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Lighting supplementation in hop cultivation in a subtropical climate region

Abstract – The objective of this work was to evaluate the use of artificial lighting on the vegeto-productive and qualitative characteristics of hop (*Humulus lupulus*) cultivation. The experiment was conducted at the Ambev Santa Catarina Experimental Farm using a randomized complete block design with four replicates in a split-plot scheme, with and without light supplementation through LEDs with blue spectral peaks at 420 nm and red at 600-620 nm. The production cycle of the cultivars Cascade and Chinook took place from August 2021 to April 2022, in two harvest seasons. The following variables were evaluated: photosynthetically active radiation, chlorophyll index, leaf area, productive height, mean cone length and width, total dry cone mass, cone index per centimeter of branch, yield per hectare and linear meter, as well as α-acid, β-acid, and essential oil content. Data were analyzed using Principal Component Analysis. Light supplementation increased leaf area, nighttime light interception, and photosynthetic efficiency. In the Chinook cultivar, it promoted higher yields, greater α-acid content, and essential oil yield. The Cascade cultivar had better cone structure in the first harvest season. Light supplementation intensifies biosynthesis of key chemical compounds, positively regulating metabolic pathways. Supplemental lighting is an effective strategy to expand hop cultivation in subtropical regions, with gains in yield, chemical quality, and feasibility of year-round harvests.

Index terms: *Humulus lupulus*, artificial lighting, productivity, quality.

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Suplementação luminosa no cultivo de lúpulo em região de clima subtropical

Resumo – O objetivo deste trabalho foi avaliar o uso de iluminação artificial nas características vegeto-produtivas e qualitativas do cultivo de lúpulo (*Humulus lupulus*). O experimento foi conduzido na Fazenda Experimental Santa Catarina, pertencente à Ambev, utilizando um delineamento em blocos ao acaso com quatro repetições, em esquema de parcelas subdivididas, com e sem suplementação luminosa por meio de luzes LED com pico espectral azul em 420 nm e vermelho em 600-620 nm. O ciclo produtivo das cultivares Cascade e Chinook ocorreu entre agosto de 2021 e abril de 2022, com duas safras. Foram avaliadas as seguintes variáveis: radiação fotossinteticamente ativa, índice de clorofila, área foliar, altura produtiva, comprimento e largura média dos cones, massa seca total dos cones, índice de cones por centímetro de ramo, produtividade por hectare e por metro linear, bem como os teores de ácidos α, ácidos β e óleos essenciais. Os dados foram analisados por meio de Análise de Componentes Principais. A suplementação luminosa aumentou a área foliar, a interceptação de luz noturna e a eficiência fotossintética. Na cultivar Chinook, promoveu maior produtividade, maior teor de ácidos α e maior rendimento de óleos essenciais. A cultivar Cascade apresentou melhor estrutura de cones na primeira safra. A suplementação luminosa

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intensifica a biossíntese de compostos químicos-chave, regulando positivamente as vias metabólicas. A iluminação suplementar é uma estratégia eficaz para expandir o cultivo de lúpulo em regiões subtropicais, com ganhos em produtividade, qualidade química e viabilidade de colheitas ao longo do ano.

Termos para indexação: *Humulus lupulus*, iluminação artificial, produtividade, qualidade.

Introduction

Hops (*Humulus lupulus* L.) are essential in beer production, contributing significantly to the beverage aroma, flavor, and bitterness (Salem & Ibrahim, 2025). Traditionally cultivated in temperate regions between latitudes 35ºN and 55ºS (Hapi, 2019), hops are short-day plants that flower when day length falls below the critical photoperiod, ranging from 15 to 17 hours (Acosta-Rangel et al., 2024). Recently, interest in domestic production has grown in Brazil, as more than 99% of the hops used by breweries are imported, primarily from Germany and the United States (Brasil, 2022). Recent efforts to tropicalize cultivars, combined with the adoption of controlled-environment technologies such as artificial lighting, have enabled cultivation in subtropical regions including Santa Catarina, São Paulo, and Goiás (Leles et al., 2023). Despite the challenges related to photoperiod sensitivity and energy consumption, studies have demonstrated economic, social, and environmental benefits associated with local production (Tavares, 2018). These advances highlight the importance of developing adapted technologies to support sustainable hop cultivation in order to reduce the brewing industry reliance on foreign supply.

During the flowering process, light radiation is captured by phytochromes, which are photoreceptors that exist in two forms: red phytochromes (Pr) and far-red phytochromes (Pfr). Pr absorbs the red spectrum light from 620 nm to 700 nm, whereas Pfr absorbs the far-red spectrum from 710 nm to 850 nm (Taiz et al., 2017; Tripathi et al., 2019; Lei et al., 2024).

Phytochromes are photoreversible photoreceptors, meaning that the absorption of red spectrum converts Pr into Pfr, while the absorption of the far-red spectrum reverts Pfr back to Pr. During the nocturnal period, due to the absence of light, Pfr is gradually reverted to the Pr form (Taiz et al., 2017).

