**	**Stem Diameter (mm)**	**Node Number**	**Leaf Number**	**LA (cm^2)**	**LAI**
B	20 ± 3.2^{b}	6 ± 1.20^{a}	3.7 ± 0.58^{b}	6.3 ± 0.58^{a}	83 ± 25^{c}	0.5 ± 0.18^{b}
Greenhouse	31 ± 3^{a}	8 ± 1.10^{a}	3.3 ± 0.58^{b}	6.0 ± 1.00^{a}	199 ± 38^{a}	1.4 ± 0.33^{a}
Outdoor	21 ± 1.2^{b}	7.9 ± 0.68^{a}	3.7 ± 0.58^{b}	6.3 ± 0.58^{a}	156 ± 25^{ab}	0.98 ± 0.06^{ab}
R	16 ± 1.5^{bc}	6 ± 1.50^{a}	4.7 ± 0.58^{ab}	7.3 ± 0.58^{a}	79 ± 22^{c}	0.7 ± 0.24^{b}
R3B3	12 ± 1.7^{c}	7.4 ± 0.38^{a}	5.3 ± 0.58^{a}	7.7 ± 0.58^{a}	102 ± 3.4^{bc}	0.8 ± 0.11^{b}

B, blue LED light treatment; greenhouse and outdoor, natural sunlight; R, red LED light; R3B3, alternating red and blue LED light in a three-day cycle. Data represent mean ± Standard Deviation (S.D.) ($n = 3$). Different letters indicate significant differences among values according to Tukey's HSD test ($p < 0.05$).

The height of okra plants varied significantly between treatments (Table 1). The tallest plants were observed in the greenhouse (31 cm) control group, followed by the outdoor (21 cm) control, with a statistically significant difference between their mean heights. Among the LED treatments, the highest plant growth was recorded under B (20 cm) treatment,

which did not differ significantly from the outdoor control. This was followed by R (16 cm) treatment, which showed a moderate effect, while the shortest plants were observed under the R3B3 (12 cm) treatment.

At 30 DAS, the stem diameter showed no significant differences between treatments. The control group (around 8 mm) exhibited the largest stem diameter, followed closely by the R3B3 (7.4 mm) treatment. Treatments B and R resulted in similar stem diameters (6 mm), which were the smallest among all groups.

The number of nodes was significantly higher under LED treatments compared with the controls. The highest values were observed with treatments R3B3 (5.3), R (4.7), and B (3.7) compared with 3.3 and 3.7 for the control groups exposed to natural light. Significant differences were observed between the different LED treatments.

No significant difference was recorded between treatments regarding leaf number at 30 DAS. However, the highest leaf number was recorded under treatment R3B3 (7.7), followed by treatment R (7.3). Treatment B (6.3) produced a similar result to the outdoor control, while the greenhouse control recorded the lowest leaf number (6).

LED treatments had a smaller leaf area than those exposed to sunlight. The largest leaf areas were recorded in both the greenhouse (199 cm^2) and outdoor (156 cm^2) control groups, with no statistically significant difference between them. Among the LED treatments, R3B3 (102 cm^2) produced the largest leaf area, followed by treatments B (83 cm^2) and R (79 cm^2), which showed no significant difference between them at 30 DAS.

Significant differences were observed between treatments in terms of leaf area index. Control plants exhibited a higher LAI compared with those grown under LED treatments, with the highest value recorded in the greenhouse control (1.4). The outdoor control showed an intermediate effect (0.98) relative to the LED-treated plants. Among the LED treatments, R3B3 produced the highest LAI (0.8), followed by R (0.7) and B (0.5). However, no significant differences were observed among the LED treatments at 30 DAS.

Additionally, Figure 9 illustrates the progression of plant height, stem diameter, number of nodes, leaves, leaf area, and leaf area index over a 70-day growth period. Stem height and diameter were consistently greater in the control groups compared with the LED treatments, with this difference clearly evident throughout the growth period, starting from 20 DAS (Figure 9A,B). Notably, at 34 DAS, treatment B began to distinguish itself from treatments R and R3B3 by promoting a better plant response in terms of stem diameter.

