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Performance of hop cultivars (*Humulus lupulus* L.) under the annual double harvest system under artificial light supplementation in a subtropical climate

Desempenho de cultivares de lúpulo (*Humulus lupulus* L.) sob o sistema de dupla safra anual sob suplementação artificial de luz em clima subtropical

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Highlights

Cultivation of two hop crops per year is possible in a subtropical climate.
Conventional summer harvest renders a greater marketable yield.
Off-season fall harvest results in higher-quality cones.
Vegetative development influences marketable yield.

Abstract

We compared growth performance, yield, and cone quality of hops cultivars grown under a double annual-harvest scheme under artificial supplementary light in a subtropical region. The experiment was conducted in Palotina, Paraná, Brazil (24°17’40.05” S; 55°50’23.16” W, at 332 m elevation). Plants were trained on a 5,5 m high vertical trellis, “V” shaped tutoring system. The experiment was laid in a randomized complete-block design in a factorial arrangement (2 × 4) to evaluate the following factors and levels: a) harvest (Conventional Summer Harvest 2022/23, CSH; Off-season Fall Harvest 2023, OFH); and b) cultivar (Hallertau Mittelfrüher; Mapuche; Northern Brewer; Spalter). In both harvests, plant growth, expressed as plant height and fresh weight, yield components (number of cones per side branch, number of cones per plant, cone fresh weight, weight of fresh cones per plant, and estimated

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productivity), and chemical components of the cones (alpha- and beta-acids and essential oil) were evaluated. Plant growth was analyzed using nonlinear log-logistic regression. The remaining data were subjected to analysis of variance and means were compared using Tukey's test at the 5% probability level. Plant growth, yield, and chemical components of cones differed between harvests, with the summer crop showing faster vegetative growth and yield, while the fall crop showed greater cone mass and quality. At both harvests, cultivars Mapuche and Spalter showed faster vegetative growth, and greater biomass accumulation and yield. Therefore, vegetative growth was considered a major factor influencing yield components, while comparing cultivars and harvests. Hops cultivation for two harvests per year (summer and fall) seems feasible in subtropical climates with the use of supplementary artificial light.
Key words: Alpha-acid. Beta-acid. Photoperiod. Essential oil. Off-season harvesting.

Resumo

Comparamos o desempenho de crescimento, o rendimento e a qualidade do cone de cultivares de lúpulo cultivadas sob um esquema de dupla safra anual sob luz artificial suplementar em uma região subtropical. O experimento foi conduzido em Palotina, Paraná, Brasil (24°17’40.05” S; 55°50’23.16” W, a 332 m de altitude). As plantas foram conduzidas em um sistema de condução em forma de “V” com treliça vertical de 5,5 m de altura. O experimento foi realizado em delineamento de blocos casualizados em arranjo fatorial (2 × 4) para avaliar os seguintes fatores e níveis: a) safras (Safra Convencional de verão 2022/23, CSH; Safra Extemporânea de outono 2023, OFH); e b) cultivares (Hallertau Mittelfrüher; Mapuche; Northern Brewer; Spalter). Em ambas as safras foram avaliados o crescimento da planta, expresso como altura e peso fresco da planta, componentes de rendimento (número de cones por ramo lateral, número de cones por planta, peso fresco do cone, peso de cones frescos por planta e produtividade estimada) e componentes químicos dos cones (teores de ácidos alfa e beta e de óleos essenciais). O crescimento da planta foi analisado usando regressão log-logística não linear. Os dados restantes foram submetidos à análise de variância e as médias foram comparadas usando o teste de Tukey à 5% de probabilidade de erro. O crescimento das plantas, o rendimento e os componentes químicos dos cones foram distintos entre as safras, encontrando para o ciclo de verão maior precocidade no crescimento vegetativo e maior rendimento, enquanto para o ciclo de outono maior massa e qualidade dos cones. Em ambas as safras as cultivares Mapuche e Spalter apresentaram precocidade no crescimento vegetativo, maior acúmulo de massa e maior rendimento. Portanto, o crescimento vegetativo foi considerado um fator de influência para os componentes de rendimento produtivo, quando comparado tanto as cultivares quanto as safras. O cultivo de lúpulo em duas safras ao ano (verão e outono) mostrou-se viável em clima subtropical com o uso de luz artificial suplementar.
Palavras-chave: Alfa-ácidos. Beta-ácidos. Fotoperíodo. Óleos essenciais. Safra extemporânea.

