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Sustainable Hop Production in the Mountainous Region of Rio de Janeiro, Brazil: Agroindustrial Waste-Based Bokashi Fertilization Enhances Yield and Soil Quality

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RESUMO

O lúpulo (*Humulus lupulus* L.), espécie trepadeira da família Cannabaceae, é uma cultura fundamental para a indústria cervejeira. Esta planta de rápido crescimento pode atingir alturas de sete metros em 90 dias após a rebrota, demandando aportes substanciais de nutrientes devido à sua elevada acumulação de biomassa. No Brasil, as pesquisas sobre a nutrição do lúpulo permanecem limitadas, sendo necessários estudos sobre estratégias sustentáveis de adubação. Este estudo avaliou os efeitos da adubação com um composto fermentado (bokashi) formulado a partir de bagaço de malte de cervejaria e torta de mamona sobre os componentes de produção do lúpulo e as propriedades químicas do solo sob manejo orgânico. O experimento testou cinco doses do composto (0, 2, 4, 8 e 16 Mg ha⁻¹) em delineamento de blocos casualizados. Os resultados revelaram aumentos lineares nas concentrações de P, K e Mg na camada de 0–20 cm do solo com as doses mais elevadas do composto. A análise foliar mostrou níveis elevados de K, Zn e Mn, proporcionais às doses aplicadas. Para os componentes de produtividade, a maior dose (16 Mg ha⁻¹) alcançou o desempenho ótimo: 639,13 cones planta⁻¹ e 0,51 kg de biomassa fresca planta⁻¹. Embora o composto tenha fornecido aportes significativos de nutrientes, a produtividade do lúpulo não atingiu o potencial máximo, sugerindo a necessidade de testes com doses mais elevadas.

Palavras-chave: *Humulus lupulus*; adubação orgânica; subprodutos agrícolas; economia circular.

ABSTRACT

Hop (*Humulus lupulus* L.), a climbing species of the Cannabaceae family, is a key crop for the brewing industry. This fast-growing plant can reach heights of seven meters within 90 days of regrowth, demanding substantial nutrient inputs due to its high biomass accumulation. In Brazil, research on hop nutrition remains limited, necessitating studies on sustainable fertilization strategies. This study evaluated the effects of fertilization with a fermented compost (bokashi) formulated from brewers' spent grain and castor bean



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meal on hop production components and soil chemical properties under organic management. The experiment tested five compost doses (0, 2, 4, 8, and 16 Mg ha⁻¹) in a randomized block design. Results revealed linear increases in P, K, and Mg concentrations in the 0–20 cm soil layer with higher compost doses. Leaf tissue analysis showed elevated K, Zn, and Mn levels, proportional to application rates. For yield components, the highest dose (16 Mg ha⁻¹) achieved optimal performance: 639.13 cones plant⁻¹ and 0.51 kg of fresh biomass plant⁻¹. While the compost delivered significant nutrient inputs, hop yields did not reach maximum potential, suggesting the need for higher dosage trials.

Keywords: *Humulus lupulus*; organic fertilization; agricultural byproducts; circular economy.

Introduction

Hop (*Humulus lupulus* L.) is a plant from the botanical family Cannabaceae, native to temperate regions of the Northern Hemisphere. The cultivation of this plant is most prominent in regions between latitudes of 30° to 55° N and S (Turner et al. 2011). Hops are fast-growing plants with strong regrowth capacity, exhibiting a herbaceous and climbing growth habit. Although perennial, the above-ground portion completely senesces during a certain period of the year, and under favorable conditions, it regrows and can reach heights exceeding seven meters within 90 days after level pruning (Spósito et al. 2019).

Despite being the third-largest beer producer in the world, with an annual production of around 14 billion liters, Brazil still heavily depends on hop imports from other countries. Sourcing this raw material from abroad increases production costs for the national beer industry. Although hop cultivation initiatives in Brazil date back to the 19th century, large-scale production in the country is recent (Guimarães et al. 2021; Almeida and Conto 2024), and there is a lack of studies to establish knowledge on fertilizer dosage recommendations and suitable regions for crop establishment.

