Australian Journal of Crop Science

AJCS

AJCS 17(4):385-391 (2023) ISSN:1835-2707
doi: 10.21475/ajcs.23.17.04.p3741

Gas exchanges and morphometric measurements of a variety of hops (*Humulus lupulus* L.) (Cannabaceae) grown in subtropical conditions under organic and conventional management

Caio Neves[1], Eduardo Aires[1], Gabriel Fortuna[1], Olivia Campos[1], Jordany Gomes[1], Elizabeth Ono[2], João Rodrigues[2], Filipe Bonfim[1]

[1]Department of Horticulture, Faculty of Agronomic Sciences, São Paulo State University, Botucatu, Brazil
[2]Department of Biostatistics, Plant Biology, Parasitology and Zoology, Biosciences Institute, São Paulo State University, Botucatu, Brazil

***Corresponding author: caio.scardini@unesp.br**

Abstract

Hops are native to the Northern Hemisphere and are widespread throughout the world; in Brazil, crops are grown on a small scale. How management differentiation can affect the physiological development of crops in subtropical climates is not well studied. The objective of this study was to evaluate the physiological and morphometric performance of five hop varieties under organic and conventional management. These experiments were conducted at Lageado Farm, at the campus of São Paulo State University in Botucatu. A 2 x 5 factorial design was adopted, with the main factor being the cultivation system (organic and conventional) and the secondary factor being the hop varieties (Cascade, Columbus, Chinook, Hallertau Mittelfrüeh and Nugget). The cultivation systems differed by fertilization and phytosanitary management. Analyses of gas exchange and chlorophyll *a* fluorescence were performed during the vegetative development of the plants and during branch elongation. Morphometric analyses of the plants were performed to determine the number of internodes (22.40; 18.20) and the heights of the plants (201.09; 131.07), with organic and conventional treatment, respectively. All the varieties showed satisfactory physiological and morphometric performance; however, plants grown under organic management had better results than those grown under the conventional cropping system. Lastly, we measured the potential efficiency of PSII; Hallertau M. (0.89), Nugget (0.89) and Columbus (0.88) presented the highest measurements, and the lowest values were observed in Cascade (0.86) and Chinook (0.85). In general, Hallertau M. and Columbus had the highest gas exchange values, while Cascade had the lowest.

Keywords: Acclimatization; photosynthetic performance; production systems; tropicalization; vegetative performance
Abbreviations: A_Carbon assimilation; A/Ci_Carboxylation efficiency; B_Boron; Ci_Internal concentration of carbon dioxide; CO_2_Carbon dioxide; Cu_Copper; E_Exudation; ETR_Relative electron transfer; Fe_Iron; F_m_Maximum fluorescence; F_v_Variable fluorescence; F_0_Initial fluorescence; F_v/F_m_Potential quantum efficiency of photosystem II; F_v'/F_m'_Quantum efficiency of the antennas; g_s_Stomatal conductance; Hallertau M._Hallertau Mittelfrüeh; IRGA_Infrared Gas Analyzer; KCl_Potassium chloride; $kg.ha^{-1}$_Kilograms per hectare; Mg_Magnesium; Mn_Manganese; Mo_Molybdenum; N_Nitrogen; NI_Number of internodes; ns_Not significant; PH_Plant height; PPFD_Photosynthetic photon flux density; PSII_Photosystem 2; S_Sulfur; $t.ha^{-1}$_Tons per hectare; WUE_Water efficiency; Zn_Zinc

Introduction

Hop (*Humulus lupulus* L.) is a perennial dioecious horticultural plant grown commercially for its female inflorescence, called a cone, which has lupulin glands that are rich in secondary metabolites (Ruggeri et al., 2018; Spósito et al., 2019).

The organoleptic properties of cones have important medicinal and industrial characteristics, especially in breweries (Keskin et al., 2019), because they add an aroma and a bitterness to beers, in addition to preserving them (Liu et al., 2015).

In 2020, Brazil reached a total of 1383 registered breweries, an increase of 14.4% compared to 2019, according to data from the Yearbook of Beer 2020 (Governo do Brasil, 2021). The country imported 3243 tons of hops, totaling US$ 57 million (Comexstat, 2020). There is an interest in reducing the external dependence on importing hops and on supplying breweries with the Brazilian hops that are under development.

The center of origin for hops is the Northern Hemisphere, and hops are grown in regions with a temperate climate where there is a daily light duration that meets the needs for the natural vegetative development of the crop; generally, hops grow within the range from 35° to 55° north or south of the Equator (Keukeleire et al., 1999; Dodds, 2017).

Botucatu is located in the state of São Paulo in southeastern Brazil at a latitude of 22°50' S, and its photoperiod reaches a maximum of 13 hours of light on the longest day of the year;

however, the ideal photoperiod for hop crop development is 16 hours (Pearson et al., 2016; Kolenc et al., 2016).