Introduction

Hops (*Humulus lupulus* L., Cannabaceae) are perennial climbing plants whose commercially important organs are their female inflorescences, known as cones (Campos et al., 2023; Rutnik et al., 2021), which contain glandular trichomes that store and secrete lupulin, an important compound mainly composed of alpha and beta acids, and essential oils highly valued in the beer industry, as they impart bitterness, flavor, and aroma to the globally popular drink (Ting & Ryder, 2017; Zhang et al., 2021). Further, these chemical compounds are not found in any other plant species (Righi et al., 2024; Spósito et al., 2019), whereby 97% of the hops produced worldwide is used as raw material in the beer industry (Almeida & Conto, 2024; Durello et al., 2019).

Hop is a short-day species that requires a photoperiod of more than 15 hours vegetative growth to avoid early flowering, and to show adequate cone production (Jastrombek et al., 2022), therefore, most of the world hop production is concentrated between 35° and 55° North or South of the Equator, which is considered the ideal cultivation range for crop development with regard to photoperiod duration (Simieli et al., 2021; Sirrine, 2014).

The climate in the main hop producing regions is predominantly temperate; thus, for a long time, hops growth and development were associated with cool temperatures (Acosta-Rangel et al., 2021). However, with the expansion of hop cultivation in areas parallel to latitudes between 35° and 55° in both hemispheres, it has been observed that the plant can adapt well to higher temperatures in subtropical climates so long as a photoperiod greater than 15 h can be provided through the use of artificial supplementary light (Agehara, 2020; Leles et al., 2023). Indeed, light supplementation in regions with mild winters enables a second crop cycle immediately after the conventional crop season ends with harvest (Agehara, 2020; Jastrombek et al., 2022). This second crop cycle can boost hops production in emerging regions such as Brazil, because in traditional growing regions, only one crop cycle per year is possible (Acosta-Rangel et al., 2024).

In Brazil, the production chain has been encouraged to expand in order to meet the demand of national breweries, whose number shows a 283,1% increase over the last ten years (Ministério da Agricultura, Pecuária e Abastecimento [MAPA], 2024). While evaluating hops cultivation in different regions of the country, promising results have been recorded with respect to adaptation to different climates and latitudes, particularly in the southern region (Almeida & Conto, 2024; Fagherazzi et al., 2023; Leles et al., 2023). However, studies on the production of hop cultivars for multiple annual crop cycles are limited. Therefore, the aim of this study was to compare plant growth performance, yield, and cone quality of hop cultivars grown in a two-harvest-per-year-scheme under artificial supplementary light in a subtropical climate region.

Material and Methods

Description of the study site

The experiment was conducted in an experimental area of the Federal University of Paraná (UFPR), located in the municipality of Palotina, Paraná, Brazil (24º17'40.05" S; 55º50'23.16" W, at an elevation of 332 m.a.s.l.). The predominant soils in the region are eutroferric red latosols with a clayey texture. The climate is classified as humid subtropical Cfa, with an average annual temperature of 20,8 ºC and an average annual rainfall of 1.508 mm. Maximum and minimum photoperiod durations are 13,5 and 10,5 h in summer and winter, respectively (Leles et al., 2023).

Vegetative and reproductive development of hops cultivars (*Humulus lupulus* L) grown under artificial supplementary light during the conventional summer season of 2022/23 (CSH) and the off-season fall 2023 (OFH) crops were evaluated. Two-year-old female plants were trained on a vertical trellis system with "V" shaped tutoring along rows, with six branches per plant (three on each support wire), height of 5,5 m and 1,0 m spacing between plants and 3,0 m between rows. At both harvests, pruning was performed close to the ground to stimulate bud development. In the conventional 2022/23 cropping cycle, pruning was performed at the end of October (mid-spring). In turn, pruning was performed at the end of March (late summer) during the off-season crop season. Monthly average air temperature (ºC) was determined from daily measurements obtained from the S824 meteorological station located at the SIMEPAR entity in the municipality of Palotina (24º31' S, 53º90' W), PR, in 2022 and 2023 (Figure 1).

The experimental area has a double-tape drip irrigation system and a light supplementation system equipped with LED lamps (Philips GreenPower DR/W 10 W LED bulbs). Artificial lighting was used during the vegetative growth phase to control early flowering. Subsequently, after plants reached a total trellis height of 5,5 m, supplementary light was permanently turned off to allow the natural short photoperiod of the season to promote flowering. The lamps used provided light with a spectrum consisting predominantly of 450 nm (blue), and a peak at 650 nm (red), designed inhibit flowering of short-day plants. The photon flux used was 25 µmol s^{-1}. The lamps were installed on top of the trellises and spaced every 10 m along the planting row. The lamp activation system was controlled automatically, such that LEDs were activated daily 30 min before sunset, keeping them on for the time necessary to complete a 17 h photoperiod, according to the daily photoperiods calculated for the latitude of Palotina, PR (Leles et al., 2023).