In addition, the number of nodes and leaves was higher under the R3B3 and R treatments compared with the B treatment and the control groups, with this difference remaining consistent throughout the growth period starting from 20 DAS (Figure 9C,D). During the first 30 days, the number of nodes was similar between the B treatment and the control group, with overlapping values observed throughout the growth cycle. A similar trend was noted for the number of leaves. It was only after 41 DAS that the outdoor control group began to distinguish itself from the B treatment and the greenhouse control by producing leaves on axillary branches, resulting in a higher total number of leaves than all other treatments.

As for leaf area and leaf area index, both were greater in the control groups compared with the LED light treatments, and this trend remained consistent throughout the growth period starting from 20 days after sowing (DAS) (Figure 9E,F). It was only at 34 DAS that the B treatment began to stimulate leaf area expansion and, consequently, increase the leaf area index, with values surpassing those observed in the R and R3B3 treatments.

In addition, Figure 10 shows the average internode length, root length and fresh and dry weight of the main stem, measured at the end of the experiment, i.e., 75 DAS. Internode length was significantly different between treatments. More precisely, internodes were significantly shorter under LED treatment compared with the controls, with the exception

of treatment B (6 cm), which was superior to the outdoor control, but the differences were not statistically significant. Treatments R and R3B3 had the shortest inter-nodes, with the shortest under R3B3 (3 cm) (Figure 10A).