Several hop crops are found in the southeastern region of Brazil, which predominantly has a subtropical climate (Guimarães et al., 2021). Thus, the crop is acclimated to Brazilian soil, where the climatic conditions are different from those of the origin of the crop cultures.

The management used in hop plantations is commonly conventional in relation to fertilization and phytosanitary control, but there are already crops being cultivated under the organic system, and although there are fewer of these systems, they are increasing worldwide (Turner et al., 2011; Rossini et al., 2021). Another important point of management differentiation is in the control of spontaneous plants, in which the herbicides commonly used in conventional management are not used on organic fields (Delahunty et al., 2015).

The practices adopted in organic management help improve the biological and physical attributes of the soil, such as the incorporation of organic matter, the use of beneficial microorganisms and the use of green manure, in addition to having a beneficial influence on soil microbial activity (Oszut et al., 2014; Dantas et al., 2015; Carvalho et al., 2020).

The physiological development of hops can be affected by cultivation practices and abiotic factors; thus, it is necessary to understand their influences on plant development (Pokorný et al., 2011; Da Silva et al., 2017).

These factors are potentiated when they occur simultaneously, such as temperature, light and solar radiation factors, which are crucial for the physiological development of plants (Galon et al., 2010; Da Silva et al., 2021).

Thus, the objective of this study was to evaluate the gas exchange and morphometric measurements of five varieties of hops grown in subtropical conditions under organic and conventional management.

Results and discussion

Gas exchange and chlorophyll a fluorescence

The gas exchange and chlorophyll *a* fluorescence results of the hop varieties grown in Brazil under organic and conventional management were elucidated for the first time in this study. Significant interactions were observed for most of the measures evaluated in the comparison between varieties and production systems. Only for the traits F_v/F_m and F_v'/F_m' were no significant interactions observed in relation to the types of management; however, significant interactions were observed between the varieties (Tables 1, 2 and 3).

The Hallertau Mittelfrüeh variety results under organic management differed statistically from those of the other varieties, with the highest values for *A*, g_s, *WUE*, A/C_i and *ETR*, and it also had the lowest *E* value, indicating good photosynthetic use.

The varieties managed under the conventional system had similar values for *E*, *WUE* and *ETR*, and the Cascade variety showed differences in these variables with the lowest value. For *A*, g_s and A/C_i, the variety with the highest values was Hallertau.

Higher internal concentrations of CO_2 (*Ci*) were observed in the conventional system; thus, plants under this cultivation system should have higher photosynthetic rates (Silva et al., 2019). However, plants under organic management showed higher values of carbon assimilation (*A*), higher carboxylation efficiency (*A/Ci*) and a higher relative electron transfer rate (*ETR*), indicating greater efficiency in photosynthetic processes. The carbon that is accumulated by the leaves is destined for photosynthesis, suggesting that the high concentration of CO_2 observed in the plants under the conventional system is not being used in photosynthesis.

Eriksen et al. (2020) of Oregon, United States, reported that the Cascade variety also showed a high rate of carbon assimilation, as observed in the present study in the organic system. It is worth noting the climatic differences between the experiments conducted in the United States and Brazil and how the physiological development of the varieties can be affected by these abiotic differences.

Plants that were cultivated under the conventional system showed higher transpiration rates and less water consumption, denoting inefficiency in the photosynthetic processes. This result can be attributed to the fertilizers in use, such as potassium chloride, which has a high salt level compared to that of the other fertilizers used in this experiment (Mantovani et al., 2017). Prazeres et al. (2015) also showed the negative effect of KCl on the transpiration rate.

Hejnák et al. (2015) obtained the lowest transpiration values when evaluating Columbus compared to Vital, Saaz Late and Magnum. Higher transpiration rates in both management types were found when compared to other varieties.

Graf et al. (2019) indicated that hops have very high daily water consumption, and in this experiment, under organic management, the plants showed higher water use efficiency for photosynthesis, with less loss, and the consumed water was destined for use in photosynthetic processes.

There were no significant differences between the adopted management systems in terms of F_v/F_m and F_v'/F_m'; however, the highest quantum yield and photochemical efficiency of PSII were found in Hallertau M., with values of 0.89 and 0.50, respectively, and the lowest values were observed in Chinook (0.85) for F_v/F_m and in Cascade (0.40) for F_v'/F_m' (Table 4).

Similar F_v/F_m values, ranging from 0.80 to 0.85, were reported by Eriksen et al. (2020) for the Chinook and Cascade varieties. Santabarbara et al. (2019) reported that photochemical quantum yield values in PSII above 0.75 are considered normal in mature and stress-free plants.