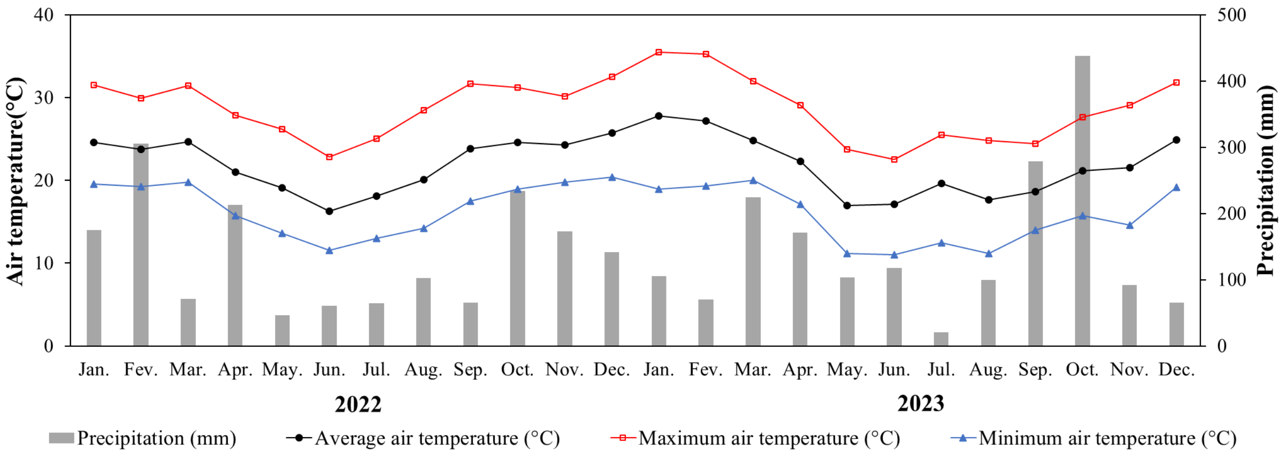

Figure 1. Maximum, average and minimum air temperatures, and monthly rainfall in Palotina, PR in 2022 and 2023 (Instituto Nacional de Meteorologia [INMET], 2024).

Experimental design and measurements

The experiment was laid in a randomized complete-block design in a factorial arrangement (2 × 4) with four replicates and four plants per plot for a total of ten treatments. The following factors and levels were evaluated: a) harvest (Conventional Summer Harvest 2022/23, CSH; Off-season Fall Harvest 2023, OFH); b) cultivar (Hallertau Mittelfrüher, Mapuche, Northern Brewer, and Spalter). During both cropping seasons, plant growth, yield components, and chemical constituents of the cones were evaluated.

Vegetative growth was evaluated based on plant height and fresh weight measurements. Plant height was defined as the extension of the main hop branch up to the insertion of the last leaf produced on the support wire, and was measured using a measuring tape from the moment plants began training on the support wires and until the they reached the height of the structure (i.e., 5,5 m), at 7 d intervals. Plant growth was analyzed by non-linear log-logistic regressions using an adaptation of the logistic model proposed by Seefeldt et al. (1995): $Y = Y_{max}+(Y_{min}-Y_{max})/ [1+ (x/ x0)^p]$, where: Y is the variable of interest; x is the number of accumulated days; Y_{max} is the maximum point obtained, "$Y_{min}-Y_{max}$" is the difference between the minimum and the maximum point, x0 is the number of days that provides 50% response of the variable and p is the slope of the curve. Plant fresh weight was measured at harvest using a digital bench scale.

Yield components evaluated at harvest included the number of cones per side branch, the number of cones per plant, fresh cone weight, the weight of fresh cones per plant, and fresh cone yield. The number of cones per side branch was determined using the formula (x/y), where x is the number of cones per plant and y is the number of branches per plant. In turn, the number of cones per plant was determined using the formula (x × 100)/y, where x is the number of cones per plant and y is the weight of 100 cones. The fresh weight of each cone (g) was measured using a digital precision balance. Weight of fresh cones per plant (kg) of each cultivar was determined by weighing all cones of each plant on a precision digital scale. The estimated crop yield (kg ha^{-1}) was determined using the formula x×(10000/y), where x is the weight of fresh cones produced per plant and y is the area occupied by each plant (3 m^2).

For the chemical analysis of the cones of the hop cultivars evaluated, 100 g cone samples were collected in each block and subjected to a forced-air drying process at 20 ºC, until sample humidity decreased to 10%, after which, samples were stored in vacuum-sealed plastic packaging until evaluation.