In hops and other short-day crops, exposure to long nights promotes the photoconversion of Pfr to Pr. Consequently, the ratio between Pfr and Pr is low at dawn, and this imbalance triggers the transcription of the *Heading Date 1* gene. The absence of this gene suppresses the *Heading Date 3* gene and activates the *Agamous Like-20* gene, which induces floral responses and activates the *Leafy* and *Apetala-1* genes, initiating the transformation of the vegetative meristem into a reproductive meristem (Taiz et al., 2017).

In this context, the photoperiod is a limiting factor for hop cultivation in Brazil, as the natural day length remains below 14 hours (Leles et al., 2023). In this scenario, the use of artificial supplementation with LEDs as a source of light radiation is a viable alternative to enable national hop production (Dou et al., 2017). This technology relies on exposing plants to artificial light radiation in order to extend the critical photoperiod (Carré et al., 2018), promoting vegetative development and inducing flowering, which consequently enhances yield indices (Silva, 2020).

The objective of this work was to evaluate the use of artificial lighting on the vegeto-productive and qualitative characteristics of hop cultivation.

Materials and Methods

The experiment was conducted at the Ambev Santa Catarina Farm experimental area, in the municipality of Lages, in the state of Santa Catarina, Brazil (27º49'42"S, 50º16'0"W at 922 m of altitude). The climate of the region is Cfb, according to the Köppen classification described as temperate, with mild summers, mean annual temperature of 14.3°C and mean annual rainfall of 1,480 mm (Cardoso et al., 2003). The soil in the experimental area is classified as a Cambissolo húmico alumínico (Santos et al., 2018), equivalent to a cambisol.

The experimental farm has a total area of 6,048 m^2, of which 864 m^2 were used for treatments with light supplementation (WL) and without light supplementation (WOL). In order to plant the seedlings imported by the Van De Bergen Nursery (Campinas SP, Brazil), a vertical V-trellis system with a post height of 4.50 m was used. Plants were spaced 1.0 m between plants and 4.0 m between rows, resulting in a population density of 2,500 plants per hectare.

The experiment followed a randomized complete block design arranged in a split-plot scheme with four replicates. The main plots consisted of the hop cultivars Chinook and Cascade. The subplots were defined by the light supplementation treatments WL and WOL.

The production cycle spanned from August 2021 to April 2022, enabling two distinct harvests (S1 and S2). S1 commenced on January 5, 2022, followed by S2 on April 7, 2022. The harvest point was determined based on the presence of brittle rachis, which indicates the ideal stage of cone maturity.

For light supplementation, the Irriluce Red-in-Blue Chip-on-Board LEDs (Fienile, Rio Maior, Portugal) with 100 W of power were used. These units feature a 120º angle lens and an aluminum housing with IP66 protection. The LEDs have been configured to emit light radiation with peaks in the blue (420 nm) and red (600–620 nm) regions of the spectrum, maintaining a red-to-blue ratio predominantly in favor of red. The LEDs were installed on the V-trellis system anchoring posts at a height of 4.5 m, with a spacing of 7.0 m between rows, and 12 m along the planting line.

The LEDs remained operational throughout the vegetative stage of the plants; their operation and positioning can be observed in Figure 1.

The capture of photosynthetically active radiation incidence per plant was performed using a LI-1500 Ceptometer (LI-COR Biosciences, Lincoln, NE, United States of America), to quantify the amount of light intercepted by the plant canopy in cmol m^{-2} s^{-1}. During the crop cycle, measurements were conducted

