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Full Length Research Paper

Three Types of Cannabis Sativa L. are Affected by LED Light in Terms of Their Cannabinoid Content, Physiological Characteristics, and Plant Architecture

Henry and Oliver

Harvard University, Massachusetts, USA

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Development and the biosynthesis and storage of secondary metabolites are affected by changes in the light spectrum. This study sought to ascertain how two light sources affected the physiological and yield characteristics of three C. sativa cultivars grown in greenhouses. During the vegetative period, two light sources—LED1 (100 percent white) and LED2 (90 percent red, 8% blue, and less than 1 percent far red)—were applied to the non-psychoactive varieties of Calotoweed, Higthcol, and Souce Cauca. Plant height (4%–26.7%), leaf area (21%–55%), and shoot dry mass (1.9%–30.3%) all decreased under LED2, although biomass was distributed more toward the inflorescences (40.1%–51.6%). The type of light has no discernible impact on the relative amount of chlorophyll. Comparing all three types cultivated under LED2 to plants grown under LED1, decreases were noted in stomatal conductance (4.7%–27.4%), PSII quantum efficiency (1%–11.7%), and electron transport rate (9.2%–15.8%). The dry flower output of the various light kinds and cultivars did not differ much. In comparison to LED2, greater CBD levels (11.9%–13.4%) and CBD per gram of inflorescence (12.9–13.8 g/inflorescence) were noted under LED1. THC concentrations were greater in the Calotoweed (0.5%) and Soucecauca (0.6%) types grown under LED2 than in the plants grown under LED1. These findings show that LED2 altered the canopy architecture, producing more compact plants with higher biomass accumulation in the inflorescence. Nevertheless, these plants showed limitations in photosynthetic capacity, which led to a decrease in CBD synthesis and an increase in THC production. In summary, the type of light altered the architecture of the plant and had an impact on photosynthetic performance as well as the production of THC and CBD.

Keywords: Canopy architecture, Biomass accumulation, Inflorescences, Photosynthetic performance, Cannabinoids

INTRODUCTION

Cannabis sativa L. is a multifunctional plant that produces secondary metabolites utilized in industry and medicine from its aerial parts, particularly the flower (Tang et al., 2016). Terpenes, flavonoids, and more than 125 cannabinoids are among the more than 500 secondary metabolites that have been found (Radwan et al., 2021). The psychoactive component of these cannabinoids is D9-tetrahydrocannabinol (THC), whereas the non-psychoactive

components are cannabidiol (CBD) and cannabinol (CBN) (Aizpurua-Olaizola et al., 2014). Commercial C. sativa cultivation takes place indoors or in greenhouses, where production cycle conditions like light and humidity are regulated (Eichhorn Bilodeau et al., 2019). The goal of this management is to give the C. sativa plant the best conditions possible so that it can produce the most flowers possible and produce a cannabinoid.

Profile in accordance with business objectives, which together establish the caliber of the product grown from this plant (Backer et al., 2019). Since light is one of the main signals that plants sense and affects their physiology, it is one of the most significant environmental elements (Li et al., 2021). Because they regulate the basic processes for plant development, namely photosynthesis and photomorphogenesis, light characteristics like intensity, wavelength, and exposure time or photoperiod have physical impacts (Ouzounis et al., 2015).
With the use of photoreceptors, plants are able to recognize variations in the light spectrum. These include, among others, cryptochromes and phototropins, which perceive blue light, and phytochromes, which perceive red/far-red light (Paik and Huq, 2019).
Photomorphogenesis, or the impact of light quality on plant development and physiology, is influenced by the spectrum and intensity of light. It controls processes like the change from vegetative to reproductive states, elongation growth, stomatal conductance, leaf expansion, and secondary metabolism (Pennisi et al., 2020). Consequently, the light has a major impact on both physiological performance and yield.

Range of environmental conditions for the plant (Hogewoning et al., 2010). The plant's photosynthetic system can be directly impacted by environmental stressors such light intensity and quantity, as well as photoperiod, which can change the electron transport chain's activity (Long et al., 2015). Reactive oxygen species (ROS), which are hazardous in high quantities and cause lipid peroxidation of cell membranes, accumulate as a result of these changes, which lower the effectiveness of the photochemical reaction (Bayat et al., 2018). When plants are exposed to adverse light circumstances, both in terms of intensity and quality, their growth is delayed because they must adapt to the new environment in order to survive (Li et al., 2014). Plants' power to regulate photosynthetic activity is linked to their ability to adapt to changes in their environment (Demura and Ye, 2010).
Artificial lights like light-emitting diodes (LEDs), which have just begun to be utilized in greenhouse horticulture, have several benefits, including low energy consumption, extended lifespan, and narrow spectral output (Wei et al., 2021). Plant shape, metabolism, and blooming are all affected by light spectrum manipulation (Wang et al., 2016). In addition to affecting chloroplast development, chlorophyll production, and enzyme synthesis, blue light lengthens internodes and controls how the body reacts to stress (Magagnini et al., 2018; Chen et al., 2021).