Cone chemical components whose concentrations were determined included, alpha- and beta-acids and essential oils. Alpha- and beta-acids levels were determined by extracting the acids from the hops samples, followed by spectrophotometric analysis at three wavelengths (EGTS et al., 2012). Acid extraction was performed by adding a 2,5 g sample of ground hops to 50 mL of methanol, followed by stirring at room temperature for 30 min and allowing to stand for 10 min. After extraction, sample filtration was performed using a Millipore membrane (0,22 µm) to remove particulate material. A 50 µL aliquot of the filtrate was placed in a 25 mL volumetric flask and the volume was completed with a methanolic-NaOH extractant solution (0,5 mL of 6M NaOH in 250 mL of methanol). The absorbance of this solution was measured at 275, 325, and 355 nm using a spectrophotometer, and 50 µL of methanol in 25 mL of methanolic NaOH as a blank. From these readings, the following were determined: alpha-acid content (%) = [(-51,26×A355nm) + (73,79×A325nm) - (19,07×A275nm)]; and beta-acid content (%) = [(55,27×A355nm) - (47,59×A325nm) + (5,1×A275nm)]; where: A = absorbance reading at each wavelength (Leles et al., 2023).

Essential oil concentration was determined by extracting the essential oils by hydrodistillation in a Clevenger apparatus with an extraction period of 4 h after boiling (Santos et al., 2004). Dry samples (20 g) from each block was placed in a volumetric flask containing 500 mL distilled water. The flask was then attached to an extractor and placed in a heating blanket. The yield of essential oil extracted from plant biomass was calculated using the formula: essential oil concentration (mL 100 g^{-1}) = (Vo×5), where: Vo = volume of oil extracted (mL).

The data were subjected to analysis of variance (ANOVA) and the F test; when significance was detected, treatment means were compared with Tukey´s test at a 5% probability of error using R Studio.

Results and Discussion

Plant growth differed across cultivars between the 2022/23 conventional summer and the off-season fall crop cycle in terms of the time needed to reach the top of the trellis (5,5 m) (Figure 2). In the conventional crop, earlier plant growth was observed, reaching the maximum height of the trellis approximately 80 d after pruning, whereas this occurred close to 100 d after pruning in the off-season crop. When comparing the four tested cultivars in both cropping seasons, we observed that, in the conventional summer crop, the growth peak was reached faster by the Mapuche and Spalter cultivars, which allowed them to be considered earlier than either Mittelfruher or Northern Brewer. Meanwhile, during the off-season fall cropping cycle, the fastest growth peak was observed for the Spalter variety, while Mapuche and Hallertau Mittelfruher were intermediate, and Northern Brewer was the latest.