These data showed that the plants in this experiment had satisfactory physiological performance and were responsive to the adopted practices; additionally, they may not have experienced strong stress levels, which could cause damage to the structures of chloroplasts and other biochemical limitations related to the performance of photosynthesis (Peloso et al., 2017).

CO_2 assimilation response curve as a function of PPFD

Table 5 shows that there were significant differences between the varieties regarding the light compensation point, the saturation point and the amount of respiration in the dark, indicating that they require different PPFDs for the absorption of CO_2 and the accumulation of dry matter.

The highest light compensation value (54.40 $\mu mol\ m^{-2}\ s^{-1}$) was observed in the Chinook variety, and the lowest was observed in Hallertau M. (28.64 $\mu mol\ m^{-2}\ s^{-1}$). Columbus had the lowest light saturation value, with a PPFD of 1303.33 $\mu mol\ m^{-2}\ s^{-1}$, and the highest value was observed in Nugget, with a PPFD of 1873.33 $\mu mol\ m^{-2}\ s^{-1}$. This result indicates that the latter variety has the greatest resistance to solar radiation stress. Hallertau M. had the lowest respiration

Table 1. Results for the CO_2 assimilation rate (A), stomatal conductance (g_s) and internal CO_2 concentration (Ci) of different hop varieties and management types.

	A µmol CO2 $m^{-2}s^{-1}$		g_s mol $m^{-2}s^{-1}$		*Ci* µmol $m^{-2}s^{-1}$	
Variety	Org.	Conv.	Org.	Conv.	Org.	Conv.
Hallertau M.	26.73 Aa	19.49 Bb	0.25 Aa	0.21 Ba	216.18 Ba	229.46 Ca
Cascade	19.64 Ba	5.61 Cb	0.22 Aa	0.12 Cb	236.52 Ab	308.55 Aa
Nugget	16.83 Ca	17.47 Ba	0.20 Aa	0.23 Ba	247.46 Aa	254.06 Ba
Columbus	16.69 Cb	22.35 Aa	0.22 Ab	0.30 Aa	254.50 Aa	256.99 Ba
Chinook	14.42 Cb	17.95 Ba	0.14 Bb	0.27 Aa	215.55 Bb	269.53 Ba
F	31.05**	56.12**	7.45**	20.84**	5.86**	15.53**
CV (%)	8.37		11.98		5.11	

**Significant at the probability level of 0.01. Equal means do not differ according to Tukey's test at 5% probability. Subtitle: Org.: Organic; Conv.: Conventional.

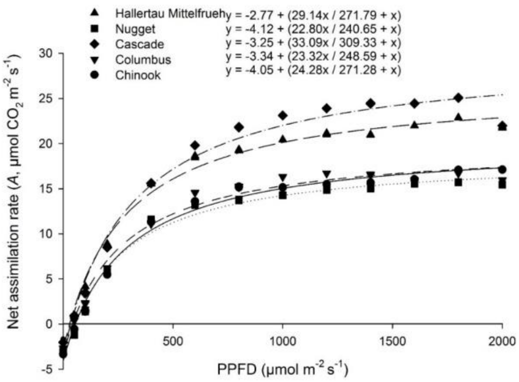

Figure 1. Net CO_2 assimilation rate (A, µmol m^{-2} s^{-1}) as a function of photosynthetic photon flux density (PPFD, µmol m^{-2} s^{-1}) of hop varieties.

Table 2. Results for the transpiration (E) and water use efficiency (WUE) of different hop varieties and management types.

	E		*WUE*	
	mmol water vapor m^{-2} s^{-1}		µmol CO_2 m^{-2} s^{-1}/mmol- H_2O m^{-2} s^{-1}	
Variety	Organic	Conventional	Organic	Conventional
Hallertau M.	2.79 Bb	3.89 Aa	9.55 Aa	4.99 Ab
Cascade	3.88 Aa	2.98 Ba	5.18 Ba	1.85 Bb
Nugget	3.29 Ba	4.16 Aa	5.40 Ba	4.19 Aa
Columbus	3.96 Aa	4.66 Aa	4.25 Ba	4.79 Aa
Chinook	3.15 Bb	4.71 Aa	4.83 Ba	3.83 Aa
F	2.70^{ns}	5.41**	19.67**	6.88**
CV (%)	13.99		16.89	

** Significant at the probability level of 0.01. ^{ns} Not significant at the probability level of 0.01. Equal means do not differ according to Tukey's test at 5% probability.

Table 3. Results for the carboxylation efficiency (A/Ci) and relative electron transfer rate (ETR) of different hop varieties and management types.