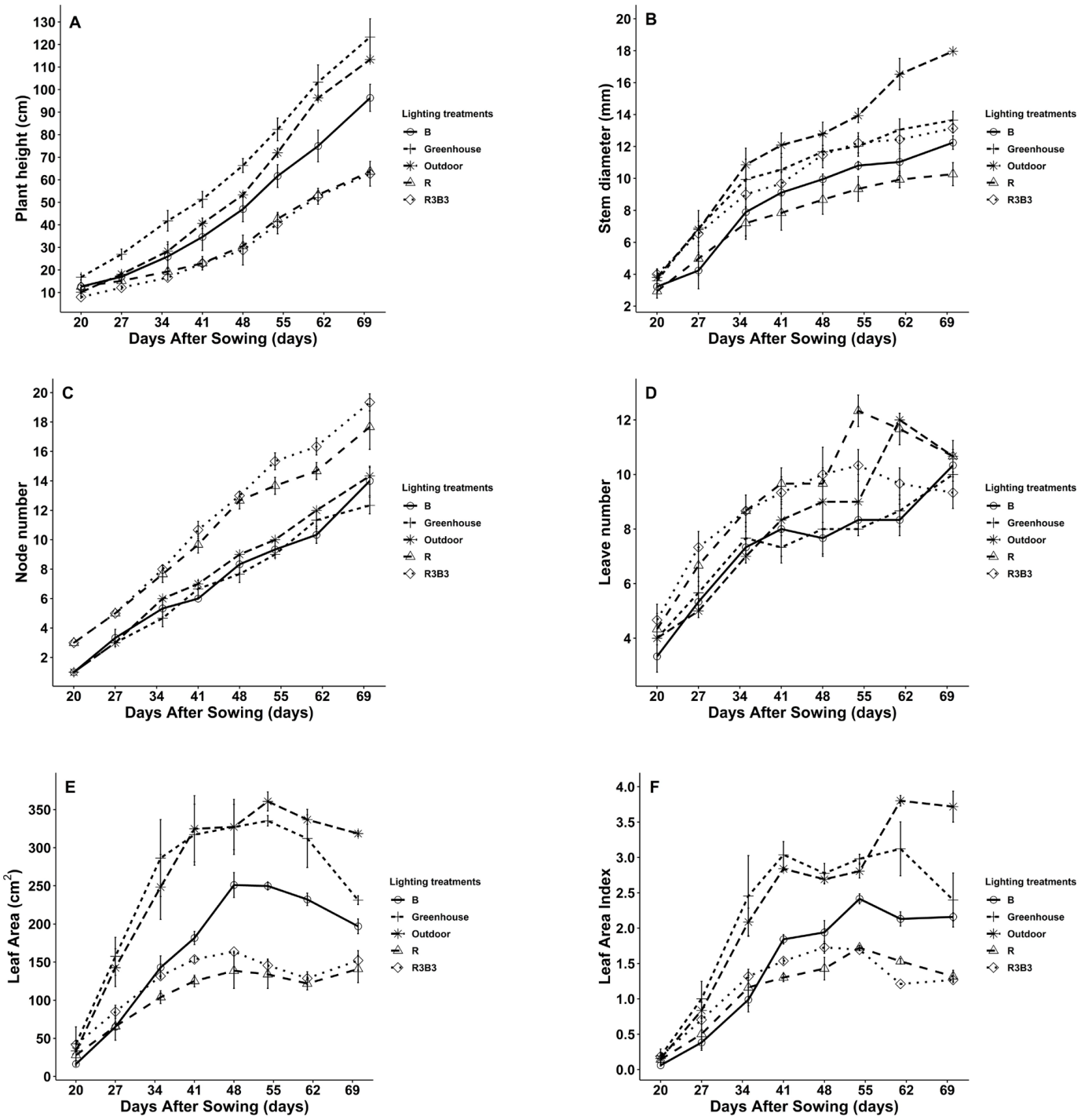


Figure 9. Plant height (**A**), stem diameter (**B**), number of nodes (**C**), number of leaves (**D**), leaf area (**E**), and leaf area index (**F**) during a 70-day growth period of okra (*A. esculentus*) plants. Each point represents mean ± Standard Deviation (S.D.) (n = 3). Error bars represent the S.D.

Root length was significantly shorter in the LED treatment than in the controls. The outdoor and greenhouse control treatments increased okra root lengths to 28 cm and 22 cm, respectively. Treatment R3B3 (13 cm) had a longer root length than treatments B (10 cm) and R (10 cm), but the differences were not statistically significant (Figure 10B).