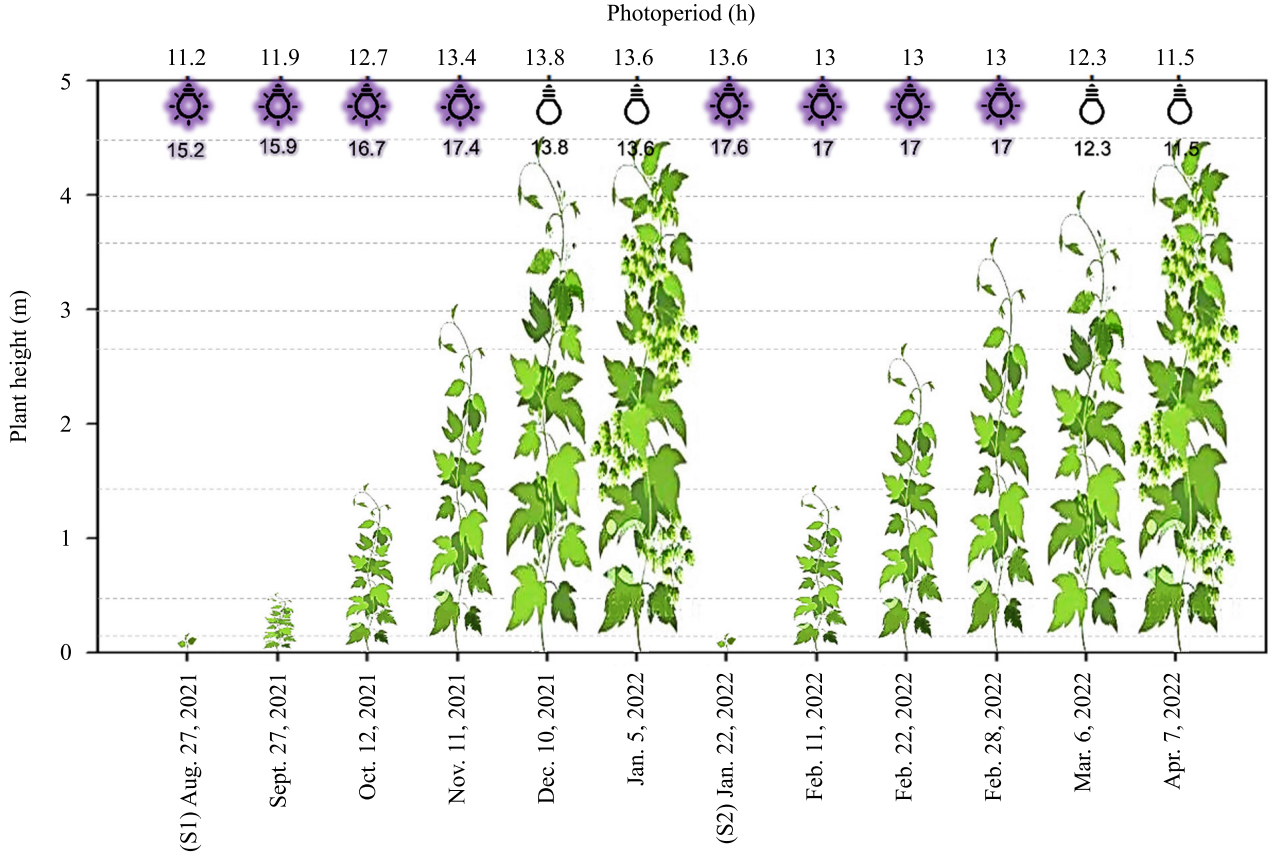

Figure 1. Photoperiod and plant height of *Humulus lupulus* L. Chinook cultivar subjected to treatments with LED light supplementation, and without LED light supplementation over the evaluation dates, distributed across two harvest seasons: 2021 (S1) and 2022 (S2). Light icons represent light supplementation, while dark icons indicate absence of light supplementation.

at the phenological stage of inflorescence emergence: once in full daylight at 10 a.m. and once at night.

The photosynthetically active chlorophyll index was determined at the cone development stage, using a SPAD-502 plus chlorophyll meter (Konica-Minolta, Tokyo, Japan). Additionally, leaf area was measured in cm^2 at the same phonological stage; for this, five leaves were collected per plant and measured using a LI-3100C Leaf Area Meter (LI-COR Biosciences Lincoln, NE, United States of America).

To determine the productive height (m), the plants were first pruned at soil level, and the height of the first productive branch insertion was recorded. The measurement of the mean length and width (cm) of the cone was carried out by randomly sampling ten cones per plant. For the total dry mass of the cone (g), all cones produced by the plant were harvested and weighed, then a sample of 144 cones were dried in an oven at 35ºC until a constant moisture content of 10–12% was achieved.

To evaluate the cone index per centimeter of branch, the cones present on five lateral branches of the plant were quantified. The estimated yield per hectare, expressed in kg ha^{-1} was calculated based on the total number of cones produced in the area, in contrast to the plant density.

The estimated yield per linear meter was calculated considering the dimensions of the trellis (4.5 m height x 2 bines per trellis) and the total dry cone yield per plant and linear meters, as shown in the following equations:

Linear meter = (4.5 × 2) - (Height of the first productive branch × 2 bines)

Yield per linear meter = Yield per plant (kg) / linear meter

For the qualitative evaluations, the methods described by the American Society of Brewing Chemists were used, specifically the α-acids and β-acids concentrations were obtained through the Hops-6 method, while the total essential oil content in mL 100 g^{-1} was quantified according to the Hops-13 methodology (ASBC, 2012).

Data were subjected to multivariate analysis, specifically principal component analysis (PCA), applied through a correlation matrix at a minimum significance level of 5%, using the Minitab software (Minitab, 2019). PCA is an unsupervised statistical method that enables the condensation and graphical representation of datasets composed of multiple interrelated quantitative variables. This approach simplifies the structure of multivariate data by converting them into principal components, which are linear combinations of the original variables, allowing for pattern identification and enhanced data interpretation (Dias et al., 2025).

Results and Discussion

For the Chinook cultivar, the first and second principal components accounted for 90.9% of the total variance, while for Cascade cultivar they explained 84.5%. These results describe the impact of light supplementation across harvest seasons (Figures 2 and 3). The first principal component revealed a greater accumulation of leaf dry mass and a lower daytime shading percentage in S1 for both WL and WOL treatments; conversely, S2 showed the opposite behavior. Regarding the variation in data explained by the second principal component, WL resulted in a greater leaf area of 75.29 cm^2 and a nighttime shading percentage of 39.90%. However, this treatment resulted in a lower SPAD index of 45.49 in S1, and 40.2 in S2.

For the Cascade cultivar, the first component showed that the highest nighttime shading percentages, leaf area, and leaf dry mass occurred in S1 under both WL and WOL treatments. Regarding the second component, the SPAD indices of 50.14 in S1 and 49.10 in S2 were more prominent in the absence of light supplementation. Additionally, in S2, 45.33 and 44.63% of daytime shading were observed under the WL and WOL treatments, respectively.