Additionally, it regulates the expression of genes that improve the electron transport rate (ETR) and PSII's maximal quantum efficiency (Fv/Fm) in plants like Solanum lycopersicum (Wu et al., 2014). Photomorphogenesis, leaf nutrition, stem growth, and flowering-related activities are all regulated by red light (Eichhorn Bilodeau et al., 2019). Research on the effects of various light wavelengths on C. sativa plant growth, development, and cannabinoid production has been done (Llewellyn et al., 2022; Danziger and Bernstein, 2021a). Depending on the species and cultivar, changes in the light spectrum might cause different reactions in secondary metabolite biosynthesis and storage as well as in development (Amrein et al., 2020; Danziger and Bernstein, 2021a; Arora. and Yun, 2023). Increased UV radiation intensity can cause changes in the plant's morphology, a reduction in the dry mass of inflorescences, and a drop in the content of cannabinoids (Rodriguez-Morrison et al., 2021; Lle-wellyn et al., 2022). The light spectrum is not the only external element that might affect variation in the manufacture of secondary metabolites in cannabis (Gorelick and Bernstein, 2017). Higher light intensity has been shown to increase inflorescence biomass in terms of photosynthetic photon flux densities (PPFD) (Eaves et al., 2020; Llewellyn et al., 2022; Li et al., 2023). Furthermore, cannabis concentration is increased by low nitrogen concentration in the inflorescences and decreased by greater nitrogen levels (Saloner and Bernstein, 2022b; Song et al., 2023). Additionally, low phosphorus levels in the plant (Cockson et al., 2020; Shiponi and Bernstein, 2021) and low potassium levels in the plant both raise cannabis concentrations (Saloner and Bernstein, 2022a). Similar findings have been made with indoor (Danziger and Bernstein, 2022) and outdoor (da Silva Benevenute et al., 2022) production, where increasing planting density from 1 to 2 plants/m2 decreases cannabinoid concentration per plant but increases yield per unit area. Plant architecture can be altered by cutting off primary and secondary branches, which raises the concentration of cannabinoids in the lower sections of the plant and increases their homogeneity across the plant (Danziger and Bernstein, 2021b; 2021c).
Artificial lighting is utilized in greenhouse systems to enhance development and attain greater yields of dry flowers and cannabinoid content. Still, not enough research has been done to provide a thorough understanding of how C. sativa plants react to supplemental light sources in terms of development and yield during the vegetative stage. Research that produces data regarding the effects of various light spectra on the growth, development, and yield of C. sativa plants grown in greenhouses is essential.

Circumstances. Using two distinct LED light sources, we examined how three non-psychoactive strains of Cannabis sativa L. responded to variations in the light spectrum composition throughout the vegetative growth phase, with an emphasis on growth and cannabinoid content. Finding out how two LED light sources affected the physiological parameters and yield of three non-psychoactive C. sativa varieties during the vegetative period was the goal of this study.

2. Materials and methods

2.1. Plant material and experiment setup

In a greenhouse at "El Candil Farm," La Conejera, Bogota´, Colombia (4°47002.6" N 74°06009.8" W), the study was carried out. The average temperature was 16.7 °C, the relative humidity was 75.4%, and the average daily light integral (DLI) was 16.7 mol m—2 day—1. At four weeks of age, plants were taken from rooted cuttings and planted at a density of four plants per square meter. Based on soil analysis and plant requirements as stated by Cockson et al. (2019), with some modifications, the plants were grown in soil that had the following characteristics: black color, loam-silt texture, fine to medium granular structure, and a pH of 6.1. Throughout the cultivation cycle, fertilization was carried out using a drip irrigation system three days a week. Pruning and phytosanitary management were done in accordance with standard procedures for greenhouse production of C. sativa.
An experimental unit of 25 plants and five replicates were employed in a split-plot design using randomized complete blocks. Two LED light sources, LED1 (48 30 W bulbs, 6500 K 100% white light, Sylvania, Toronto) and LED2 (48 13 W bulbs, 90% red, 8% blue, <1% far red, a high red proportion, and a lower blue:red ratio Phillips, Amsterdam), made up the main plot. Three types of medical Cannabis sativa L. were present in the subplots: Souce Cauca (SC), Higthcol (HC), and Calotoweed (CW). To avoid light contamination, the experiments with the various light sources were divided by black plastic curtains. In order to create an 18/6 h light/dark photoperiod during the vegetative phase (from planting to 43 days after planting), the lights within the greenhouse were turned on from 18:00 to 0:30. In order to get a 12/12 h light/dark photoperiod from natural sunshine, the lights were then switched off. The light sources were positioned three meters apart and 2.40 meters above the plant canopy.