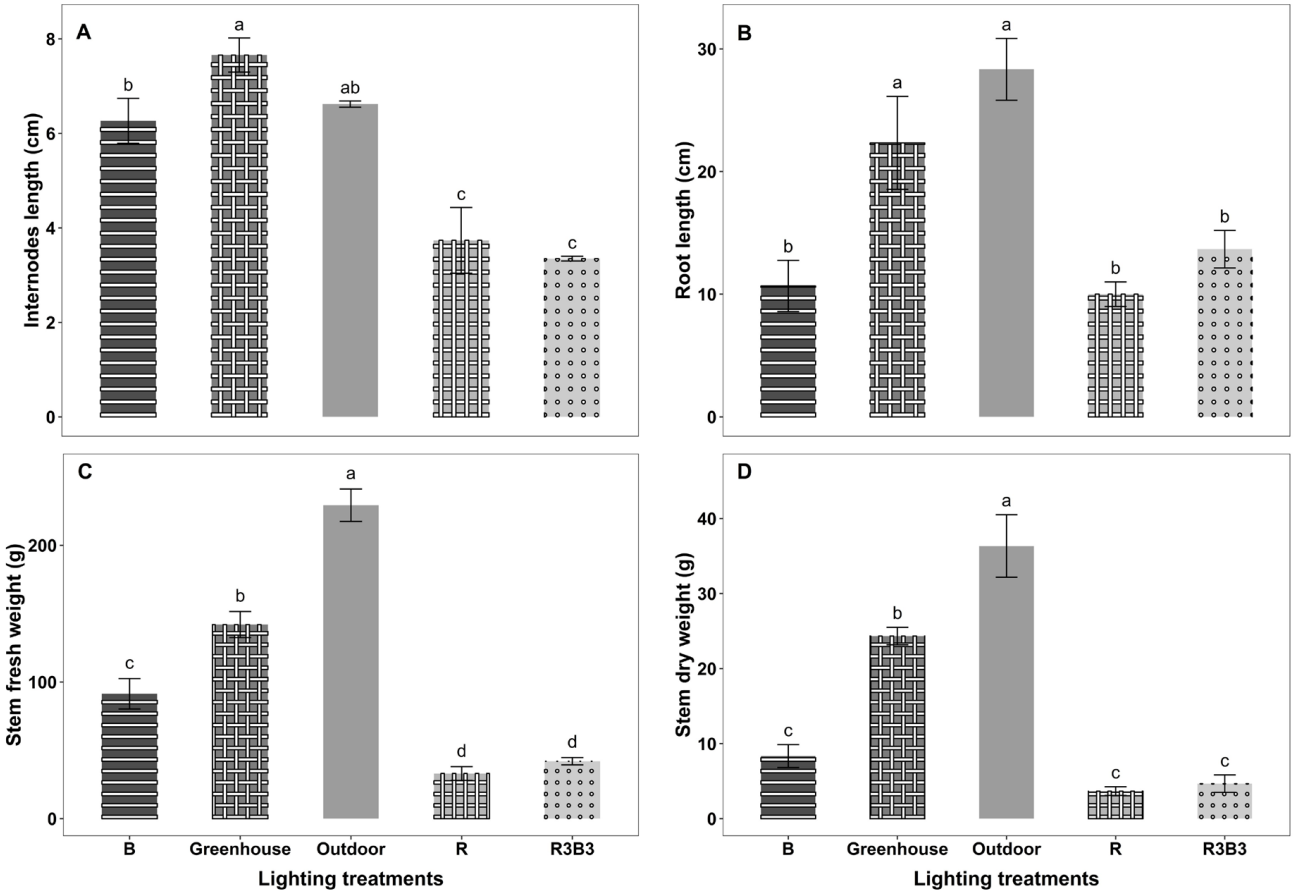


Figure 10. Internode length (**A**); root length (**B**); stem fresh weight (**C**) and stem dry weight (**D**) of okra (*A. esculentus*) plants grown in different LED light treatments blue (B), red (R), and red-blue light alternating in three-day cycle (R3B3) and controls, greenhouse, outdoor. Vertical bars represent mean ± Standard Deviation (S.D.) (n = 3). Different letters above the bars indicate significant difference at $p < 0.05$ according to Tukey's HSD test.

Fresh stem weight was significantly higher under the outdoor control (229 g) and under the greenhouse (142 g). Treatment B (91 g) had a significantly higher fresh stem weight under LED treatment, followed by treatment R3B3 (42 g). Treatment R (33 g) had the lowest value, but was not statistically different from treatment R3B3 (Figure 10C).

Dry stem weight showed the same trend as fresh weight, but the differences between light treatments were not statistically significant (Figure 10D).

4. Discussion

4.1. Effects of Light Spectrum on Okra Seed Germination

The objective of this part of the study is to examine the effects of different LED light treatments on okra germination in comparison to control conditions in the greenhouse and outdoors. Mean germination time (MGT) reflects the speed of seed germination over time [59]. In our study, seeds grown in LED grow boxes showed a higher germination rate and shorter mean germination time than controls (Figure 5). This improved performance may be linked to the difference in day/night temperatures inside the boxes (28.8/28.0 °C), which were higher at night, in contrast to the control conditions (30.8/25.0 °C) with lower night temperatures (see Figures 4 and 5). These results are in agreement with those of Takahata et al. [61], who studied the optimal temperature for germination of okra (*A. esculentus*) and observed that seed emergence began earlier in groups exposed to 30 °C, 35 °C and 40 °C than in those exposed to 25 °C, 20 °C, and 17.5 °C. These observations confirm