The directly proportional relationship between leaf area and nighttime shading percentage suggest a physiological strategy to optimize light radiation capture, avoiding disruptions to light-dependent physiological processes (Ptushenko et al., 2016).

The SPAD index directly affects the photosynthetic rate and, consequently, the production of metabolites for physiological processes. Plants subjected to shading regimes exhibit lower leaf dry mass as a compensatory effect caused by reduced radiation availability, decreasing the synthesis of certain components in order to maintain the photosynthetic process. Martinazzo et al. (2007) and Meira et al. (2012) observed similar behavior in *Eugenia uniflora L*.

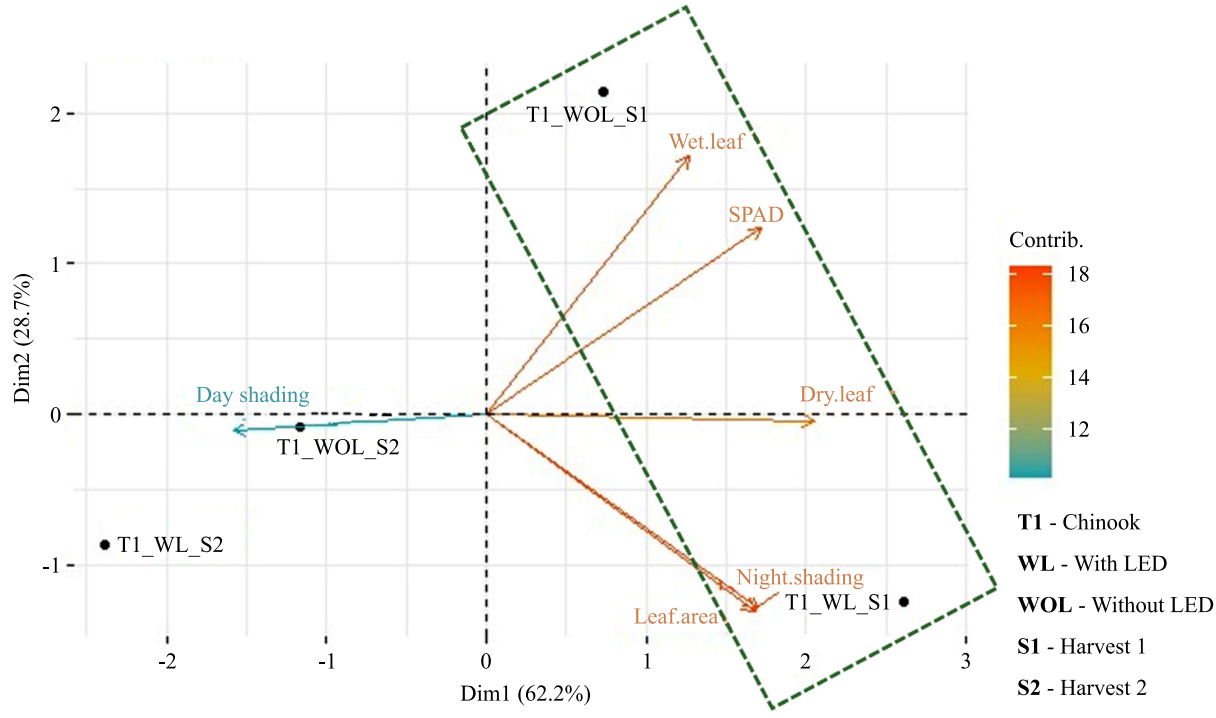

Figure 2. Principal Component Analysis applied to the *Humulus lupulus* L. Chinook cultivar (T1) subjected to treatments with LED light supplementation (WL), and without LED light supplementation (WOL) across two harvest seasons: 2021 (S1) and 2022 (S2).