2.2. Growth parameters

From the base of the stem to the apical branch, the height of the plant (n=15) was measured. ImageJ® software (National Institutes of Health (NIH), Maryland) was used to calculate the leaf area (n=15). By dividing the plant into its stem, lateral branches, leaves, and flowers (n=15), the dry weight of the shoot was ascertained. Each component was then baked at 70 °C until a consistent weight was reached. Measurements of plant height were made 20, 35, 50, 65, and 95 days after planting (dap), while measurements of the aboveground portion's dry mass and leaf area were made at 20, 60, and 95 dap.

2.3. Photosynthesis associated parameters

A SPAD-502 plus chlorophyll meter (Konica Minolta, Osaka, Japan) was used to assess the relative chlorophyll content (RCC) by taking five measurements on fully grown leaves on the second branches of the plants (n=15). A Decagon SC-1 leaf porometer (Decagon Devices, Inc., Pullman, Washington) was used to measure stomatal conductance (gs). Using a pulse amplitude-modulated fluorescence analyzer (JUNIOR-PAM, Walz, Germany), parameters pertaining to chlorophyll fluorescence, electron transport rate (ETR), and maximal potential photosystem II quantum yield (Fv/Fm) were measured between 9:00 and 11:00 a.m. Before beginning the measurements, the leaves were dark-adapted for half an hour using leaf clips. Actinic light was then used to stimulate chlorophyll molecules for 0.8 seconds at a photosynthetic photon flux density (PPFD) of 2000 mmol m—2 s—1. A fully developed leaf from the upper part of the plant was used to measure these variables. At days 20, 35, 50, 65, 80, and 95 dap, measurements were made.

2.4. Yield

When 30% of the trichomes were amber in color and 50% +1 of the population's apical inflorescence pistils were brown, the harvest time was determined. The fruitful branches of each plant were chopped off and dried in a drying room with a temperature of 19 °C and 40% relative humidity until the moisture content reached 9%. Branches were destemmed after drying, and the dry flower weight per plant was used to calculate the yield. For each treatment, 15 plants were used to measure this variable.

2.5. Total cannabinoid content

Thirty grams of inflorences were harvested (n=15), and the amount of cannabinoids was measured. A GemmaCert Lite potency analyzer (GemmaCert, Germany) was used to measure the amount of cannabidiol (CBD) and D9-tetrahydrocannabinol (THC) in the dried inflorescences after they had been ground manually in a plastic grinder. The percentage (%) of the inflorences' total dry weight is used to represent the content.

2.6. Data analysis

R software was used to perform the statistical analysis (R Core Team, 2018). To determine the combined influence of light, plant material, and time, statistical comparisons between treatments were conducted using a three-way analysis of variance (ANOVA) and a repeated measures analysis for the variables measured over time. The standard error bars criterion, as outlined by Cumming et al. (2007), served as the foundation for the interpretation and discussion of interactions. Lastly, a one-way ANOVA was conducted for yield factors in terms of dry flower and total cannabis content. For mean comparisons, Tukey's post hoc test was employed ($p < 0.05$).

3. Results

The combined influence of lighting (L), variety (V), and time (T) as a result of their interactions is shown in Table 1. The height variable was found to have multiple interactions with

the following factors: lights by time LxT, variety by time VxT, and variety by lights VxL. For the leaf area variable, two interactions between the factors lights and time LxT were found. For the stem and branch dry weight variables involving the variety by time VxT components, double interactions were found. Lastly, multiple interactions for the variety by time VxT and lighting by time LxT factors were found for the leaf dry weight and shoot dry weight variables. For the relative chlorophyll content variable, the lights by time VxLxT variables identified three interactions. For the electron transfer rate and stomatal conductance variables involving the variety by time VxT factors and lighting by time LxT factors, double interactions were found. Meanwhile, the lights by time LxT interaction was found for the PSII quantum yield variable. As a result, the study relied on graphical representations of the interactions and did not interpret the p-value of the main effects implicated in the interactions.