that the speed of germination increases as the temperature rises, within a certain optimum range. Consequently, a night-time temperature of 28 °C is more favorable to germination than 25 °C, as was observed in our study. Similarly, the study by Limprasitwong et al. [62] showed that shallot plants subjected to artificial lighting (LEDs and grow lights) had a higher germination rate during the first seven days compared with those grown under natural light. These results confirm the beneficial effect of artificial LED lighting on the speed and percentage of germination. The higher germination percentage and shorter MGT were observed under the R3B3 (87% and 4.7 days) treatment. This observation may be explained by the activation of physiological processes mediated by phytochrome (PHY) and cryptochrome (CRY) photoreceptors. Red light induces the conversion of PHY between two photoreversible forms: Pr, which absorbs red light (peak at 650–670 nm), and Pfr, which absorbs far-red light (peak at 705–740 nm) [63]. The Pr form absorbs R light and is converted to its active form Pfr, which promotes germination by affecting the growth capacity of the embryo and reducing the constraints of the surrounding structure during the three days of exposure. Thus, promoting germination by acting mainly on the synthesis and signaling of gibberellin (GA) [64]. Exposure to three days of blue light activates CRY1 and CRY2. These are activated by wavelengths between 400 and 500 nm and trigger a signaling cascade leading to the activation of genes linked to dormancy release. [64]. Furthermore, exposure to blue light induces a decrease in the synthesis of abscisic acid (ABA), a hormone inhibiting germination, and increases the biosynthesis of GA, hormones favorable to this process [64]. MGT is lower under red light compared with blue light due to the predominant effect of phytochromes on germination [44]. Our results are consistent with those of a previous study on okra, which found that seeds germinated more quickly under blue light than under green or red light. However, seeds exposed to red light had the shortest MGT [44].

4.2. Effects of Light Spectrum on Growth Parameters of Okra

This study demonstrated that okra plants grown under natural light conditions (outdoors and in a greenhouse) exhibited significantly greater growth performance, including in terms of plant height, stem diameter, LA, LAI, internode length, root length, and fresh and dry stem biomass, compared with those exposed to LED treatments (B, R, and R3B3) (see Figures 9 and 10). However, the number of leaves and nodes increased under LED treatments, suggesting that the light spectrum influences specific aspects of growth. These findings are consistent with previous studies showing that plants with robust stems, compact architecture, and well-developed root systems accumulate more biomass and are considered higher quality [65,66]. The observed differences can be attributed to the broader light spectrum and higher DLI under natural light conditions, which are known to promote vegetative growth and physiological activity [67,68]. Several studies have used DLIs levels ranging from 2 to 5 mol $\cdot$ m^{-2} $\cdot$ d^{-1} for the cultivation of okra and cotton under different light spectra, without observing any signs of light-induced stress at these levels [21,25,26]. Therefore, the growth performance observed in this study under DLIs of 5, 10, and 7 mol $\cdot$ m^{-2} $\cdot$ d^{-1} cannot be attributed to light stress. Both outdoor and greenhouse-grown okra plants received the full PAR spectrum (400–700 nm), with an average DLI of 14.41 mol $\cdot$ m^{-2}$\cdot$d^{-1}, nearly double that of LED treatments (7.44 mol $\cdot$ m^{-2}$\cdot$d^{-1}). This higher DLI under control conditions likely contributed to the enhanced growth performance observed in these treatments, as supported by previous studies showing optimal growth in cucumber and tomato seedlings at similar DLI levels (13–14.4 mol $\cdot$ m^{-2}$\cdot$d^{-1}) [66,69]. These conditions have been shown to improve not only morphological traits but also root vitality, biomass accumulation, and photosynthetic pigment synthesis. Our results confirm that a higher DLI positively influenced several growth parameters in okra, highlighting the

need for further studies on the effect of DLI on okra morphology and physiology under controlled environments with artificial LED lighting.