Due to its rapid growth and high above-ground biomass accumulation, hops have a high nutrient demand, making fertilization management essential to ensure high crop productivity, preserve and improve soil fertility, and guarantee production sustainability (Gingrich et al. 2000; Gent et al. 2019; Iskra et al. 2019). While adaptable to different soil types, hops thrive best in a pH range of 6.3 to 6.5, with available phosphorus levels above 41 mg kg⁻¹, and potassium and magnesium above 241 and 51 mg L⁻¹, respectively (Fink et al. 2022).

Despite these recommendations, no specific fertilization programs have been developed for Brazil's edaphoclimatic conditions for hop cultivation. As a result, fertilization recommendations from other countries, primarily relying on concentrated synthetic sources, are typically adopted. In this context, conducting studies in Brazil focused on hop nutrition becomes crucial. Considering the UN Sustainable Development Goals, particularly regarding sustainable agriculture, one way to meet hops' nutritional demands while strengthening environmental sustainability is through the production of fermented organic composts made from brewery industry byproducts.

In this regard, brewers' spent grain is an abundant resource in the industry, with Brazil producing approximately 2.8 million tons annually (Mussatto 2014). As an energy-rich material, spent grain can be used in fermented compost formulations, delivering high nutrient quantities (Souza Junior et al. 2023). Recycling nutrients from this byproduct reinforces circular economy principles, contributes to sustainable development, and the resulting fermented compost can serve as an excellent fertilizer source for agroecological hop cultivation in Brazil. Based on this premise, this study aimed to evaluate the effects of topdressing fertilization with a fermented compost formulated from brewers' spent grain and castor bean meal on hop production components under agroecological management, as well as on soil chemical properties.

Materials and Methods

The experiment was conducted in a single growing season, from 2021 to 2022, at Fazenda São Francisco. Managed by Grupo Petrópolis, the farm is located in Serra do Capim, in the municipality of



Teresópolis, in the mountainous region of Rio de Janeiro state, at geographic coordinates 22° 24' 44" S and 42° 57' 59" W, with an altitude of 730 meters. The hop production area at Fazenda São Francisco was established in 2019, cultivating various genetic materials. Starting in 2021, a plot exclusively planted with the Cascade cultivar was selected for the fertilization study.

The experimental design was a randomized block design, with five treatments corresponding to different doses of fermented compost (0, 2, 4, 8, and 16 Mg ha⁻¹, based on dry matter percentage) and four replications. The fermented compost was prepared by mixing 120 kg of brewers' spent grain, 80 kg of castor bean meal, and fermenting microorganisms. Initially, the spent grain and castor bean meal were homogenized using a concrete mixer. Next, inoculation was performed with a concentrated solution containing *Lactobacillus plantarum* and *Saccharomyces cerevisiae* from the commercial product Embiotic[®], at a dose of 0.5 mL per kg of the mixture. This solution was prepared by mixing 200 mL of the commercial product, 200 g of brown sugar, and 1600 mL of water, stored in a plastic bottle for seven days (activation phase).

After mixing and inoculation, the residues were added and compacted inside a water tank, sealed with plastic, and covered. The residues remained under microaerophilic conditions for 21 days (fermentation phase). After this period, samples were taken to determine nutrient concentrations, revealing the following results (g kg⁻¹): N - 41.8; P - 4.61; K - 7.08; Ca - 5.96; and Mg - 3.04.

The nutrient quantities applied with the different compost doses are described in Table 1. Each experimental plot consisted of five plants - two for data collection and three as borders. The spacing used was 3.0 m between rows and 1.0 m between plants, resulting in a density of 3,333 plants per hectare.

Table 1. Nutrient quantities applied via fertilization with different doses of fermented compost.

Doses of compost (Mg ha ⁻¹)	Quantities applied (kg ha ⁻¹)				
	N	P	K	Ca	Mg
2	83,6	9,20	14,1	11,9	6,1
4	167,2	18,4	28,2	23,8	12,2
8	334,4	36,8	56,4	47,6	24,4
16	668,8	73,6	112,8	95,3	48,8

Source: prepared by the authors.