3.1. Growth parameters

The VxL and VxT interactions showed that variations in plant height happened throughout time, both within and between varieties, as well as within the lights factor. While CW (23.2 cm - 133.1 cm), HC (16.2 cm - 137 cm), and SC (18.8 cm - 144.6 cm) were taller between 20 dap and 95 dap, plants under LED2 showed shorter heights than those under LED1 (Fig. 1A). In the LED2 treatment at 95 dap, the variety with the smallest height was CW. Furthermore, under LED2, the length growth rate per week was 2 cm slower than under LED1. Under both LED2 and LED1, variety SC was higher (122.7 cm - 144.6 cm) than types CW (113.3 cm - 133.1 cm) and HC (121.9 cm - 137 cm). In the LxT interaction, variations in leaf area across time within the lighting factor were observed. While CW (333 cm2 - 7042 cm2), HC (446 cm2 - 8625 cm2), and SC (303 cm2 - 5549 cm2) showed bigger leaf areas, those grown under LED2 between 20 dap and 95 dap had smaller leaf areas than those developed under LED1 (Fig. 1B). Variety HC under LED1 had the biggest leaf area (8625 cm2) at 95 dap, while variety CW under LED2 had the smallest leaf area (3756 cm2).

3.2. Dry weight and biomass allocation

The VxT interaction shows that variations within the variety factor happened throughout time in both stem and branch dry weight. Plants produced under LED2 weighed less than those growing under LED1 starting at 20 dap. Under LED2, the stem dry weight was lower at 95 dap than under LED1, where the varieties' greatest dry weights were 42.4 g for SC, 36.7 g for HC, and 23.2 g for CW (Fig. 2A). Compared to plants produced under LED1, those grown under LED2 between 20 and 95 dap showed decreased branch dry weight in CW (0.1 g — 19.2 g) and SC (0.1 g — 62.8 g) (Fig. 2B). Out of the three varieties, variety HC had the greatest branch dry weight value (79.8 g) under LED1 at 95 dap. For leaf dry weight, double interactions VxT and LxT were seen, suggesting that variations were impacted by the time within the lights factor and between the variety factor. Compared to LED1 (Fig. 2C), the harvested dry weight under LED2 was lower for CW (1 g — 40.8 g), HC (1.3 g - 84.3 g), and SC (1.3 g - 99.7 g) between 20 and 95 dap.

Double interactions VxT and LxT were seen in the shoot dry weight, suggesting that the time effect within the lights factor and between the variety factor were responsible for the variations. In contrast to plants under LED1, plants under LED2 showed decreased shoot dry weight between 20 and 95 dap. The weights of CW (4.1 g — 162.7 g), HC (3.7 g — 256.3 g), and SC (5.8 g — 252.5 g) were higher (Fig. 2D). Variety HC exhibited the largest weight (256.3 g) under LED1 at 95 dap, while variety CW displayed the lowest weight (93.4 g) under LED2 (Fig. 2D).
Plants grown under LED2 and those cultivated under LED1 showed different biomass allocation, especially in the distribution of biomass across stems, leaves, and inflorescences. In comparison to LED1, a greater percentage of weight in the stems was seen under LED2 in CW (11.7%), HC (12.8%), and SC (14.04%).
Differences across kinds were noted, however there was no light effect on the dry weight distribution in the branches. Of the varieties under LED2 and LED1, variety HC had the greatest value (25.6%). The distribution of dry weight in the leaves showed the impact of the light type. CW (19.1%), HC (11.3%), and SC (8.5%) all had higher values under LED1 than under LED2. Lastly, under LED2, the flowers in CW (51.6%), HC (40.1%), and SC (45.5%) had the largest distributions of dry weight (Fig. 2E). While all three types showed a larger distribution of dry weight toward the inflorescences, under LED2, CW (194.4 g) and HC (295.6 g) showed lower shoot dry weight (Fig. 2F) than plants under LED1, while HC (399.7 g) and SC (391.8 g) showed higher values. Out of all the treatments and varieties, variety HC under LED1 had the greatest shoot dry weight.