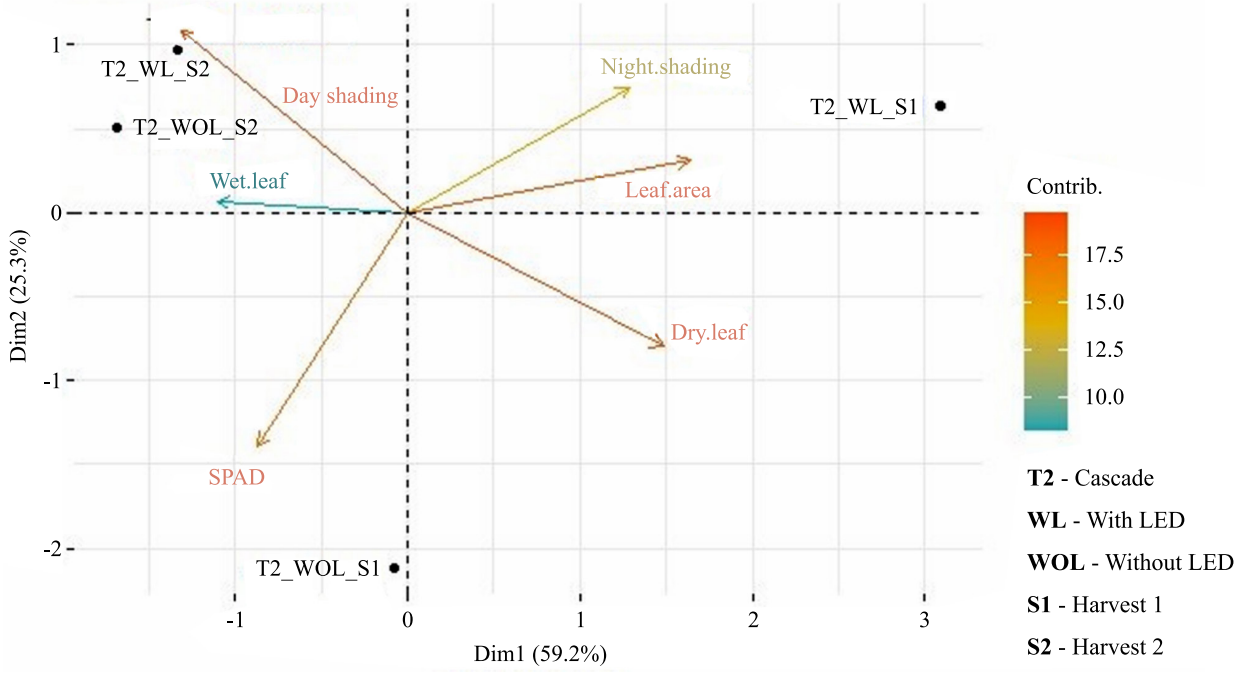

Figure 3. Principal Component Analysis applied to the *Humulus lupulus* L. Cascade (T2) cultivar subjected to treatments with LED light supplementation (WL), and without LED light supplementation (WOL) across two harvest seasons: 2021 (S1) and 2022 (S2).

Furthermore, the lower SPAD indices observed in plants with larger leaf areas is attributed to the dilution of available constituents in the leaves, leading to a reduction in chlorophyll concentration and, consequently, a lower mean SPAD value.

For the vegetative and yield evaluations, the first two principal components accounted for 93% of the variability in yield results for the Chinook cultivar (Figure 4). Similar to the first component, higher yield results were observed in WL across both harvests (Table 1). Additionally, according to the second component, S1 presented higher values for mean cone length and width compared with S2. Specifically, 'Cascade' produced cones with a mean length of 3.5 cm and width of 2.4 cm, while 'Chinook' reached a mean length of 2.9 cm and width of 1.8 cm.

The use of light supplementation demonstrates a direct correlation with crop yield, as it delays flowering, allowing for adequate vegetative growth before flowering, ultimately resulting in higher