Before the experiment, soil samples (0-20 cm depth) were collected for chemical and physicochemical analysis, yielding the following results: pH (H₂O) = 5.7; Al³⁺ = 0.03 cmolc dm⁻³; Ca²⁺ = 2.85 cmolc dm⁻³; Mg²⁺ = 1.05 cmolc dm⁻³; K⁺ = 3.49 mmolc dm⁻³; and available P = 31 mg dm⁻³. At the start of the experiment, a leveling pruning was performed to standardize shoot regrowth.

Topdressing fertilization with the fermented compost was split into three applications at 10, 55, and 85 days after pruning. Additionally, potassium silicate rock (Ekosil[®]) was applied at 600 g plant⁻¹, split into two applications (10 and 55 days after pruning), supplying 160 kg of K₂O per hectare. Bone meal was also applied at 150 g plant⁻¹ (equivalent to 80 kg of P₂O₅ per hectare) at 10 days after pruning.

Plants were trained on high trellises with a double sisal cord "V" system, maintaining two shoots per stem. Emerging shoots were pruned during growth. Drip irrigation (0.2m emitter spacing) was used, with periodic activation. Cultural practices included weed removal and spider mite control using Auin[®].

Soil chemical properties (P, K, Ca, Mg, pH) were analyzed at two sampling times: 15 days after the first fertilization and 15 days after the third fertilization. Samples were analyzed at Fundenor Laboratory (Fundação Norte Fluminense de Desenvolvimento Regional).



Hop agronomic evaluations included: number of cones per plant, fresh cone biomass yield, fresh and dry plant biomass, and leaf tissue nutrient concentrations (N, P, K, Ca, Mg, S, Fe, Cu, Zn, Mn, B).

Leaf sampling was conducted at 120 days after experiment initiation, collecting 15 leaves per plant (30 per plot) from fully expanded leaves below the first inflorescence (Gingrich et al. 2000). Leaves were dried, ground, and analyzed at Fundenor Lab. Nitrogen was determined using the Bremner and Mulvaney (1982) method, phosphorus and potassium via nitric-perchloric digestion, calcium and magnesium by atomic absorption spectrometry, sulfur by turbidimetry, micronutrients (Fe, Cu, Zn, Mn) by atomic absorption, and boron by colorimetry. Nutrient accumulation was calculated by multiplying dry matter mass by tissue nutrient content. Data were analyzed using ANOVA (F-test) and regression models (5% and 10% significance) in R (R Core Team 2021) and Sisvar (Ferreira 2011).

Results and Discussion

Soil chemical properties as a function of applied fermented compost doses

Significant effects of fermented compost doses were observed for soil P, K, and Mg levels in hop cultivation cv. Cascade (Table 2). Soil pH remained stable across doses (5.98 to 6.50), with higher mean values in collection 2 (6.39) compared to collection 1 (6.16), indicating a slight increase over time regardless of the applied doses. For available phosphorus, levels ranged from 222.75 to 655.25 mg dm⁻³, with significant differences between the two collections ($p < 0.05$), whereby collection 2 showed higher values (up to 655.25 mg dm⁻³ at the 16 Mg ha⁻¹ dose) compared to collection 1, indicating a positive linear response to organic fertilization with cumulative effect over time. Similarly, exchangeable potassium levels showed a linear increasing trend, ranging from 2.33 mmolc dm⁻³ at the 2 Mg ha⁻¹ dose to 3.90 mmolc dm⁻³ at the 8 Mg ha⁻¹ dose in collection 2, corroborating the efficiency of the compost as a source of this nutrient, with higher levels observed at 8 and 16 Mg ha⁻¹. For calcium, no significant dose effect was observed, with stable levels ranging from 50.50 to 67.48 mmolc dm⁻³, which may be explained by surface application (approximately 5 cm) while soil sampling was performed at 0-20 cm depth, resulting in a dilution effect that did not represent the gradual increase of this nutrient in the soil. In contrast, exchangeable magnesium levels showed distinct behavior, with lower values at 2 and 8 Mg ha⁻¹ (17.48 and 22.15 mmolc dm⁻³, respectively), suggesting a possible antagonistic effect with excess potassium or saturation of cation exchange capacity at intermediate doses. Finally, sodium showed a marked increase in the second collection (mean of 2.46 mmolc dm⁻³) compared to the first (1.41 mmolc dm⁻³), regardless of the applied doses. In summary, fermented compost was efficient in supplying P and K to the soil, with cumulative effects between collections, while Ca stability and Mg differential behavior indicate the need for complementary management strategies for these nutrients.