	A/C_i		*ETR*	
Variety	Organic	Conventional	Organic	Conventional
Hallertau M.	0.12 Aa	0.08 Ab	157.36 Aa	124.64 Ab
Cascade	0.08 Ba	0.01 Cb	149.86 Aa	56.32 Bb
Nugget	0.06 Ca	0.06 Ba	95.96 Bb	125.47 Aa
Columbus	0.06 Cb	0.08 Aa	136.49 Aa	133.65 Aa
Chinook	0.06 Ca	0.06 Ba	143.67 Aa	144.83 Aa
F	40.66**	51.84**	7.82**	16.48**
CV (%)	9.09		11.73	

** Significant at the probability level of 0.01. Equal means do not differ according to Tukey's test at 5% probability.

Table 4. Results of the quantum (*Fv/Fm*) and effective yield of PSII for the hop varieties.

Variety	F_v/F_m	F_v'/F_m'
Hallertau M.	0.89 A	0.50 A
Cascade	0.86 B	0.40 B
Nugget	0.89 A	0.47 A
Columbus	0.88 A	0.44 A
Chinook	0.85 B	0.45 A
F	3.11*	7.39**
CV (%)	2.61	7.24

*Significant at the 0.05 probability level. ** Significant at the 0.01 probability level. Equal means do not differ according to Tukey's test at 5% probability.

Table 5. Light compensation point (μmol m^{-2} s^{-1}), light saturation point (μmol m^{-2} s^{-1}) and dark respiration (μmol m^{-2} s^{-1}) of hop varieties.

Variety	Light compensation point	Light saturation point	Dark respiration
Hallertau M.	28.64 D	1558.87 B	-2.87 A
Cascade	53.17 A	1392.22 D	-4.21 C
Nugget	33.79 C	1873.33 A	-3.44 B
Columbus	41.65 B	1303.33 E	-3.43 B
Chinook	54.40 A	1425.55 C	-4.14 C
F	70.9**	46.9**	61.92**
CV (%)	8.79	9.36	5.06

** Significant at the probability level of 0.05. Equal means do not differ according to Tukey's test at 5% probability.

Table 6. Results for the number of internodes (NI) and the plant height (PH) of hops (cm) in the organic and conventional management systems.

Management	NI	PH (cm)
Organic	22.40 a	201.09 a
Conventional	18.20 b	131.07 b
F	8.70**	8.25**
CV (%)	24.80	51.90

** Significant at the probability level of 0.05. Equal means do not differ according to Tukey's test at 5% probability.

Table 7. Results of the number of internodes (NI) and the plant height (PH) (cm) of the hop varieties.

Variety	NI	PH (cm)
H. Mittelfrüeh	21.30 a	152.48 a
Columbus	20.70 a	196.15 a
Cascade	20.40 a	167.04 a
Chinook	19.80 a	156.65 a
Nugget	19.30 a	158.10 a
F	0.24^{ns}	0.42^{ns}
CV (%)	24.80	51.90

^{ns} Not significant at the probability levels of 0.01 and 0.05. Equal means do not differ according to Tukey's test at 5% probability.

Table 8. Soil analysis of the conventional cropping system collected in March 2020.

Samples	pH	O. M.	P_{resin}	K	Ca	Mg	CEC	V%	B	Cu	Zn
	$CaCl_2$	$g.dm^{-3}$	$mg.dm^{-3}$	$mmol_c.dm^{-3}$					$mg.dm^{-3}$		
0 – 20	4.9	19	16	2.6	20	5	64	42	1.09	6.1	0.9
20 – 40	4.4	15	6	1.4	13	4	63	29	0.86	5.3	0.4

Subtitle: O. M.: Organic matter; CEC: Cation exchange capacity.

Table 9. Soil analysis of the organic cropping system collected in March 2020.

Samples	pH	O. M.	P_{resin}	K	Ca	Mg	CEC	V%	B	Cu	Zn
	$CaCl_2$	$g.dm^{-3}$	$mg.dm^{-3}$	$mmol_c.dm^{-3}$					$mg.dm^{-3}$		
0 – 20	5.0	25	56	3.4	39	11	77	70	1.00	4.7	3.8
20 – 40	4.8	19	30	2.2	23	10	70	50	0.90	5.4	1.7

Subtitle: O. M.: Organic matter; CEC: Cation exchange capacity.

value in the dark (-2.87 µmol m^{-2} s^{-1}), and Cascade had the lowest value of -4.21 µmol m^{-2} s^{-1}.

Figure 1 shows the CO_2 assimilation curve in relation to the PPFD values for the five varieties. The highest CO_2 assimilation value was achieved by the varieties with approximately 1500 µmol m^{-2} s^{-1}, with Cascade having the highest value and Nugget and Chinook having the lowest values.

Morphometric data

Significant differences were found in the comparison of management types regarding the number of internodes and the plant height (Table 6).