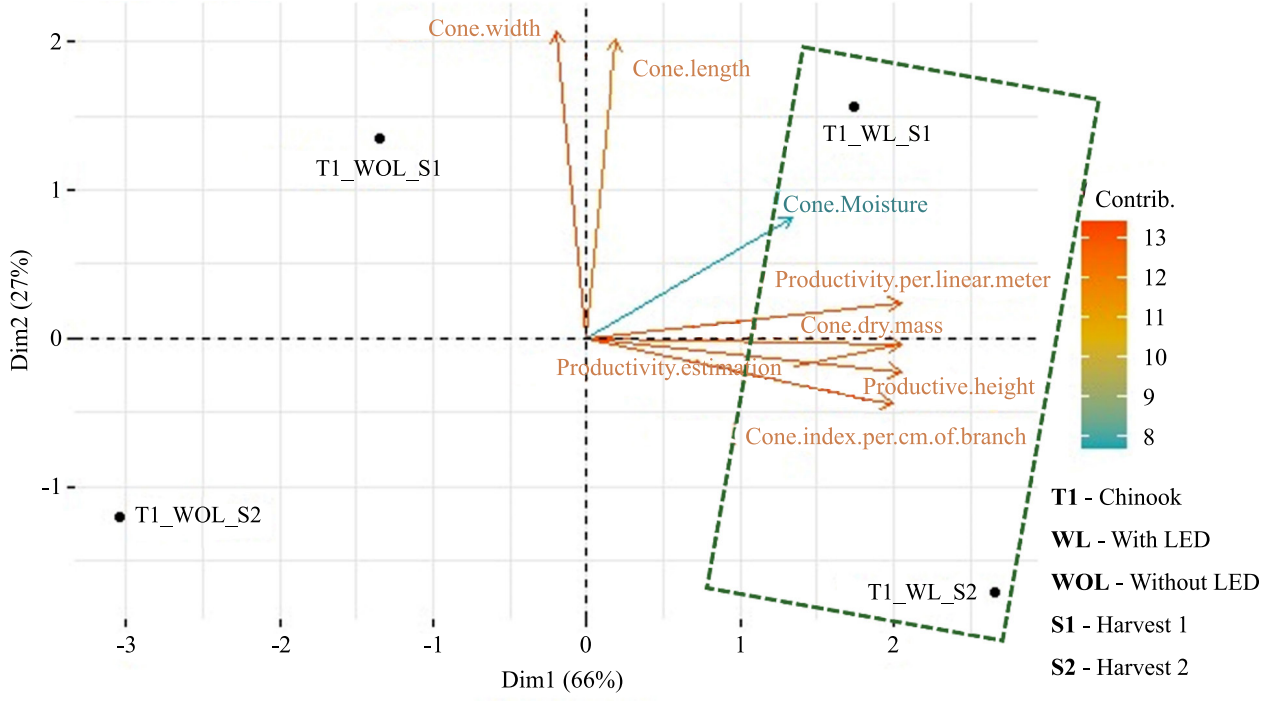

Figure 4. Principal components representation of productive variables for the *Humulus lupulus* L. Chinook cultivar (T1) subjected to treatments with artificial LED lighting supplementation (WL), and without artificial LED lighting supplementation (WOL) across two harvest seasons: 2021 (S1) and 2022 (S2).

Table 1. Mean values of agronomic parameters for *Humulus lupulus* L. Chinook cultivar subjected to LED lighting supplementation treatments across two harvest seasons[(1)].

Harvest	PH (m)	CIBC	YPH (kg ha^{-1})	YLM (kg m^{-1})	DCM (g)	CMP (%)
S1	3.40	0.65	467.34	0.03	0.19	25.07
S2	3.72	0.99	510.42	0.03	0.20	27.13

[(1)]S1, harvest season 1; S2, harvest season 2; PH, productive height; CIBC, cone index per branch centimeter; YPH, yield per hectare; YLM, yield per linear meter; DCM, dry cone mass; and CMP, cone moisture percentage.

yields (Acosta-Rangel et al., 2021). Furthermore, the yield increase to WL was verified by field estimates, reaching 467 kg ha^{-1} in S1 and 511 kg ha^{-1} in S2. In contrast, the WOL treatment yielded only 99 kg ha^{-1} in S1, and plummeted to 14 kg ha^{-1} in S2.

For the Cascade cultivar, the sum of the two principal components accounted for 96.2% of the total variance (Figure 5). According to the first component, higher yield results were identified in S1, regardless of light supplementation treatment (Table 2).

Regarding the second component, the highest values for cone index were observed under the WL treatment in S1 at 0.48 cones per cm of branch, and 0.54 cones per cm of branch at S2. Conversely, the highest cone moisture percentages were observed in the WOL treatments, at 28.45% in S1 and 25.13% in S2. These treatments also showed lower dry cone mass, with values of 0.08 g in S1 and 0.04 g in S2. This condition reflects the lower overall yield compared with plants that received light supplementation treatment.

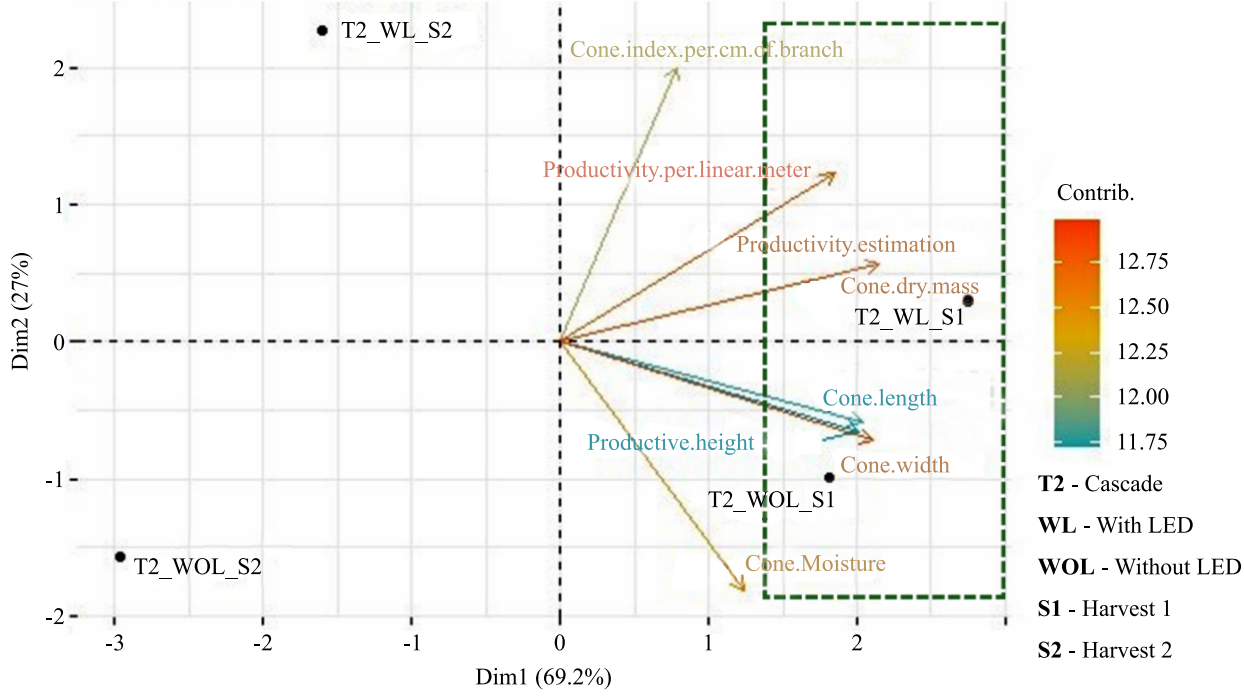

Figure 5. Principal components representation of productive variables for the *Humulus lupulus* L. Cascade cultivar (T2) subjected to treatments with artificial LED lighting supplementation (WL), and without artificial LED lighting supplementation (WOL) across two harvest seasons: 2021 (S1) and 2022 (S2).