Table 2. Soil chemical properties as a function of increasing Bokashi doses in hop cultivation (cv. Cascade), comparing two collection periods.

Dose (Mg ha ⁻¹)	pH		P (mg dm ⁻³)		K (mmolc dm ⁻³)		Ca (mmolc dm ⁻³)		Mg (mmolc dm ⁻³)		Na (mmolc dm ⁻³)	
	C1	C2	C1	C2	C1	C2	C1	C2	C1	C2	C1	C2
0	6.43 a A	6.48 a A	407.00 a A	376.75 b A	2.55 a A	3.03 b A	67.48 a A	59.08 a A	28.00 a A	23.85 a A	1.25 a B	2.13 a A
2	5.98 a A	6.20 a A	222.75 a A	288.75 b A	2.33 a A	2.68 b A	50.50 a A	52.23 a A	17.48 b A	18.60 a A	1.35 a B	2.28 a A
4	6.18 a A	6.50 a A	372.25 a A	616.75 a A	2.63 a A	3.05 b A	59.00 a A	66.15 a A	25.05 a A	24.28 a A	1.50 a B	2.30 a A
8	6.03 a A	6.30 a A	311.25 a B	590.50 a A	3.35 a A	3.90 a A	53.20 a A	56.55 a A	22.15 b A	20.15 a A	1.50 a B	2.78 a A
16	6.18 a A	6.45 a A	338.25 a B	655.25 a A	2.88 a A	3.68 a A	59.50 a A	59.05 a A	29.63 a A	22.40 a A	1.43 a B	2.80 a A
Mean	6.16 B	6.39 A	330.30 B	505.60 A	2.75 B	3.27 A	57.94 A	58.61 A	24.46 A	21.86 A	1.41 B	2.46 A
CV (%)	3.73		42.12		20.89		15.85		22.12		32.78	

C1 = Collection 1; C2 = Collection 2. Lowercase letters in the same row indicate significant differences among doses within each collection; uppercase letters indicate significant differences between collections for the same dose (Scott-Knott test, $p \leq 0.05$). CV = coefficient of variation. Source: prepared by the authors.



Leaf nutrient concentrations in hop as a function of applied fermented compost doses

Significant effects of fermented compost doses were observed at 5% probability for potassium, boron, zinc, and manganese levels in the leaf tissues of hop cv. Cascade, with the linear model providing the best data fit (Figure 1). For potassium (Figure 1-C), a linear increasing response was observed as a function of increasing compost doses, with levels ranging from 12.94 g kg⁻¹ in the control to 15.85 g kg⁻¹ at the highest dose (16 Mg ha⁻¹). The highest potassium levels were found in plants from treatment 5 (16 Mg ha⁻¹), with a mean of 16.3 g kg⁻¹, a value within the normal range for the crop (16 to 34 g kg⁻¹), indicating greater uptake of this nutrient compared to the other treatments, which remained below the expected range. Potassium is highly relevant for hops, being the most demanded nutrient after nitrogen, essential for growth and cone yield (Gingrich et al. 2000; Dodds 2017).

For zinc (Figure 1-I) and manganese (Figure 1-J), positive linear responses were also observed, with expressive increases at higher doses, reaching 36 mg kg⁻¹ and 210 mg kg⁻¹, respectively, at 16 Mg ha⁻¹. The highest mean zinc levels were obtained in treatment 5 (32.50 mg kg⁻¹), within the established critical range of 23 to 108 mg kg⁻¹ for cone growth and yield, except for treatment 2 (2 Mg ha⁻¹), which fell below this range. For manganese, treatment 5 showed the highest mean level (173.50 mg kg⁻¹), with treatments 3 (4 Mg ha⁻¹) and 5 (16 Mg ha⁻¹) presenting values above the indicated sufficiency range of 54 to 125 mg kg⁻¹ (Afonso et al. 2021).