The distance between the nodes and the number of internodes in the hop plants determine the length of the branches and the number of productive nodes (Bauerle, 2021). A higher number of internodes was found in plants subjected to organic management; therefore, it is possible to hypothesize that these plants will have a higher production capacity than those grown in a conventional manner.

Plant height is another characteristic that directly represents the productive capacity of plants (Fagherazzi, 2020) because the larger the plant is, the greater the possibility of the formation of productive branches. The organic system resulted in plants with greater heights (201.09 cm) than those in the conventional system (131.07 cm).

Thus, it is possible to affirm that the supply of natural fertilizers generated greater vegetative and productive capacities for the plants. Amoriello et al. (2020) also obtained positive effects from the use of natural fertilizers, such as biochar, in hop plants not only in terms of vegetative development but also in terms of physiological development.

There was no significant differentiation between the means of different varieties (Table 7).

Hallertau M. was the variety with the highest number of internodes (NI) (21.30), and Nugget had the lowest NI (19.30). The highest plant height was in the Columbus variety (196.15 cm), and the lowest was in Hallertau M. (152.48 cm), which was different from the results found by Rossini et al. (2016), in which Cascade was the variety with the highest plant height.

This is a pioneering work that has generated information on the physiological and vegetative development of hop varieties grown under organic and conventional management systems during the fall-winter season in Brazil. Thus, this study can contribute to the Brazilian hop production chain.

Materials and methods

Experimental conditions

These experiments were conducted at the orchard of the Lageado Farm at the Faculty of Agronomic Sciences (FCA) of São Paulo State University (UNESP) in Botucatu, São Paulo, Brazil (latitude 22°50'S, longitude 48°26'W and altitude 791 m). According to Köppen (1948), the climate is classified as subtropical with a hot summer (Cfa). During this period, the minimum average temperature was 17.94 °C, the maximum average temperature was 28.45 °C, and the rainfall amount was 1257.61 mm. The soil is a clayey dystroferric Red Latosol (Santos et al., 2018).

Treatments and experimental design

A randomized block experimental design was adopted in a 2 × 5 subdivided plot scheme, with the main factor being the cultivation system (conventional and organic) and the secondary factor being the hop variety (Cascade, Columbus, Chinook, Hallertau Mittelfrüeh and Nugget); there were four blocks and four useful plants per plot. The organic and conventional management systems were differentiated primarily by fertilization and phytosanitary control.

Conventional cultivation

Fertilizations were performed according to the needs observed in the soil analyses, which were measured in March 2020 (Table 8).

Topdressing fertilization was performed with calcium nitrate (375 $kg.ha^{-1}$), urea (94 $kg.ha^{-1}$), chicken litter (3.12 $t.ha^{-1}$) and potassium chloride (186 $kg.ha^{-1}$) with a mix of the micronutrients in Oligogreen® (Mg: 2.7%; S: 4.4%; B: 0.5%; Cu: 1%; Fe: 2%; Mn: 4%; Mo: 0.05%; Zn: 3%; N: 3%) (20 $kg.ha^{-1}$). Borate fertilization was performed with boric acid (4 $kg.ha^{-1}$), and foliar fertilization was performed with zinc sulfate (5 $kg.ha^{-1}$). For phytosanitary control, applications were performed with abamectin (Abamex®) (20 ml for 20 liters of water) for spotted mites (*Tetranychus urticae*), and fipronil (Regent®) was used for leaf-cutting ants.

Organic farming

Fertilizations were also performed according to the needs determined using the soil analysis, which was performed in March 2020 (Table 9).

Fertilization was performed with bokashi (1.5 $t.ha^{-1}$), castor bean cake (1.4 $t.ha^{-1}$) and organic poultry litter (2 $t.ha^{-1}$). Potassium sulfate (94 $kg.ha^{-1}$), potassium silicate (312 $kg.ha^{-1}$), thermophosphate (203 $kg.ha^{-1}$), boric acid (4 $kg.ha^{-1}$) and bone meal (1 $t.ha^{-1}$) were also used. Spraying was performed with Super Magro biofertilizer, and biological activation of the soil was performed with effective microorganisms (EM) (2 liters of EM for 20 liters of water). For phytosanitary control, when pests and diseases were identified, sulfocalcium spray was applied to treat for streaked mites (*Tetranychus urticae*), with organic formicide (Bioisca®) used to treat powdery mildew (*Podosphaera macularis*). *Metarhizium anisopliae* + *Beauveria bassiana* (B Exchange ®) was applied as a form of pest control.