3.3. Relative chlorophyll content and stomatal conductance

Under both light treatments, variety HC had a greater value from 20 dap (43.6 SPAD) to 95 dap (62 SPAD) than varieties CW and SC, according to the triple interaction VxTxT in the CRC (Fig. 3A). In comparison to variants SC and HC, variety CW exhibited the lowest RCC in both light treatments, varying between 3.2% and 37%. Double interactions VxT and LxT were noted for gs, where variations in the lighting factor and variety factor were caused by the time effect. Higher values for CW (1082.9 mmol H2Om—2s—1–729.3 mmol H2Om—2s—1), HC (994.2 mmol H2Om—2s—1–812.2 mmol H2Om—2s—1), and SC (962.8 mmol H2Om—2s—1–791.6 mmol H2Om—2s—1) were found in plants cultivated under LED1 from 50 daps to 95 daps (Fig. 3B).

3.4. Chlorophyll fluorescence parameters

The maximum quantum efficiency of PSII was found to have a double interaction LxT. Compared to plants produced under LED1, plants grown under LED2 showed noticeably

lower Fv/Fm values at 20 dap, 35 dap, 65 dap, 80 dap, and 95 dap. Compared to plants produced under LED1, the values of plants cultivated under LED2 are 2.7% to 5.9% higher at 50 dap. In both light treatments, SC outperformed cultivars CW and HC in terms of Fv/Fm (0.7) at 95 dap under LED1 (Fig. 3C). Variations in the variation factor for the double interaction VxT for ETR were observed throughout time. Compared to LED1, ETR was substantially reduced under LED2 between 35 and 95 dap (Fig. 3D). Compared to the other types in both LED2 and LED1, SC showed the greatest ETR values (24.64–24.5) at 65 dap and 80 dap.

3.5. Flower yield per plant and cannabinoid content

For every variety examined, flower output was unaffected by the type of light (Fig. 4A). Under both light treatments, the average bloom output for all cultivars was 90 g/plant. However, the amount of THC and CBD was impacted by the type of light. Under LED1, HC had the highest value (15.6%), and under LED2, CW had the lowest value (11.3%) (Fig. 4B). In comparison to plants produced under LED1, SC displayed a considerably higher THC value under LED2 (0.6%) (Fig. 4C). It was observed, nevertheless, that the THC concentration of HC and SC was the same in both light treatments (0.2%). The highest THC level (0.4%) for CW was found under LED1, whereas the highest THC value for SC was found under LED2. CBD concentration in g/inflorescence was higher under LED1 than under LED2, with values ranging from 16.1% to 18.4%. However, across all light treatments, no discernible differences between the HC and SC cultivars were seen (Fig. 4D).

4. Discussion

LED lights have recently been used more often as regulated artificial lighting for crops in an effort to increase yields. This study described how a commercial Cannabis sativa L. crop grown in a greenhouse was affected physiologically by an LED2 source applied during the vegetative phase.

The findings demonstrated that C. sativa plants' physiological performance under LED2 differed from that of plants produced under LED1. The plants cultivated with LED2 showed a decline in leaf biomass (Fig. 2C) and height (Fig. 1A). Flower yield was unaffected by light type (Fig. 4A). However, plants grown under LED2 showed a change in cannabinoid content, with a drop in CBD and an increase in THC (Figs. 4B and C). Consequently, the architecture, biomass distribution, leaf area, and secondary metabolite synthesis of plants were all impacted by the type of light that was supplied during the vegetative phase.
In comparison to plants cultivated under LED1 (Fig. 1A), plants grown under LED2 showed a 2 cm decrease in weekly elongation rate, which led to shorter heights from 20 dap to 95 dap.