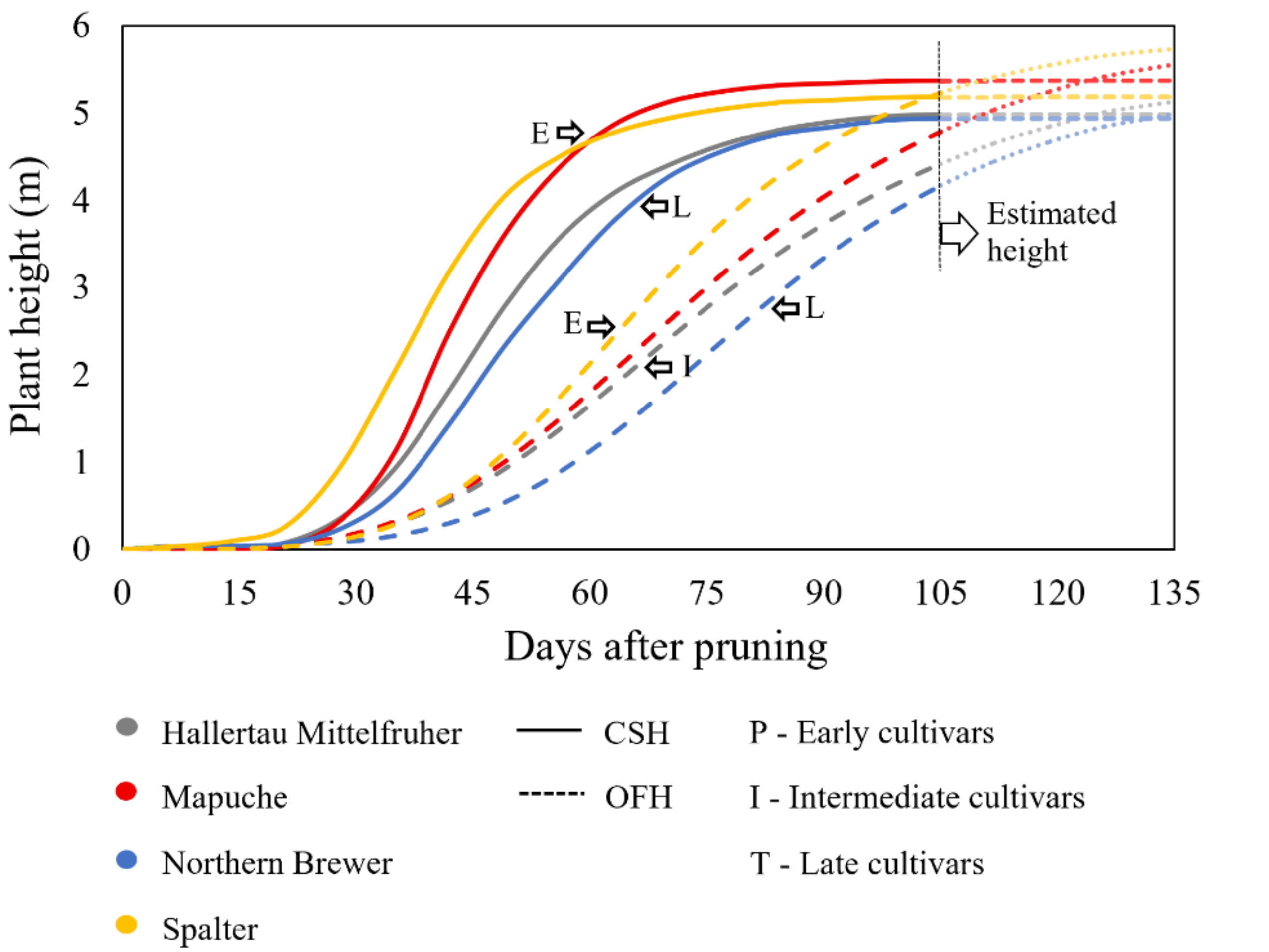

Figure 2. Estimation of plant growth (m) of hop cultivars in the conventional summer 2022/23 (CSH) and off-season fall 2023 (OFH) harvests.

Hops are considered short-day plants; thus, a photoperiod of less than 15 h stimulates early flowering and does not allow adequate vegetative growth and development for commercial production. In contrast, when the photoperiod was extended by supplementary artificial lighting, as in both cropping seasons in this study, the flowering response was delayed and plants were able to reach the maximum height of the trellis, forming a sufficient number of nodes for cone production (Acosta-Rangel et al., 2021; Jastrombek et al., 2022).

In Brazil, daylength greatly varies between the seasons of the year. Specifically, during the conventional summer cropping cycle, the days are longer, reaching approximately 14 h of natural light; however, in the extemporaneous autumn cropping season, the photoperiod reaches only 11 h, making the use of supplementary artificial light even more necessary (Fagherazzi et al., 2023; Neves et al., 2024).

However, the use of supplementary artificial light does not eliminate the differences in daylight quality between seasons. Therefore, the greater irradiance (µmol s^{-1}) observed in summer days likely influenced the photosynthetic rate, increasing the supply of photoassimilates and, consequently, plant growth during the summer season (Kluge et al., 2015). In addition, the earlier growth peak observed during the conventional summer cropping season may be associated with higher average air temperature during vegetative growth and development. Air temperatures between 21 and 39 ºC increase the photosynthetic capacity of hop plants (Eriksen et al., 2020), therefore, higher temperatures positively influence plant growth, resulting in shorter cropping cycles, as in the conventional cropping season, whereas a late cycle at milder temperatures, as the off-season fall cropping season, may have only a weak effect on photosynthesis (Acosta-Rangel et al., 2024; Fortuna et al., 2023).

When we compared cultivar behavior in each cropping season, we observed that the growth curves were different in both seasons. The genotype of each variety shows a distinct ability to adapt to the environment in which it grows (Eriksen et al., 2020; Rossini et al., 2016). Additionally, regardless of environment, each variety requires an optimum number of days for vegetative growth prior to flowering (McAdam et al., 2014).

With respect to plant fresh weight, a significant interaction was observed between crop season and hop cultivar (Table 1). Greater fresh weight was observed for Mapuche and Spalter in the conventional summer season, with the Mapuche cultivar showing a greater fresh weight than those of Hallertau Mittelfruher or Northern Brewer, whereas, in the off-season fall cropping season, there was no statistical difference between the four cultivars under study.