Table 2. Mean values of agronomic variables for *Humulus lupulus* L. Cascade cultivar subjected to LED lighting supplementation treatments during the first harvest season[(1)].

Treatment	PH (m)	MCW (cm)	MCL (cm)	YPH (kg ha^{-1})	YLM (kg m^{-1})	DCM (g)
WL	3.51	2.25	3.24	271.56	0.02	0.11
WOL	2.86	2.24	3.05	221.09	0.01	0.09

[(1)]WL, light supplementation; WOL, without light supplementation; PH, productive height; MCW, mean cone width; MCL, mean cone length; YPH, yield per hectare; YLM yield per linear meter; and DCM, dry cone mass.

Additionally, the lower yield observed for the Cascade cultivar can be attributed to the excessive precipitation recorded in the region in March 2022, resulting in insufficient time for recovery. While the total rainfall volume during the four-month duration of the productive cycle in S2 met the crop demands of 500 to 600 mm over the crop cycle (Skomra, 2015), the distribution was irregular. In March, during the pre-flowering phase, precipitation reached 260.40 mm (Epagri, 2020), corresponding to 48.3% of the total precipitation for the cycle.

Regarding the qualitative evaluations of the cones, the first component accounted for 45.6% of the data variation for the Chinook cultivar. During S2, the results indicated β-acid concentrations of 2.46% in the WOL and 2.04% in the WL treatments (Figure 6).

Meanwhile, the second component accounted for 37.4% of the data variance. During S2, the highest α-acid concentration was observed under WL conditions, reaching 7.77%, while the lowest was found under WOL conditions, with 6.86%. Additionally, the highest essential oil contents were recorded in the WL treatments, reaching 0.74 mL $100g^{-1}$ in S1 and 0.38 mL $100g^{-1}$ in S2.

For the Cascade cultivar, the first component accounted for 96.9% of the data variability (Figure 7). Under the WL treatment in S1, α-acids and β-acids concentrations were 6.67, and 2.80% respectively. Furthermore, essential oils could not be quantified due to insufficient dry cone mass for laboratory analysis.

Lighting is an abiotic condition that influences the biosynthesis of α-acids, β-acids, and essential oils, stimulating changes in both yield and concentrations produced by the plant. Light supplementation within the adequate spectrum allows the plant to positively regulate biosynthesis and manage this environmental condition (Trancoso et al., 2022). Hawley et al. (2018) and Morello et al. (2022) observed a similar behavior when evaluating the effect of light supplementation on *Cannabis sativa* L.