Analysis revealed no significant differences between the greenhouse and outdoor controls for internode length, root length, plant height, stem diameter, number of leaves, or number of nodes (see Table 1 and Figure 10). However, LA and LAI were greater in the greenhouse during the growth period (Figure 9E,F), while fresh and dry stem weights were higher under outdoor conditions. These observed differences between the control treatments may be explained by slightly higher temperatures in the greenhouse, which promoted stem elongation and increased leaf development, although they also led to a reduction in stem diameter starting at 34 DAS (Figure 9B). The observed internode elongation is consistent with previous findings showing that day/night temperature differences influence stem morphology, with warmer nights favoring elongation [70]. These results suggest that modest differences in day/night temperature regimes (28.8/24 °C in control outdoors vs. 30.8/25 °C under control greenhouse) influenced stem architecture and leaf expansion in okra.

LED treatments resulted in a higher number of nodes and leaves compared with the control groups, suggesting that targeted light spectra can enhance structural leaf development and stimulate photosynthetic activity. This increase in leaf and node production may be attributed to the alignment between LED emission peaks and the absorption spectra of photosynthetic pigments, thereby improving photosynthetic efficiency. Similar effects have been reported in lettuce grown under LED lighting compared with neon light sources. [71], confirming the role of targeted wavelengths in promoting leaf development. Significant differences in leaf and node numbers were found between LED treatments, with R3B3 (7.7 and 5.3) showing the highest values (Table 1). This can be attributed to the combined effect of red and blue light activating complementary photoreceptors, enhancing photosynthesis and vegetative growth through improved light signaling and assimilate partitioning [31] The higher number of leaves under red light compared to blue may be due to more efficient photon capture for photosynthesis, as shown in tomato and okra plants [39,72]. This supports the observed effect of red light on promoting leaf development. Despite its role in leaf number, red light can inhibit chloroplast development and leaf thickness, leading to reduced LA compared to blue light [27]. Studies in cucumber showed higher LA under blue light, consistent with our findings [27,73,74]. Blue light improves photosynthesis and promotes stem elongation by enhancing stomatal opening and quantum yield. This explains the greater height observed under B treatment, likely due to cryptochrome activation and its interaction with photomorphogenic regulators [22,74]. The shortest plant height and the greatest stem diameter were recorded under the R3B3 (12 cm and 7.4 mm) treatment. Red light is known to promote stem elongation through phytochrome-mediated signaling, while blue light regulates photomorphogenesis and modulates auxin levels. The alternation between red and blue light may disrupt auxin signaling pathways, thereby reducing elongation and promoting stem thickening. This results in more compact plants, which may be better adapted to fluctuating light spectra [75,76]. Moreover, root length was significantly greater under R3B3 (13 cm) compared with R and B treatments (10 cm), possibly due to the involvement of plant hormones such as auxins, jasmonic acid (JA), and abscisic acid (ABA) in PhyB-mediated photoreceptor signaling during root development (Figure 10B) [77]. Additionally, blue light regulates root phototropism through CRYs and PHOTs, further promoting root growth [78]. Higher stem fresh and dry weights, along with greater internode lengths, were recorded under blue light B treatment compared with R and R3B3 treatments (Figure 10). Mio et al. [27] reported that blue light promotes stem elongation in cucumber seedlings by enhancing photosynthesis despite reduced chlorophyll content. Moreover, blue light has been shown to upregulate IAA (indole-3-acetic

acid) synthesis, thereby supporting shoot growth [75,79]. These observations are consistent with findings in red leaf lettuce and potato seedlings, where blue light improved both fresh and dry biomass accumulation [80,81]. Overall, these findings indicate that both monochromatic and alternating light spectra influence specific aspects of okra growth, with a more pronounced effect under blue light treatment.

4.3. Effects of Light Spectrum on Time to First Flower Bud Initiation and First Flower Open on Okra

This study shows that okra flowering can be induced under artificial light using blue, red, or alternating red-blue LED treatments. Okra is sensitive to photoperiod, with long days generally delaying floral bud initiation and anthesis, depending on the variety [35]. The 'Clemson' variety, although tolerant to long photoperiods, showed delayed flowering [35]. Similar responses are seen in other Malvaceae, such as *Hibiscus* spp. and semi-wild cottons, where most species exhibit short-day sensitivity, though exceptions like upland cotton (*G. hirsutum*) are day-neutral [80,81].