Table 1
Plant fresh weight of hop cultivars in the conventional summer 2022/23 (CSH) and off-season fall 2023 (OFH) harvests

Cultivars	Fresh Weight of Plants (kg)	
	CSH	OFH
Hallertau Mittelfrüher	1.31 Ab	1.6 Aa
Mapuche	2.29 Aa	1.3 Ba
Northern Brewer	1.36 Ab	1.3 Aa
Spalter	2.13 Aab	1.5 Ba
CV %	27.75	
F (cultivars × harvests)	3.36*	

Means followed by distinct letters, capitalized in the row and lowercase in the column, differ from each other by the Tukey test ($p<0.05$). *: significant ($p<0.05$).

Average plant fresh-weight was associated with the speed of growth, such that the earlier cultivars, i.e., Mapuche and Spalter, showed a greater average fresh-weight in both cropping seasons, indicating that plants of these cultivars were more vigorous. Furthermore, during the off-season fall crop cycle, a reduction in fresh weight of Mapuche and Spalter was observed concomitantly with slower growth during that season (Acosta-Rangel et al., 2024; Eriksen et al., 2020).

With regard to the number of cones per side branch, the number of cones per plant, and cone weight, a significant interaction was detected between cropping season and hops cultivar (Table 2). The lowest mean number of cones per side branch and number of cones per plant were observed for the Mapuche and Spalter cultivars during the off-season fall crop, whereas, the highest numbers of cones per lateral branch and per plant were observed for the same cultivars in the conventional summer crop. In contrast, in the off-season fall cropping season, the highest number of cones per lateral branch was observed for the Mapuche and Hallertau Mittelfruher cultivars, while the highest number of cones per plant was observed for Mapuche, compared to cultivar Northern Brewer. Further, the lowest mean cone weights were observed in the off-season fall crop for the Mapuche, Northern Brewer, and Spalter cultivars. Additionally, we observed that in the conventional summer crop, there was no statistical difference among cultivars, whereas in the off-season fall crop, a higher mean cone weight was observed for the Spalter cultivar compared to Northern Brewer or Hallertau Mittelfruher.

The number of cones per lateral branch and per plant, and cone weight are considered important hop yield components (Fortuna et al., 2023; Leles et al., 2023). Furthermore, they are directly related to the potential for plant height development and the accumulation of plant biomass, because plants showing an adequate extent of vegetative growth and development are more likely to render a greater production in relation to the emission of lateral branches and the number of inflorescences (Gutiérrez et al., 2024; Neves et al., 2024; Ruggeri et al., 2018).

Table 2
Number of cones per side branch, number of cones per plant and cone weight of hop cultivars in the conventional summer 2022/23 (CSH) and off-season fall 2023 (OFH) harvests

Cultivars	Nº of cones per side branch		Nº of cones per plant		Weight of Cones (g)	
	CSH	OFH	CSH	OFH	CSH	OFH
Hallertau Mittelfrüher	7.3 Ab	7.3 Aa	624.6 Ab	573.0 Aab	0.4 Aa	0.4 Ac
Mapuche	20.1 Aa	7.6 Ba	2120.4 Aa	881.5 Ba	0.3 Ba	0.7 Aab
Northern Brewer	5.4 Ab	1.7 Ac	571.3 Ab	185.4 Ab	0.4 Ba	0.5 Abc
Spalter	18.6 Aa	4.5 Bb	2192.5 Aa	627.7 Bab	0.3 Ba	0.7 Aa
CV %	33.4		31.4		17.3	
F (cultivars × harvests)	10.1**		10.8**		9.4**	

Means followed by distinct letters, capitalized in the row and lowercase in the column, differ from each other by the Tukey test (p<0.05). **: significant (p<0.01).

Normally, cone formation occurs in the lateral branches; therefore, the number of visible nodes on the main branch, the number of side branches, and their lengths are critical yield components in terms of cone numbers (Ruggeri et al., 2018; Skomra et al., 2013). The relationship between growth and the number of cones can be observed in the rapid pace of vegetative development of the Mapuche and Spalter cultivars in the conventional summer season, or that of Mapuche, Hallertau Mittelfruher, and Spalter in the off-season fall crop, and their respective high mean number of cones produced per lateral branch or plant.

Cone weight generally shows a negative relationship with the number of cones per lateral branch and per plant; therefore, hop plants with fewer cones tend to have cones of larger weight and size, as observed for the Mapuche, Northern Brewer, and Spalter cultivars when comparisons were made between the conventional summer and off-season fall crops (Leles et al., 2023).