The CW variation was the shortest, measuring between 17 and 113 cm. The recognition and control of signals in photoreceptors, such as phytochromes, produced by variations in light, resulted in an inhibition of stem elongation (Liu et al., 2018). Through transcriptional regulation and post-translational modification, phytochromes send signals to phytochrome interacting factors (PIFs), which control the expression of genes involved in auxin (Aux) production (Luo and Shi, 2019). Additionally, by preventing the production of gibberellin (GA), cryptochromes control processes related to photomorphogenesis. This is because cryptochromes prevent DELLA proteins from degrading by blocking ubiquitination (Xu et al., 2021). In the meantime, by altering the direction of cortical microtubules, ethylene prevents elongation and encourages lateral growth of intercalary meristematic cells of the stem and epidermal cells (Wie et al., 2016). By controlling gene expression, red light influences ethylene biosynthesis and speeds up ethylene production (Wang et al., 2022). Lalge et al. (2017) discovered similar outcomes in Tagetes erecta, Calibrachoa £ hybrida, Pelargonium £ hortorum, C. sativa plants, and Petunia £ hybrida (Gautam et al., 2015).
Additionally, C. sativa plants cultivated under LED2 showed changes in leaf morphology. Compared to plants cultivated with LED1 (333 cm2 — 8625 cm2), plants treated with LED2 showed a reduced leaf area (209 cm2 — 5549 cm2) (Fig. 1B). It has also been noted that Solamun lycopersicum, Platanus orientalis plants (Arena et al., 2016), and C. sativa plants (Lalge et al., 2017) exhibit decreased morphological traits like height and leaf area when exposed to LED2. By altering cellular structure in response to environmental changes, photoreceptors control light-dependent growth, also known as photomorphogenesis, which results in morphological alterations (De Carbonnel et al., 2010). Due to overexcitation of phytochrome, the rate of cell elongation and expansion reduces in environments with a large proportion of red light and a very low proportion of far-red light (Danziger and Bernstein, 2021a). Moreover, phytochrome controls how plants react to light, including by inhibiting petiole and internode elongation, when the R:FR ratio is high (Su et al., 2017). This is because the two types of phytochrome have a photo-balance that controls elongation growth and shade avoidance responses, which decreases as the R:FR ratio rises (Zhang et al., 2020).
Due to the decrease in plant height, leaf area (Fig. 1A-B), and shoot dry weight (Fig. 2D), C. sativa plants cultivated under LED2 showed a more compact canopy. Danziger and Bernstein (2021) reported similar outcomes for C. sativa plants. Therefore, a morphological change linked to phytochrome activity, which also controls leaf growth, can be linked to canopy compaction in C. sativa plants exposed to LED2 (Claypool and Lieth, 2021). According to Miao et al. (2016), a higher concentration of red light causes a decrease in biomass and leaf area, changing the plant architecture to one that is more compact.

Because of the decreased biomass accumulation in vegetative structures such stems, branches, and leaves (Fig. 2E), C. sativa plants produced under LED2 had lower shoot dry weight than plants grown under LED1 (Fig. 2A-F). Comparable findings have been reported for Spinacia oleracea (Vitale et al., 2020), Petunia £ hybrida (Gautam et