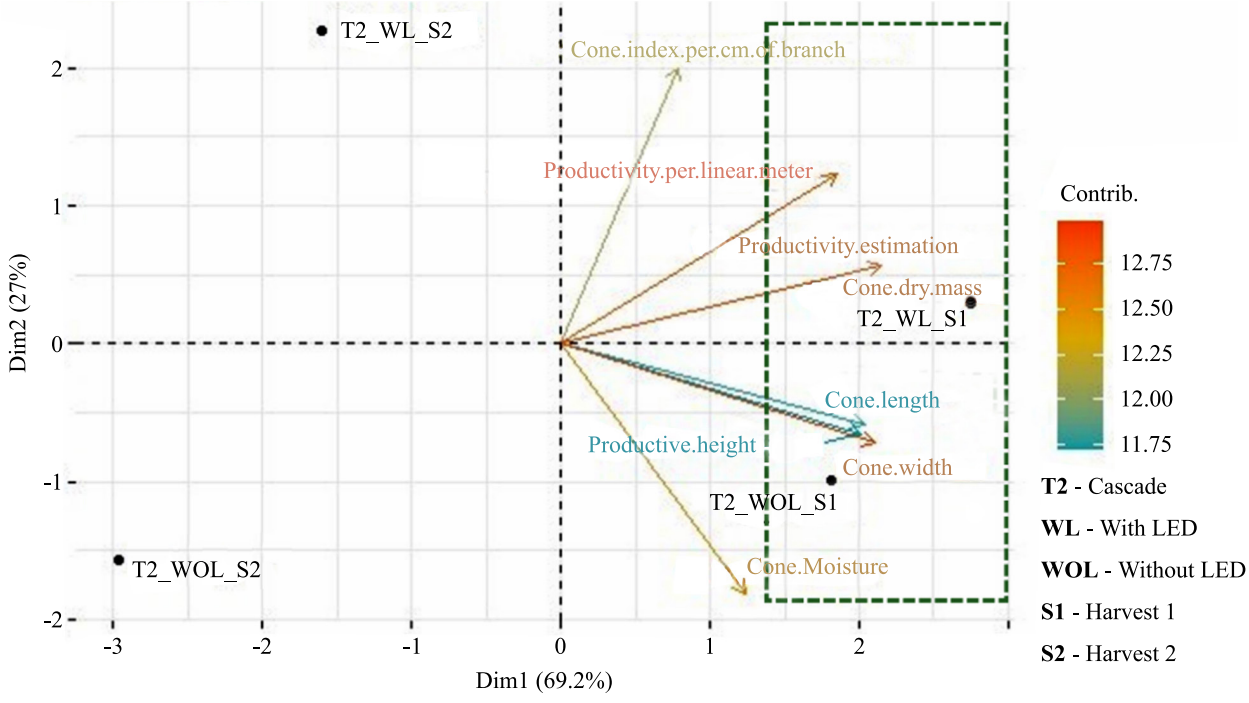

Figure 6. Principal components representation of qualitative variables for the *Humulus lupulus* L. Chinook cultivar (T1) subjected to treatments with artificial LED lighting supplementation (WL), and without artificial LED lighting supplementation (WOL) across two harvest seasons: 2021 (S1) and 2022 (S2).

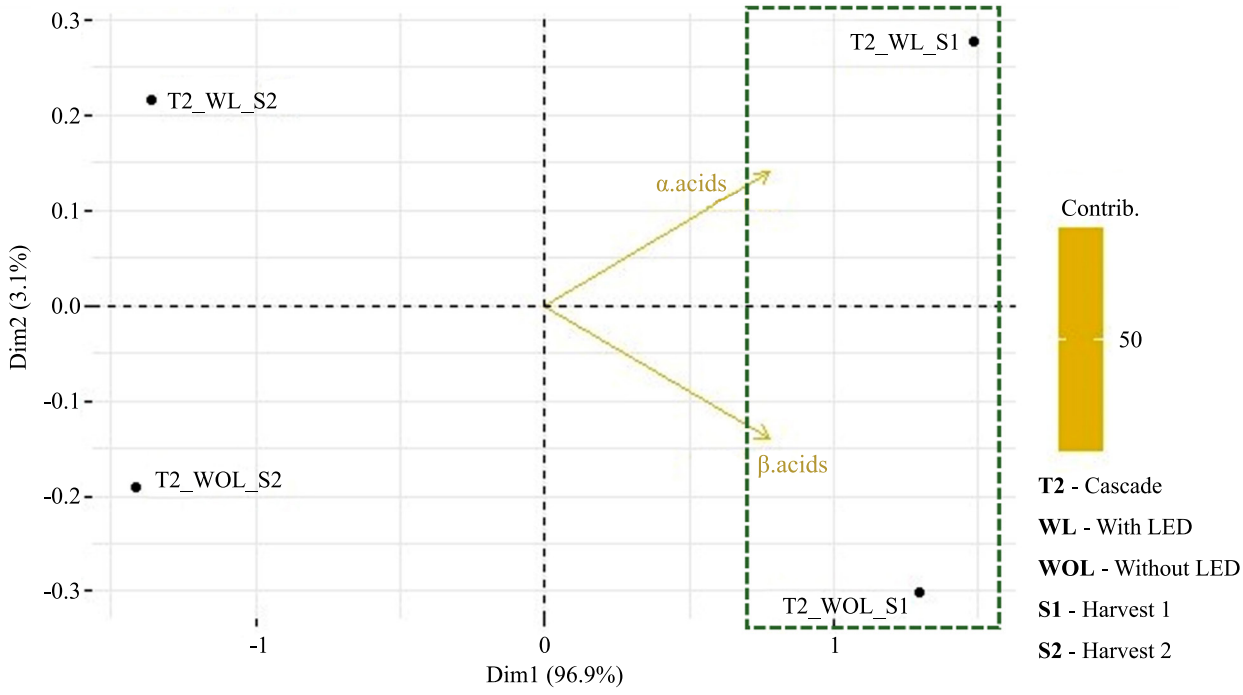

Figure 7. Principal components representation of qualitative variables for the *Humulus lupulus* L. Cascade cultivar (T2) subjected to treatments with artificial LED lighting supplementation (WL), and without artificial LED lighting supplementation (WOL) across two harvest seasons: 2021 (S1) and 2022 (S2).

Conclusions

1. Light supplementation with LEDs, specifically within the red and blue spectra, enhances vegetative, productive, and qualitative characteristics of hop (*Humulus lupulus*) cultivation.

2. Light supplementation with LEDs enables two hop harvests per year, and promotes the synthesis of key compounds such as essential oils, α-acids, and β-acids.

3. The artificial lighting is recommended as a viable strategy to intensify and enhance hop yield in subtropical regions.

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Hyan de Cássio Pierezan: conceptualization, formal analysis, investigation, methodology, writing – original draft, writing – review & editing; **Caroline Aparecida Matias Pierezan**: investigation, resources, writing – original draft, writing - review & editing; **Daiana Petry Rufato**: data curation, software, writing – review & editing; **Mariana Mendes Fagherazzi**: writing – review & editing; **Leo Rufato**: conceptualization, funding acquisition, project administration, resources, supervision, visualization, writing – review & editing.

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No generative artificial intelligence (AI) was used in this study.

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The authors declare no conflicts of interest.

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