Lupulin, a compound of high commercial value, is synthesized in hop cones; therefore, the better development of cones in terms of fresh weight suggests a greater capacity for the production of chemical components, such as alpha- and beta-acids, and essential oils (Fortuna et al., 2023; Giacomini et al., 2023). However, an excessive increase in cone size can hinder post-harvest drying, resulting in a loss of quality (Raut et al., 2021).

In this study, we did not observe any significant interaction between cropping season and cultivar for the weight of fresh cones per plant or yield, which were evaluated in isolation (Table 3). The highest weight of fresh cones per plant and yield were observed in the Mapuche and Spalter cultivars. However, when the harvest factor was evaluated, the highest weight of fresh cones per plant and yield was observed in the conventional summer crop.

The yield of hop cultivars is also associated with their vegetative growth, and when they are early and vigorous, cone production and yield are higher (Ruggeri et al., 2018), as observed for the Mapuche and Spalter cultivars in both cropping season and for all cultivars in the conventional summer crop.

Table 3
Weight of fresh cones per plant and yield of hop cultivars in the conventional summer 2022/23 (CSH) and off-season fall 2023 (OFH) harvests

Cultivars		Weight of fresh cones per plant (kg)	Yield (kg ha^{-1})
Hallertau Mittelfrüher		0.2 b	761.1 b
Mapuche		0.5 a	1626.1 a
Northern Brewer		0.1 b	530.4 b
Spalter		0.6 a	1902.7 a
Harvests			
CSH		0.4 a	1410.7 a
OFH		0.3 b	999.5 b
Causes of variation	GL	F	
Cultivars	3	22.9**	22.9**
Harvests	1	8.8**	8.8**
Cultivars × harvests	3	1.4^{ns}	1.4^{ns}
Residue	21		

Means followed by the same letter in each column do not differ from each other by the Tukey test (p<0.05). ns: not significant. **: significant (p<0.01).

The lower production in the off-season fall cropping cycle, compared to that of the summer crop, was also observed by Acosta-Rangel et al. (2024), who correlated this behavior with the distinct vegetative growth and development between cropping seasons owing to the contrasting climatic conditions. In contrast, Bauerle (2019) tested the use of supplementary artificial light in a controlled environment and obtained successive cropping cycles over the course of a year with no variation in yield between cycles, which can be explained by the effective reduction of the external environmental variation in a controlled environment.

Despite the variation in yield between cropping seasons, our results showed that the use of supplementary artificial light allowed the control of plant flowering, which in turn resulted in a more adequate vegetative growth and development of hop cultivars and the potential for the production of cones in more than one cropping cycle per year.

A significant interaction was observed between harvest and hop cultivar for alpha- and beta-acids, (Table 4). In particular, for alpha-acid, lower mean contents were observed for the Mapuche, Northern Brewer, and Spalter cultivars in the conventional summer cropping season than in the fall crop. In turn, when cultivars were compared, the highest alpha-acid concentration was observed in Mapuche during the conventional summer crop cycle, whereas in the off-season fall crop, the highest mean contents were observed in Mapuche and Spalter. Further, when beta acid contents were compared, lower mean contents were observed for Mapuche, Northern Brewer, and Spalter in the conventional summer crop cycle, whereas in the off-season fall crop, the lowest mean content was observed for Hallertau Mittelfruher. Lastly, when cultivars were compared, we observed no significant differences for beta-acid concentrations in the conventional summer crop, whereas in the off-season fall crop, the highest beta acid concentrations were observed in cultivars Northern Brewer and Spalter.

Hop quality is defined by the alpha- and beta-acids, and essential oils that accumulate in the lupulin glands at the base of the cone bracts. These components make hop cones an essential ingredient in beer-making, as alpha-acids (humulones) and beta-acids (lupulones) have bittering and preservative properties that contribute to beer bitterness, microbial stability, and foam stability (Jastrombek et al., 2022; Ting & Ryder, 2017).

Table 4
Alpha- and beta-acid contents of hop cultivars in the conventional summer 2022/23 (CSH) and off-season fall 2023 (OFH) harvests

Cultivars	Alpha-acid (%)		Beta-acid (%)	
	CSH	OFH	CSH	OFH
Hallertau Mittelfrüher	2.4 Ac	2.7 Ac	1.4 Aa	0.2 Bc
Mapuche	5.5 Ba	8.9 Aa	2.3 Ba	4.1 Ab
Northern Brewer	3.2 Bbc	4.5 Ab	1.7 Ba	7.3 Aa
Spalter	4.1 Bb	7.7 Aa	1.9 Ba	6.7 Aa
CV %	10.1		18.2	
F (cultivars × harvests)	16.6**		42.6**	

Means followed by distinct letters, capitalized in the row and lowercase in the column, differ from each other by the Tukey test (p<0.05). **: significant (p<0.01).