In contrast, boron (Figure 1-K) showed a decreasing linear response, with a sharp reduction as compost doses increased, ranging from 117 mg kg⁻¹ in the control to 57 mg kg⁻¹ at the maximum dose. The control (0 Mg ha⁻¹) promoted the highest boron uptake and accumulation in shoot biomass (108.75 mg kg⁻¹), whereas with increasing doses, mean levels decreased significantly, although they remained above the adequate range of 18 to 63 mg kg⁻¹ (Afonso et al. 2021). This behavior suggests possible competition with other micronutrients (notably Zn and Mn), limiting boron uptake in plant tissue in response to increasing fermented compost doses.

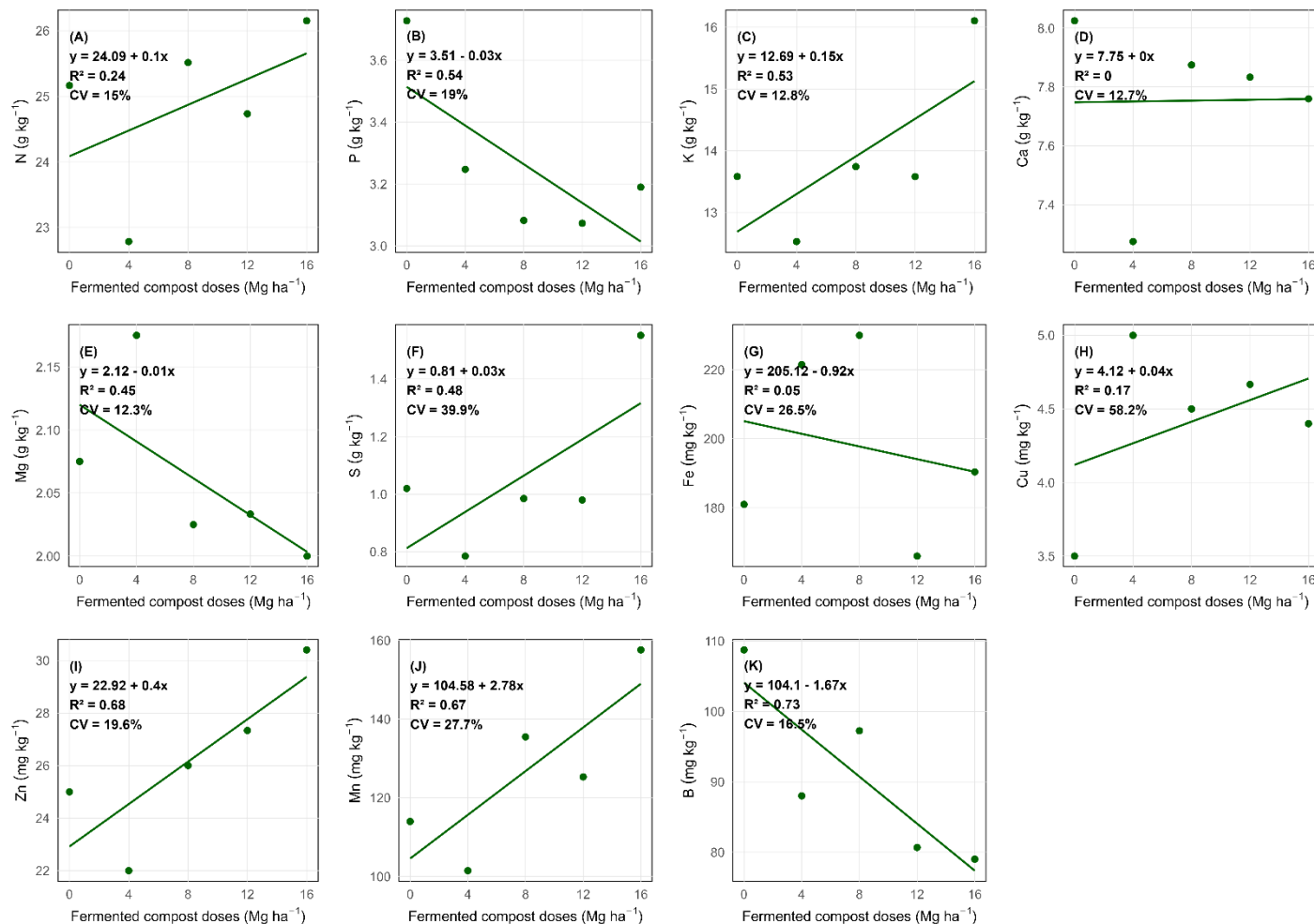


Figure 1. Leaf nutrient concentrations in hop cv. Cascade as a function of increasing fermented compost (Bokashi) doses. (A) Nitrogen (N, g kg⁻¹), (B) Phosphorus (P, g kg⁻¹), (C) Potassium (K, g kg⁻¹), (D) Calcium (Ca, g kg⁻¹), (E) Magnesium (Mg, g kg⁻¹), (F) Sulfur (S, g kg⁻¹), (G) Iron (Fe, mg kg⁻¹), (H) Copper (Cu, mg kg⁻¹), (I) Zinc (Zn, mg kg⁻¹), (J) Manganese (Mn, mg kg⁻¹), and (K) Boron (B, mg kg⁻¹). Solid lines represent linear regression fits, with equations, R² values, and coefficients of variation (CV) shown in each panel. Teresópolis, RJ, Brazil. Source: prepared by the authors.



Phytotechnical performance of hop cv. Cascade as a function of fermented compost doses

Linear regression analysis revealed differential responses of hop productive variables to increasing Bokashi doses (Figure 2). For the number of cones per plant, the best mathematical fit was provided by the increasing linear model (Figure 2-A), with response proportional to increasing doses, whereby the dose of 16 Mg ha⁻¹ of compost yielded the best result, with 639.13 cones plant⁻¹. This indicates that the crop may not have expressed its maximum response potential, suggesting that higher fertilizer doses are needed to achieve this. The highest dose provided a 77% increase in cone number compared to the lowest dose applied (control). Cone number is a component that directly influences crop productivity and can