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SCIENTIFIC ARTICLE

Sugar industry waste transformed into organic fertilizer: effect of different doses on carrot (*Daucus carota* L.) growth and yield

Residuos de la industria azucarera transformados en fertilizante orgánico: efecto de diferentes dosis en el crecimiento y rendimiento de la zanahoria (*Daucus carota* L.)

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The authors declare no conflict of interest.

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ABSTRACT

Carrot is a food source rich in bioactive compounds essential for human nutrition. Being a short-cycle crop, it has high nutritional demands that are commonly satisfied through intensive use of chemical fertilizers, which increase production costs and deteriorate soil health. As a sustainable alternative, the valorization of organic waste for fertilizer production emerges. The objective of this work was to evaluate the effect of different doses of composted organic fertilizer, derived from sugar byproducts, on carrot crop growth and yield. The experiment was conducted at the experimental field of the Paraguayan Institute of Agricultural Technology (IPTA) in Caacupé, Paraguay, using the Shin Kuroda variety under a randomized complete block design with three replications per treatment. Treatments consisted of four increasing doses of organic fertilizer (2, 4, 6, and 8 t ha^{-1}) and a control treatment without fertilization. Plant height, root length and diameter, root weight, and total yield were evaluated. Data were analyzed using analysis of variance ($p < 0.05$). Results showed that plant height, root weight, and yield were not significantly influenced by the applied organic fertilizer doses. However, significant differences were observed in root diameter and length. It is concluded that the evaluated organic fertilizer doses were not sufficient to completely satisfy the nutritional demands of the carrot crop.

Keywords: organic amendments, circular economy, sustainable horticulture, plant nutrition.

RESUMEN

La zanahoria es un alimento rico en compuestos bioactivos esenciales para la nutrición humana. Por ser un cultivo de ciclo corto, presenta una alta demanda nutricional que comúnmente se satisface mediante el uso intensivo de fertilizantes químicos, los cuales elevan los costos de producción y deterioran la salud del suelo. Como alternativa sustentable, surge la valorización de residuos orgánicos para la producción de fertilizantes. El objetivo del trabajo fue evaluar el efecto de diferentes dosis de fertilizante orgánico compostado, derivado de subproductos azucareros, sobre el crecimiento y rendimiento del cultivo de zanahoria. El experimento se realizó en el campo experimental del Instituto Paraguayo de Tecnología Agraria (IPTA) en Caacupé, Paraguay, utilizando la variedad Shin Kuroda bajo un diseño de bloques completos al azar con tres repeticiones por tratamiento. Los tratamientos consistieron en cuatro dosis crecientes del fertilizante orgánico (2, 4, 6 y 8 t ha^{-1}) y un tratamiento testigo sin fertilización. Se evaluaron altura de planta, longitud y diámetro de raíz, peso de raíz y rendimiento total. Los datos se analizaron mediante análisis de varianza ($p < 0,05$). Los resultados mostraron que la altura de planta, peso de raíces y rendimiento no fueron significativamente influenciados por las dosis de fertilizante orgánico aplicadas. Sin embargo, se observaron diferencias significativas en el diámetro y longitud de la raíz. Se concluye que las dosis de fertilizante orgánico evaluadas no fueron suficientes para satisfacer completamente las demandas nutricionales del cultivo de zanahoria.

Palabras clave: enmiendas orgánicas, economía circular, horticultura sostenible, nutrición de plantas.

INTRODUCTION

Carrot (*Daucus carota* L.) is one of the most consumed vegetables worldwide due to its high nutraceutical value provided by carotenoids, fibers, vitamins, and minerals that possess high antioxidant capacity and generate important benefits for food security (Martínez-Saldarriaga, Henao-Rojas, Flórez-Martínez, Cadena-Chamorro, and Yepes-Betancur, 2025; Que et al., 2019). However, being a short-cycle crop, it demands high nutrient requirements to sustain optimal development in terms of growth, yield, and quality (Hailu, Hassen, Hussen, Belete and Alemu, 2024; Oleszkiewicz et al., 2025). To meet these demands, chemical fertilizers have been used intensively over recent decades (Mitsigiorgi et al., 2024). Although the application of these inputs has increased crop yields (Andualem, Kemal, Mekonen, Yenet and Kassa, 2025), their excessive use has generated high costs for producers and triggered serious problems in the agroecosystem (Urra, Alkorta, Mijangos and Garbisu, 2020; Wu et al., 2025).