al., 2015), and C. sativa plants (Wei et al., 2021). Thus, biomass allocation is linked to the light spectrum's influence on C. sativa plants; under LED2, more biomass was allocated to flowers, while under LED1, more biomass was allocated to vegetative structures (Fig. 2E). Through signaling pathways, phytochrome controls the distribution of photoassimilates, resulting in increased carbohydrate accumulation in shoot organs (Claypool and Lieth, 2021; Islam et al., 2021). As demonstrated by Kim et al. (2018) in S. lycopersicum plants, a greater percentage of red light is thought to boost biomass allocation towards reproductive structures at the expense of vegetative structures, according to the results given.
Plant photosynthetic performance is impacted by changes in light amount and quality, which ultimately results in changes in growth (Islam et al., 2021). Several factors related to photosynthetic performance were assessed in this study. There was no discernible impact of light type on relative chlorophyll content (RCC), which is in line with findings from studies on C. sativa (Danziger and Bernstein 2021) and S. tuberosum (Chen et al. 2021). Varieties were found to differ in RCC, with HC exhibiting the highest RCC and CW the lowest (Fig. 3A). Blue light, which controls chlorophyll growth through cryptochrome activation, is present in the two treatments used in this investigation (10% blue in LED2 and 30% blue in LED1) (Wang et al., 2016; Li et al., 2021). Furthermore, blue light stimulates stomatal opening and chlorophyll biosynthesis by activating phytotropins (Boccalandro et al., 2012). Chlorophylls are not a limiting factor for photosynthetic activity in C. sativa plants under this sort of light during the vegetative phase, according to this study's observation that LED2 has no effect on chlorophyll production. In comparison to plants under LED1, a decrease in stomatal conductance was noted in plants under LED2 starting at 35 dap (Fig. 3B). Nevertheless, as previously noted by Danziger and Bernstein (2021), these values stay over 400 mmol H2O m—2 s—1, suggesting that stomatal restriction of photosynthesis is not present in C. sativa plants. It is significant to remember that the light treatment used in this study was paired with 12 hours of daily exposure to natural sunlight. The duration of the artificial light (6 hours) had no effect on these metrics.
C. sativa plants under LED2 showed a decrease in Fv/Fm compared to plants under LED1, despite the absence of stomatal restriction (Fig. 3C). This suggests that Fv/Fm was impacted by only 6 hours of light exposure. Lower PSII quantum efficiency values were found in plants subjected to a stronger red light spectrum, which was also the case for plants growing under continuous exposure to higher amounts of red light (Hogewoning et al., 2010; Wang et al., 2022). Triticum spp. (Yano and Fujiwara, 2012), Lactuca sativa (Muneer et al., 2014), and C. sativa plants (Khajuria et al. 2020) have all been shown to exhibit this same influence on PSII quantum efficiency. These findings imply that under strong red light circumstances, plants' ability to adapt their photosynthetic system for CO2 fixation is restricted (Landi et al., 2020). A reduction in the rate of electron transport and modifications to the PSI and PSII multiple component protein complexes may be linked to the decline in photosynthetic rate (Miao et al., 2016). Comparatively speaking, C. sativa plants grown under LED2 had a slower rate of electron transfer than plants grown under LED1 (Fig. 3D). According to research, blue light is more important than red light for preserving electron transport and PSII and PSI photosystem activity (Bayat et al., 2018). As a result, under LED1, both photosystems were excited in balance, which increased PSII's electron transport efficiency (Ji et al., 2019). As seen in plants exposed to LED2, variations in the spectral composition of light impact photochemical efficiency. Similar results were observed in Brasenia schreberi plants (Li et al., 2021), which showed poorer photochemical efficiency values under red/blue light conditions than under LED1.
There were no discernible variations in flower yield between types or between light treatments (Fig. 4A). According to earlier research, LED2 changed the distribution of photo-assimilates in C. sativa plants, which led to a greater biomass allocation towards the inflorescences (Fig. 2E-F) (Wei et al., 2021). But compared to plants grown under LED1, these plants were shorter in height and had a lower total dry weight (Fig. 1A-Fig. 2E). As a result, the light treatments had comparable dry weights since this biomass allocation was produced at the expense of vegetative growth. Therefore, processes linked to the regulation of photosynthetic activity and the morphological traits of plants are stimulated by altering the light spectrum, specifically the ratio of blue to red light. The imbalance in photoreceptor activity caused by these alterations affects yield (Landi et al., 2020; Izzo et al., 2020; Danziger and Bernstein, 2021a). Khajuria et al. (2020) found similar outcomes in C. sativa plants.
In terms of CBD content, plants under LED2 accumulated less CBD per gram of dry flower than plants under LED1 (Fig. 4D) in CW. One possible explanation for this lower CBD concentration is that plants showed photosynthetic limits under LED2 (Fig. 3C-D). Previous studies have documented the impact of light on the synthesis of cannabinoids in C. sativa plants (Namdar et al., 2019; Khajuria et al., 2020; Danziger and Bernstein, 2021a). LED2 contains less blue and far-red light, which affects secondary metabolite synthesis and raises the content of CBD in plants (Magagnini et al., 2018; Islam et al., 2021). Conversely, both THC and CBD are cannabinoids with antioxidant properties; however, THC only contains one hydroxyl group in its chemical composition, whereas CBD has two, making it more powerful in scavenging free radicals. Because it protects the photosynthetic system, CBD may therefore be linked to the photosynthetic efficiency seen in plants grown under LED1 (Hacke et al., 2019).
Compared to plants produced under LED1, CW and SC plants cultivated under LED2 had greater THC levels, at 0.5% and 0.6%, respectively (Fig. 4C). Islam et al. (2021) and Namdar et al. (2019) found similar outcomes with C. sativa plants. The suppression of energy absorption, energy trapping, and electron transport in PSII and PSI has been linked to the high THC content of C. sativa plants (Khajuria et al., 2020). The CW and SC strains under LED2 were found to have the highest THC concentrations in this investigation, and they also showed the lowest ETR values.

This implies that the amount of THC has an impact on how well the photosynthetic system functions. Additionally, even though the THC level of plants grown under LED2 was larger than that of plants grown under LED1, it was still under the 1% allowed limit for Colombian non-psychoactive C. sativa plants (Ministerio de Salud y Proteccio´n social, 2021).