Photosynthetic measurements

Chlorophyll *a* fluorescence measurements were performed using a fluorometer coupled to an LI-6400 photosynthesis analyzer (IRGA), Li-Cor, using the saturated pulse method (Maxwell et al., 2000), with the nomenclature recommended by Baker et al. (2004). Thus, the maximum photochemical yield of photosystem II (PSII), initial fluorescence (F_0), maximum fluorescence (*Fm*) and variable fluorescence (*Fv*) were measured, which enabled the calculations of the following measurements: PSII potential quantum efficiency (*Fv/Fm*), representing the quantum yield of the photochemical phase of photosynthesis; quantum efficiency of the antennas (F_v'/F_m'), representing the efficiency of the capture of the excitation of the electrons by the open reaction centers of PSII; and the apparent *ETR*, which was calculated according to Schreiber et al. (1986). To calculate the *ETR*, the fraction of energy excitation distributed to PSII was considered to be 0.5, and the fraction of photosynthetically active photon flux density (PPFD) absorbed by the leaf was 0.84 (Demmig et al., 1987). For these analyses, the leaves were wrapped with aluminum foil for 15 min to adapt them to the dark.

The following characteristics were also obtained: the rate of carbon assimilation (*A*, µmol CO_2 m^{-2} s^{-1}); stomatal conductance (g_s, mol m^{-2} s^{-1}); internal carbon concentration (C_i, µmol m^{-2} s^{-1}); transpiration (*E*, mmol water vapor m^{-2} s^{-1}); water use efficiency (*WUE*, µmol CO_2 m^{-2} s^{-1}/mmol H_2O m^{-2} s^{-1}), which was determined by the relationship between CO_2 assimilation and the transpiration rate; and the carboxylation efficiency (*A/Ci*, µmol CO_2 m^{-2} s^{-1}/µmol m^{-2} s^{-1}), which was determined by taking the ratio between the CO_2 assimilation rate and the internal CO_2 concentration in the leaves.

The photosynthetic photon flux density (PPFD, µmol m^{-2} s^{-1}) was used to confirm the consistency of the experimental conditions; therefore, standardization was performed during each evaluation period using a light-emitting diode coupled to the IRGA in accordance with the PPFD. During the evaluation, the ambient air concentration was the reference for the CO_2 concentration, with values ranging from 380–400 µmol mol^{-1} of air.

CO_2 assimilation response curve as a function of PPFD

The CO_2 assimilation rate curve (*A*, µmol CO_2 m^{-2} s^{-1}) was obtained as a function of the density of photosynthetically active photons (PPFD, µmol m^{-2} s^{-1}) by reducing the PPFD from 2000 µmol m^{-2} s^{-1} to 0 µmol m^{-2} s^{-1} in intervals of 200 µmol m^{-2} s^{-1} to 200 µmol m^{-2} s^{-1} and then in intervals of 50 µmol m^{-2} s^{-1} for a more precise curve. The experiment was conducted at 25 ± 3 °C, close to room temperature.

The response curve was defined for the hyperbolic function $A = a\ [(A\ \max * \text{PPFD})/(\text{b} + \text{PPFD})]$, where *A* max is the maximum CO_2 assimilation, and “a” and “b” are the parameters of the hyperbolic equation. The dark respiration (equation parameter a) and light point compensation (equivalent to the PPFD value where *A* is zero) were calculated using this function. A straight line (y = 1) was fitted at the highest points of the curve to establish the light saturation point.

Morphometric analyses

In terms of the morphometric measurements, the number of internodes and the plant height (PH) were obtained. The plants were harvested, the number of internodes on the most vigorous branch of each plant was counted, and the total plant height was measured using a tape measure.

Statistical analysis

The data were subjected to homogeneity and normality tests using the Shapiro–Wilk test in Minitab 17. The analysis of variance and the means were compared using the Scott–Knott test with a 5% probability in AgroEstat. The SAS 9 statistical program was used to adjust the hyperbolic function of the light response curves.

Conclusions

The test varieties presented satisfactory and responsive physiological performances, showing that the practices adopted here met the existing needs for the vegetative development of these varieties during the autumn-winter cropping period in Brazil.

Hop plants grown under organic management had higher values regarding physiological performance and morphometrics than those grown under the conventional system.

The Hallertau M. and Columbus varieties had the highest measures of gas exchange under both organic and conventional management, and Cascade had the lowest observed values.

Acknowledgments

This work was supported by the São Paulo Research Support Foundation - FAPESP under the grant (235 (2019/27066-8)); Coordination for the Improvement of Higher Education Personnel - CAPES under subsidy (001).

References

Amoriello T, Fiorentino S, Vecchiarelli V, Pagano M (2020) Evaluation of spent grain biochar impact on hop (*Humulus lupulus* L.) growth by multivariate image analysis. Appl. Sci.-Basel. 10(2):533. https://doi.org/10.3390/app10020533.

Baker NR, Rosenqvist E (2004) Applications of chlorophyll fluorescence can improve crop production strategies: an examination of future possibilities. J. Exp. Bot. 55(403):1607-1621. https://doi.org/10.1093/jxb/erh196.