vary according to the cultivar used (Rybacek 2014). In Brazil, the Cascade cultivar has the potential to reach between 200 and 3,000 cones per plant, as observed in the study by Fagherazzi (2020) in three distinct locations. However, depending on the region's climatic conditions and crop management practices, this number can vary, as described by Ruth (2018).

As described for cone number, the 16 Mg ha⁻¹ dose also provided the highest fresh cone biomass production, with 0.51 kg plant⁻¹ (Figure 2-B). Notably, the application of 16 Mg ha⁻¹ provided a 104% increase for this parameter compared to the lowest dose (control) that received no fertilization. As previously reported, the absence of a maximum point for all analyzed variables suggests that higher doses of fermented compost may result in greater responses for hop yield components.

Fortuna et al. (2023), evaluating fresh inflorescence biomass production of cv. Cascade in Botucatu, SP, under two production systems, obtained mean values of 940.4 g plant⁻¹ under organic management and 433.91 g plant⁻¹ under conventional management. The values found by that author in organic management were higher than those found in the present study. The crop's response to top-dressing organic fertilization using fermented compost formulated with malt bagasse may have been affected by two-spotted spider mite (*Tetranychus urticae*) infestation during plant development, influencing the results for yield components.

In contrast, total fresh plant weight (Figure 2-C) did not show a consistent response pattern, with values ranging from 1.62 to 2.19 kg, without evident relationship with the applied doses. Similarly, plant dry weight (Figure 2-D) remained relatively stable across doses (0.60 to 0.83 kg). Finally, it is noteworthy that the soil of the experimental area at the time of study implementation had high nutrient levels (Table 2), which may have impacted the response of fresh and dry biomass production variables to the applied doses. Thus, the nutrients contained in the soil were likely sufficient to meet plant requirements.