Changing the photoperiod (from 14 h to 10 h) at 30 DAS in our study delayed okra flowering (68 DAS under red light, the earliest among the LED treatments) compared with the constant 12 h photoperiod in the control groups (51 DAS outdoors, the earliest among controls), where floral buds appeared earlier (36 DAS) (see Figure 6). Our results align with the study on the 'Clemson' variety of okra (*A. esculentus*), which showed that a 14 h photoperiod delayed floral bud initiation (33 days versus 26 days at 12 h) and the first anthesis (70 days versus 41.3 days at 12 h) [35]. This highlights the predominant role of photoperiod in regulating okra flowering. Also, despite the same day of floral bud initiation, differences were observed in the timing of the first flower opening between the greenhouse and outdoor treatments. The only notable difference between the two conditions was the average daytime temperature, which was slightly higher in the greenhouse (30.8 °C compared with 28.87 °C outdoors). These results suggest that an increase of around 2 °C can also affect the timing of okra flowering. Moreover, previous studies have shown that high temperatures delay floral development under both short and long photoperiods [82]. In addition to temperature, light availability also plays a key role in the flowering process. Dada and Adejumo [83] reported that a 76% reduction in light intensity increased fruit production in okra by 50%, but delayed flowering. This delay under LED treatments with lower DLI compared with controls may be explained by reduced light availability. Further studies are needed to clarify the role of DLI on okra flowering.

The flowering process is regulated by genetic and environmental factors, including photoperiodic signals. In Arabidopsis, a long-day plant, the FLOWERING LOCUS T (FT) gene acts as a key florigen. Synthetic in leaves, it is transported to the shoot apical meristem to induce flowering [84,85]. Its expression is controlled by the accumulation of CONSTANS (CO) [86]. Although Arabidopsis is widely used as a model, okra is a short-day plant, and the underlying molecular mechanisms related to it remain poorly understood. However, studies on related short-day species, such as *G. hirsutum*, which belongs to the same family as okra, have identified homologs of CO, FT, and FD as key regulators of photoperiodic flowering [80]. In *G. hirsutum* of the Malvaceae family, short-day flowering is regulated by genes such as GhCOL, GhFT, and GhFD, whose expression is influenced by light signaling pathways. This depends on the regulation of photoreceptors that are involved in the perception of light quality and duration. Among them, PHYA is unstable in light and active in darkness; blue light photoreceptors, CRY1 and CRY2, also contribute to CO stabilization. In cotton, GhCRY2 interacts with CIB2 to promote the transcription of GhFT, which then activates GhFD and thus induces flowering [81]. These regulatory pathways suggest that light quality, particularly red and blue wavelengths, plays a crucial role in flowering regulation. In line with this, red light in our study induced earlier floral