5. Conclusion

The growth and development of C. sativa plants in all three assessed cultivars changed as a result of LED2 exposure. During the vegetative phase, morphological and physiological changes were caused by changes in the light spectrum composition for six hours each day. The reason for the shift in reactions is that LED2 modifies photoreceptor signals, which limits the photosynthetic apparatus. The transfer of photoassimilates was affected by this photosynthetic constraint, which resulted in a greater allocation to the aerial portions, particularly the inflorescences. The canopy architecture of C. sativa plants cultivated under LED2 was changed, becoming more compact than those grown under LED1, due to the disruption of photoreceptor signals, the restriction on the photosynthetic machinery, and the buildup of photoassimilates. Additionally, there was a change in the synthesis of secondary metabolites, which led to a higher THC level and a lower CBD content.
Increased growth and a more open canopy structure were observed in the plants under LED1, which is linked to improved photosynthetic performance and a rise in photoassimilation. It was shown that HC and SC had the highest growth among the cultivars under LED1, however there were no variations in bloom production when compared to CW. Under LED2, it was discovered that the SC variety had the maximum THC level, followed by the CW variety. In this study, C. sativa plants exposed to LED1 for 6 hours during the vegetative phase had higher CBD content, while plants exposed to LED2 were more compact, which may increase planting density and enhance management during applications and pruning. The influence of THC concentration in the C. sativa cultivars under study must be taken into account because it may be linked to restrictions on plant growth and development.

Declaration of generative AI in scientific writing

In the process of preparing this work, author Julian Eduardo Carranza translated the material using Chatgpt. The authors took full responsibility for the publication's content after utilizing Chatgpt, reviewing and editing it as necessary.

Declaration of competing interest

The following financial interests and personal connections are disclosed by the authors and could be viewed as possible conflicts of interest:
According to Julian Eduardo Carranza, Medcolacanna supplied the funding. According to Julian Eduardo Carranza, Medcolcanna has a connection with them that involves sponsoring awards. Other authors, if any, affirm that they have no known conflicting financial interests or personal ties that might have seemed to have an impact on the work described in this publication.

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Table 1
Significance for the sources of variation (SF) in the ANOVA for the height (H), leaf area (LA), and shoot biomass variables: dry stem weight (STDW), dry branch weight (BDW), dry leaf weight (LDW), and shoot dry weight (SDW), on relative chlorophyll content (RCC), stomatal conductance (gs), PSII quantum yield (F_v/F_m), and electron transfer rate (ETR).

SF	H	LA	STDW	BDW	LDW	SDW	RCC	gs	Fv/Fm	ETR
						p Value				
Varieties	<0.001	0.001	<0.001	<0.001	<0.001	<0.001	<0,001	0.567	<0,001	<0,001
Lights	<0.001	<0.001	0.143	0.085	<0.001	<0.001	0.456	0.055	<0.001	<0.001
Time	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
VxL	0.008	0.606	0.951	0.542	0.539	0.929	<0.001	0.856	0.263	0.528
VxT	<0.001	0.014	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	0.142	<0.001
LxT	<0.001	<0.001	0.161	0.121	<0.001	<0.001	<0.001	<0.001	<0.001	0.010
0.146	0.147	0.148	0.149	0.150	0.151	0.152	0.153	0.154	0.155	0.156

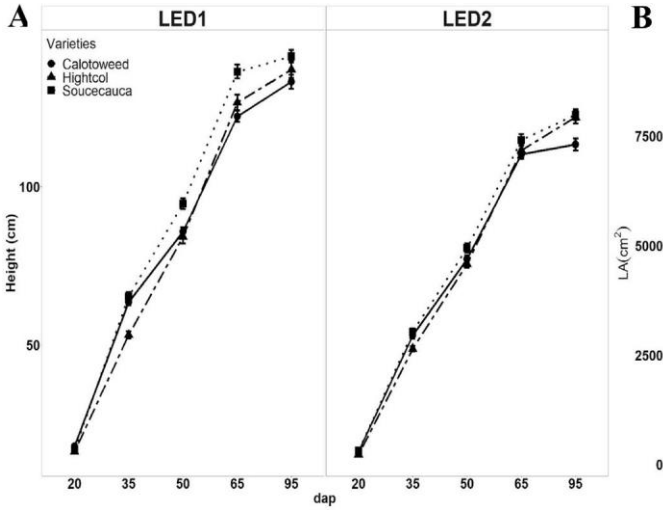

Fig. 1. Growth parameters of *Cannabis sativa* L. plants under two light conditions. A) Plant height and B) Leaf area of varieties Calotoweed (CW), Higthcol (HC), and Souce Cauca (SC) at 20, 35, 50, 65, and 95 days after planting (dap) grown under two LED light sources, LED1 (100% white light) and LED2 (90% red, 8% blue, <1% far red) in a greenhouse. The data presented are means of replicates § SD (n = 15). Vertical bars represent the standard error, and overlapping bars towards the center indicate interaction effects between time, treatments and varieties.