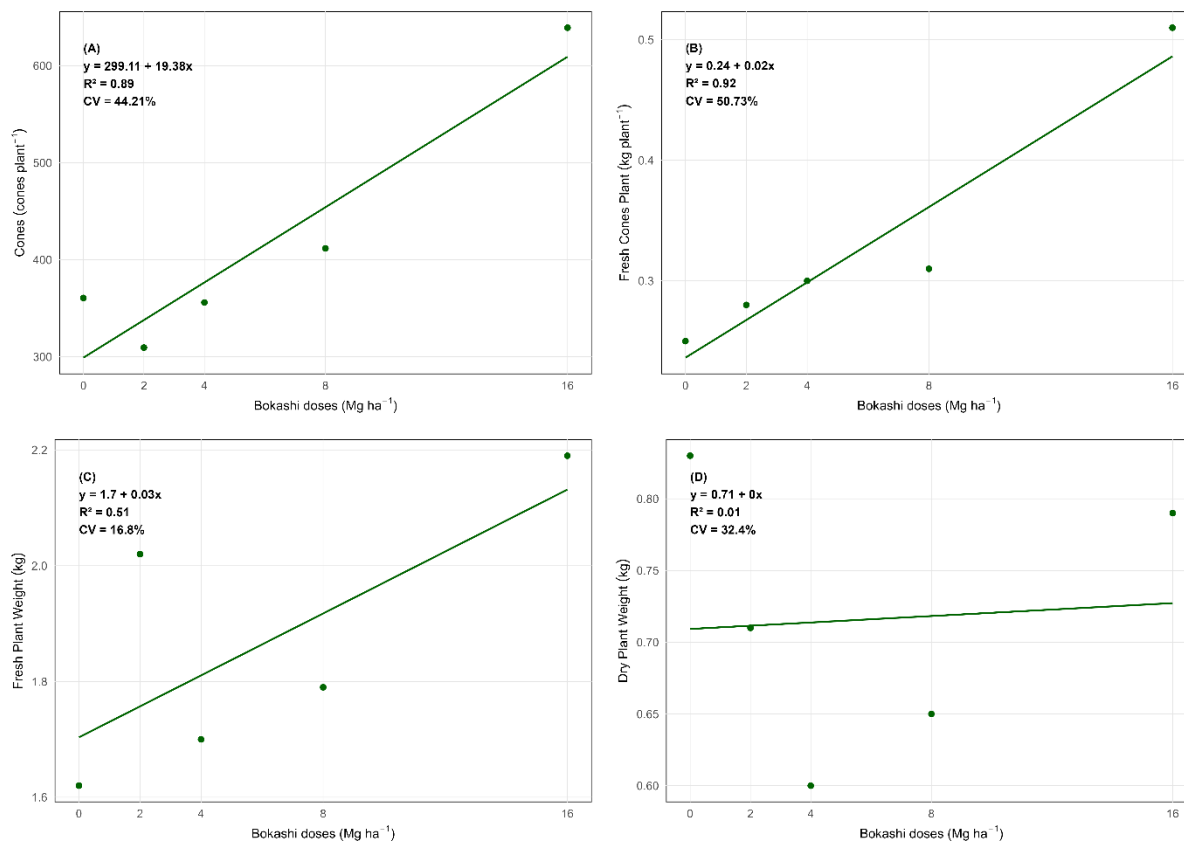


Figure 2. Phytotechnical performance of hop cv. Cascade under increasing fermented compost (Bokashi) doses. (A) Number of cones (cones plant⁻¹), (B) Fresh cone weight (kg plant⁻¹), (C) Total fresh plant weight (kg), and (D) Total plant dry weight (kg). Solid lines represent linear regression fits, with equations, R² values, and coefficients of variation (CV) shown in each panel. Regression analysis considered a significance level of 5% probability.

Teresópolis, RJ, Brazil. Source: prepared by the authors.

Conclusions

Top-dressing fertilization using a fermented compost formulated with brewery malt bagasse results in increased inflorescence productivity of hop, cultivar Cascade, under the climatic conditions of the Serrana Fluminense region.

The fresh inflorescence biomass production of hop, cultivar Cascade, shows a linear and proportional increase with the applied dose of fermented compost formulated with brewery malt bagasse, up to the applied dose equivalent to 16 Mg ha⁻¹ under the climatic conditions of the Serrana Fluminense region. This denotes the agronomic efficiency of this organic fertilization source for achieving high hop inflorescence yield.

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