Bauerle WL (2021) Internode elongation and strobili production of *Humulus lupulus* cultivars in response to local strain sensing. Sci. Rep.-UK. 11(1):1-10. https://doi.org/10.1038/s41598-021-88720-8.

Carvalho JS de, Bizerra EC, Marques PRR, Donato SLR, Magalhães DB, Rampazzo MC (2020) Características fitotécnicas e nutricionais de bananeiras submetidas a fontes de fertilizantes para o manejo orgânico. Nativa. 8(3):367-375. https://doi.org/10.31413/nativa.v8i3.8424.

Comexstat (2020). Online. Available from: <http://comexstat.mdic.gov.br/pt/geral/49697>. Accessed: Feb. 2, 2022.

Da Silva ARA, Bezerra FML, Lacerda CF de, Sousa CHC de, Chagas KL (2017) Pigmentos fotossintéticos e potencial hídrico foliar em plantas jovens de coqueiro sob estresses hídrico e salino. Rev Agro@mbiente On-line. 10(4): 317-325.

Da Silva TRG, Da Costa MLA, Farias LRA, Dos Santos MA, Rocha JJ de L, Silva JV (2021) Fatores abióticos no crescimento e florescimento das plantas. Res., Soc. Dev. 10(4): e19710413817. doi: 10.33448/rsd-v10i4.13817.

Dantas R de A, Carmona R, Carvalho AM de, Rein TA, Malaquias JV, Santos Júnior J de DG dos (2015) Produção de matéria seca e controle de plantas daninhas por leguminosas consorciadas com cana-deaçúcar em cultivo orgânico. Pesqui. Agropecu. Bras. 50(8):681-689. https://doi.org/10.1590/S0100-204X2015000800006.

Delahunty KM, Johnston JC (2015) Strategies for weed management in organic hops, a perennial crop. Agron. J. 107(2):634-640. https://doi.org/10.2134/agronj14.0403.

Demmig B, Björkman O (1987) Comparison of the effect of excessive light on chlorophyll fluorescence (77K) and photon yield of O_2 evolution in leaves of higher plants. Planta. 171(2):171-184.

Dodds KA (2017) Hops: a guide for new growers, 1ª ed. New South Wales (NSW): New South Wales Department of Primary Industries; (accessed 2021 Nov 03). https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0007/712717/hops-guide-for-new-growers.pdf.

Eriksen RL, Rutto LK, Dombrowski JE, Henning JA (2020) Photosynthetic Activity of Six Hop (*Humulus lupulus* L.) Cultivars under Different Temperature Treatments. HortScience. 55(4):403-409. https://doi.org/10.21273/HORTSCI14580-19.

Fagherazzi MM (2020) Adaptabilidade de cultivares de lúpulo na região do planalto sul catarinense [doctoral thesis]. Lages (UDESC): Universidade do Estado de Santa Catarina.

Governo do Brasil (2021). Online. Available on: https://www.gov.br/pt-br/noticias/agricultura-e-pecuaria/2021/08/mercado-cervejeiro-cresce-no-brasil-e-aumenta-interesse-pela-producao-nacional-de-lupulo-e-cevada.

Graf T, Beck M, Portner J, Baumgartner A, Mauermeier M, Ismann D, Maier M, Schmidhalter U (2019) A new approach for predicting the water balance of hops. Acta Hortic. 1236:63-74.

Guimarães BP, Nascimento PGBD, Ghesti GF (2021) Intellectual property and plant variety protection: Prospective study on Hop (*Humulus lupulus* L.) cultivars. World Pat. Inf. 65:102041. https://doi.org/10.1016/j.wpi.2021.102041.

Hejnák V, Hniličková H, Hnilička F (2015) Physiological response of juvenile hop plants to water deficit. Plant, Soil Environ. 61(7):332-338. doi: 10.17221/279/2015-PSE.

Jeong JH, Lee OM, Jeon YD, Kim JD, Lee NR, Lee CY, Son HJ (2010) Production of keratinolytic enzyme by a newly isolated featherdegrading *Stenotrophomonas maltophilia* that produces plant growth-promoting activity. Process Biochem. 45:1738–1745. https://doi.org/10.1016/j.procbio.2010.07.020.

Keskin Ş, Şirin Y, Cakir HE, Keskin M (2019) An investigation of *Humulus lupulus* L.: Phenolic composition, antioxidant capacity and inhibition properties of clinically important enzymes. S. Afr. J. Bot. 120:170-174. https://doi.org/10.1016/j.sajb.2018.04.017.