Secondary metabolite levels are greatly influenced by the interaction between genotype and environment. Thus, each variety presents a typical bitterness and aroma under different climatic conditions during the growth cycle (Sawicka et al., 2021; Van Holle et al., 2021). Therefore, the objective being to preserve quality, the greater the control of environmental conditions, the smaller the variation in hop quality between growth cycles (Bauerle, 2019).

Among the compounds evaluated, the accumulation of alpha-acids is allegedly affected by higher temperatures that increase plant evapotranspiration during cone development (Sawicka et al., 2021; Srečec et al., 2008), which suggests that the higher mean temperatures (24,2 °C) during the conventional summer crop cycle may have reduced the accumulation of alpha-acids in the cones. In addition, cone size may be related to the capacity for lupulin accumulation (Neves et al., 2024), therefore, the larger the cone size (represented by cone weight), the higher the alpha- and beta-acid contents, as found in the off-season fall crop for the Mapuche, Northern Brewer, and Spalter cultivars.

Variability in cultivar growth in each cropping cycle can further increase the variation in cone quality (Acosta-Rangel et al., 2024). Cultivars showing faster vegetative growth and development tend to exhibit a greater accumulation of alpha-acids (Srečec et al., 2008), as observed in this study for the Mapuche and Spalter cultivars, which in both cropping cycles showed rapid plant growth and the highest mean alpha-acid contents relative to the other cultivars studied herein.

Additionally, there was no significant interaction between crop cycle and cultivar with respect to the concentrations of the essential oils evaluated in isolation (Table 5), and a higher concentration of essential oils was observed in Spalter than in Hallertau Mittelfruher, while no significant differences were observed between summer and fall crop cycles.

Essential oils are volatile aromatic compounds that give beer a unique hop aroma because they are extremely complex metabolites composed of more than 300 aromatic compounds formed mainly of hydrocarbons, oxygenated compounds, and sulfur compounds (Durello et al., 2019; Rutnik et al., 2021; Ting & Ryder, 2017). The amount of essential oils and the proportion of individual fractions of each constituent vary widely among hop cultivars (Sawicka et al., 2021), thus determining the purposed use for each one. The Mapuche, Hallertau Mittelfruher and Spalter cultivars are considered for aroma contribution (Healey, 2016; Testa et al., 2019), requiring essential oil concentrations close to 1,0 mL 100 g^{-1} for use in aromatic hopping techniques (Muller, 2021). In this study, only Hallertau Mittelfruher showed a lower concentration of this compound than the cited threshold.

Table 5

Concentration of essential oils in hop cultivars in the conventional summer 2022/23 (CSH) and off-season fall 2023 (OFH) harvests

Cultivars		Essential oils (mL $100g^{-1}$)
Hallertau Mittelfrüher		0.7 b
Mapuche		0.9 ab
Northern Brewer		0.9 ab
Spalter		1.0 a
Harvests		
CSH		0.8
OFH		0.9
Causes of variation	GL	F
Cultivars	3	4.2*
Harvests	1	0.1^{ns}
Cultivars × harvests	3	2.7^{ns}
Residue	14	

Means followed by the same letter in each column do not differ from each other by the Tukey test (p<0.05). ns: not significant. *: significant (p<0.05).

Based on the results summarized above, we concluded that obtaining two hop harvests per year under the local soil and climate conditions, especially if supplementary artificial light is used, is quite feasible, considering that, in general, quantitatively and qualitatively, both cropping cycles rendered satisfactory results. However, it is clear that there are differences in vegetative growth and plant phenology associated to both cultivar and crop cycle, which require attention from the producer while defining and planning management practices, such as pruning and harvesting. Another factor to be considered is the difference in the qualitative aspects of the cones, as the alpha acid values were higher in the off-season fall crop. An alternative would be to combine the two harvests; that is, to mix the production of the conventional harvest with that of the off-season crop, and thus standardize the quality of the overall annual production to meet the demands of the beer industry, which generally prefers quality raw materials with a uniform standard over the years.

Conclusions

Hop production in two cropping cycles per year seems possible under subtropical climatic conditions with the use of supplementary artificial lighting, with the first cycle in the summer and the second in the fall. Vegetative growth, yield, and cone quality differed between crop cycles, with faster vegetative growth and higher yield observed in the summer crop, whereas the fall crop showed greater cone weight and quality. Vegetative growth was considered a major driver of yield components. When the four cultivars and two crop cycles were compared, fast vegetative growth and greater biomass accumulation resulted in a higher yield.

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