bud initiation (51 DAS) and first flower opening (68 DAS) compared with the R3B3 (53 DAS and 70 DAS) and blue light treatments (56 DAS and 73 DAS), demonstrating a more pronounced promotive effect on flowering. This indicates that both phytochrome (PHY) and cryptochrome (CRY) pathways are likely involved in the modulation of flowering in okra. New insights into the regulation of CO stability have emerged from studies in Arabidopsis, where red and blue light photoreceptors finely adjust CO protein accumulation. Under long-day conditions, CRY stabilizes CO by antagonizing phyB-mediated degradation, while this stabilization is reduced under short-day conditions [87,88]. The PHL gene (PHYTOCHROME-DEPENDENT LATE-FLOWERING) has been identified as a specific modulator of phyB that stabilizes CO by forming a red light-dependent complex with CO and phyB (PhyB–PHL–CO), thereby promoting FT expression [89]. This mechanism helps explain the effect of PhyB on flowering. During the day, this tripartite interaction stabilizes CO to trigger flowering, while CRY2 acts in the afternoon to prevent CO degradation via COP1, thus contributing to CO stability [86,90]. These findings explain the earlier flowering of okra under red light compared to blue light in short-day conditions. Our results are consistent with observations in the short-day plant Sorghum, where phyB mutations lead to early flowering [91]. Similar patterns have been reported in Kalanchoe *blossfeldiana*, a typical short-day plant, where red light significantly accelerated flowering, whereas blue light caused delays [34]. It can therefore be assumed that under SD conditions in SD plants, the tripartite complex PhyB-PHL-CO allows FT to be activated more efficiently than CRY2. The intermediate response to R3B3 could result from the activation of FT by red light via the PhyB–PHL–CO complex, while blue light has a weaker effect via CRY2 in short days. In contrast to the results of Hamamoto and Yamazaki [33], red light delayed flower bud formation and opening more than blue light in okra in long days. This suggests that the effects of phytochromes and cryptochromes on flowering are photoperiod dependent. A better understanding of flowering mechanisms in okra requires in-depth research on the interaction between light photoreceptors and flowering genes, particularly in response to different photoperiods. Furthermore, fruit diameter one day after petal fall was significantly larger in plants exposed R3B3 (6.6 mm) treatment than in those exposed to only B (5 mm) or R (3.8 mm) treatment (see Figure 6D). This could be due to the synergistic effect of alternating exposure to both wavelengths, which stimulates growth more effectively than monochromatic exposures, in agreement with the results of Cho et al. [92] Nevertheless, all LED treatments produced fruits with smaller diameters than those observed in the control groups (12.9 mm outdoors and 10.3 mm greenhouse), likely due to the greater vigor of the control plants.

5. Future Directions

Blue light (B) is known to promote flowering in long-day plants and inhibit it in short-day plants [93]. Our results confirm this, as okra showed delayed flowering under blue light compared with red light in SD conditions, suggesting a complex regulatory process involving multiple factors [14]. Although blue light improves okra biometric traits, its inhibitory effect on flowering poses challenges for practical applications. Further research is needed to clarify the role of blue and red light on flowering genes in okra and to optimize their use. A well-balanced light spectrum could support okra cultivation under a 10 h photoperiod, accelerating flowering and fruiting. Similar approaches in SD soybean have led to compact plants flowering in 23 days and maturing in 77 days, allowing up to five generations per year [94].

This study highlights the benefits of growing okra in controlled environments, particularly the ability to regulate external factors. However, it focused solely on LED light treatments, with variations in spectrum, intensity, and photoperiod, without experimentally

addressing other key factors such as temperature, relative humidity, or CO_2 concentration, despite their known impact on plant development [95]. Notably, these environmental parameters differed between LED and control treatments, which likely contributed to the observed variations in growth and morphophysiological responses. Future research should therefore include these variables to assess their combined effects on okra development under controlled conditions and help optimize indoor cultivation strategies.

6. Conclusions

Okra is a tropical vegetable of great economic interest in many countries. Its cultivation under artificial LED lighting offers significant potential, as it allows for overcoming seasonal cycles and controlling growth, flowering, and fruiting with optimal energy efficiency.

Our study, which can be cited as a reference, highlights the potential of LED lighting to modulate okra development under controlled conditions, from growth to flowering.

Alternating red and blue light improved germination as well as the number of leaves and nodes; however, overall vegetative and reproductive growth remained higher in the control group under broad-spectrum natural light. The delayed flowering observed under LED treatment with 14 h photoperiods for 30 days confirms okra's sensitivity to daylength. Red light was more effective for flower bud initiation and flowering.

These results clearly demonstrate that okra flowering can be modulated by adjusting the light spectrum and photoperiod.

Future studies focused on optimizing artificial LED lighting and the molecular mechanisms of flowering will contribute to the implementation of lighting strategies for sustainable and economical okra production. Studies on indoor cultivation under artificial lighting must, therefore, necessarily involve adapting various parameters to achieve an optimal balance between plant morphology, yield, and energy efficiency.

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