Keukeleire DD, Cooman LD, Rong H, Heyerick A, Kalita J, Milligan SR (1999) Functional properties of hop polyphenols. In: Gross GG, Hemingway RW, Yoshida T, Branham SJ (eds) Plant Polyphenols 2. Basic Life Sciences. Springer, Boston, MA. https://doi.org/10.1007/978-1-4615-4139-4_41.

Köppen W (1948) Climatologia: con un estudio de los climas de la tierra. México: Fundo de Cultura Econômica.

Liu M, Hansen PE, Wang G, Qiu L, Dong J, Yin H, Qian Z, Yang M, Miao J (2015) Pharmacological profile of xanthohumol, a prenylated flavonoid from hops (*Humulus lupulus*). Molecules. 20(1):754-779. https://doi.org/10.3390/molecules20010754.

Mantovani A, Ribeiro FJ, Veiga M, Zilio M, Felicio TP (2017) Métodos de aplicação de potássio na soja em nitossolo vermelho. U&C-ACBS. 8(2):169-176.

Maxwell K, Johnson GN (2000) Chlorophyll fluorescence—a practical guide. J. Exp Bot. 51(345):659-668. https://doi.org/10.1093/jexbot/51.345.659.

Oszust K, Frac M, Gryta A, Bilinska N (2014) The influence of ecological and conventional plant production systems on soil microbial quality under hops (*Humulus lupulus*). Int. J. Mol. Sci. 15(6):9907-9923. https://doi.org/10.3390/ijms15069907.

Peloso A de F, Tatagiba SB, Reis EF dos, Pezzopane JEM, Amaral JFT do (2017) Limitações fotossintéticas em folhas de cafeeiro arábica promovidas pelo déficit hídríco. Coffee Sci. 12(3):389-399.

Pokorný J, Pulkrabek J, Nesvadba V (2011) The physiological parameters of hop plant (*Humulus lupulus* L.). Paper presented in the minutes of the scientific committee of the international convention of hop growers, Lublin, Poland, 19 – 23 June 2011.

Prazeres SS, Lacerda CF de, Barbosa FEL, Amorim AV, Araujo IC da S, Cavalcante LF (2015) Crescimento e trocas gasosas de plantas de feijão-caupi sob irrigação salina e doses de potássio. Rev. Agro@mbiente On-line. 9(2):111-118.

Rossini F, Loreti P, Provenzano ME, Santis D de, Ruggeri R (2016) Agronomic performance and beer quality assessment of twenty hop cultivars grown in Central Italy. Ital. J. Agron. 11(3):180-187. https://doi.org/10.4081/ija.2016.746.

Rossini F, Virga G, Loreti P, Iacuzzi N, Ruggeri R, Provenzano ME (2021) Hops (*Humulus lupulus* L.) as a Novel Multipurpose Crop for the Mediterranean Region of Europe: Challenges and Opportunities of Their Cultivation. Agriculture. 11(6):484. https://doi.org/10.3390/agriculture11060484.

Ruggeri R, Loreti P, Rossini F (2018) Exploring the potential of hop as a dual purpose crop in the Mediterranean environment: shoot and cone yield from nine commercial cultivars. Eur. J. Agron. 93:11-17. https://doi.org/10.1016/j.eja.2017.10.011.

Santabarbara S, Monteleone FV, Remelli W, Rizzo F, Menin B, Casazza AP (2019) Comparative excitation-emission dependence of the FV/FM ratio in model green algae and cyanobacterial strains. Physiol. Plantarum. 166(1):351-364. https://doi.org/10.1111/ppl.12931.

Santos HG, Jacomine PKT, Anjos LHC dos, Oliveira VA de, Lumbreras JF, Coelho MR, Almeida JA de, Araujo Filho JC de, Oliveira JB de, Cunha TJF (2018) Sistema brasileiro de classificação de solos, 5ª ed. Brasília: EMBRAPA SOLOS.

Schreiber U, Schliwa U, Bilger W (1986) Continuous recording of photochemical and nonphotochemical chlorophyll fluorescence quenching with a new type of modulation fluorometer. Photosynth. Res. 10(1):51-62. https://doi.org/10.1007/BF00024185.

Silva BEP, Costa AVL, Simmi FZ, Reolon F, Deuner S (2019) Parâmetros fisiológicos e fotossintéticos de aveia branca submetidas à salinidade. Rev. Científica Rural. 21(1):60-71. https://doi.org/10.30945/rcr-v21i1.303.

Spósito MB, Ismael RV, Barbosa CM de A, Tagliaferro AL (2019) A cultura do lúpulo, 1ª ed. Piracicaba: Divisão de Biblioteca – ESALQ.

Turner SF, Benedict CA, Darby H, Hoagland LA, Simonson P, Sirrine JR, Murphy KM (2011) Challenges and opportunities for organic hop production in the United States. Agron. J. 103(6):1645-1654. https://doi.org/10.2134/agronj2011.0131