Excessive use of chemical inputs leads to soil acidification, loss of organic carbon and microbial biodiversity, and alteration of nutrient cycles through processes such as volatilization, leaching, and erosion (De Carolis et al., 2024; Mitsigiorgi et al., 2024; Windisch et al., 2020). These alterations not only affect soil quality, but also impact water and atmospheric resources, contributing to eutrophication and increased greenhouse gas emissions, which endangers global ecological balance (Villalba Algarin, 2025). Faced with these challenges, it is necessary to explore nutritional management alternatives that mitigate these adverse effects, promoting more sustainable horticultural production in harmony with the natural environment.

The use of agro-industrial waste as organic fertilizers has gained relevance as a viable alternative to restore soil health, promote plant growth, and mitigate environmental impacts (Maomao et al., 2023; Urra et al., 2020). This strategy, aligned with circular economy principles, facilitates the reuse of byproducts from industries such as sugar, which generate large volumes of bagasse rich in organic matter and essential nutrients (Gálvez Torres, Legua Cárdenas, Cruz Nieto, Caro Soto and Inga Sotelo, 2019; García-Ramos, Quirós-Roque and Rosales-Mendoza, 2022; Velasco-Velasco, Gomez-Merino, Hernández-Cázares, Salinas-Ruiz and Guerrero-Peña, 2017).

Composting, an aerobic treatment, presents significant advantages by requiring less time for the bioconversion of organic waste into biofertilizer, with lower operating costs and a relatively simple process (Srivastava and Chakma, 2023). This treatment transforms waste into amendments that release nutrients gradually, promotes balanced supply for crops, and optimizes soil nutritional efficiency (Velasco-Velasco et al., 2017; Yagüe and Lobo, 2024). Additionally, its use decreases dependence on synthetic fertilizers, improves agricultural profitability, and contributes to environmental sustainability (LI et al., 2017; Wang, Zhu, Zhang and Wang, 2018; Parađiković et al., 2019).

Recent studies have demonstrated that organic fertilizers significantly improve crop agronomic performance, due to increased organic carbon levels and soil enrichment with essential macro and micronutrients, while stimulating microbial diversity (Chen et al., 2023; Dao et al., 2020; El-Mogy et al., 2020; Pinter et al., 2019; Urra et al., 2020; Windisch et al., 2021). Furthermore, these inputs strengthen soil physical structure, improve water retention capacity, and favor a more stable environment for the root system (Chae et al., 2024; Duan et al., 2023). Plants with greater root growth manage to explore environmental resources in deeper soil layers (Villalba Algarin, González, Szostak and Sanabria Franco, 2024a), which ultimately translates into better plant morphology and yield (Fernandes et al., 2024; Krzyżak et al., 2024; Yagüe & Lobo, 2024).

Organic fertilizers derived from sugar industry waste have shown promising results in various horticultural and agricultural crops (Gálvez Torres et al., 2019; Matheus, 2004). However, limited data are still available on their performance under Paraguay's agro-environmental and productive conditions, particularly in crops such as carrot. This knowledge gap restricts their adoption as a viable alternative for more sustainable fertilization in local productive systems and limits the utilization of these byproducts as organic amendments.

Based on these premises, the hypothesis was posed that sugar industry waste, converted into organic fertilizers through composting, improves both carrot growth and yield, with more marked effects as applied doses increase. To verify this hypothesis, a field experiment was designed whose objective was to evaluate the effect of different doses of composted organic fertilizer, derived from sugar byproducts, on carrot crop growth and yield.

MATERIALS AND METHODS

Experimental area

The experiment was conducted from July to November 2021 at the experimental plot of the Horticultural Research Program, located at the Hernando Bertoni Research Center (CIHB-IPTA), in the City of Caacupé, Paraguay (25°23′16.38′′ S, 57°11′22.24′′ W). Meteorological data for the period were obtained from the CIHB-IPTA weather station, recording minimum and maximum temperatures of 16.7 °C and 29.2 °C, respectively, with a total accumulated precipitation of 534 mm, whose monthly variations are presented in Figure 1. The soil of the experimental area is classified as Arenic Kandiudult, characterized by a dark reddish-brown color (López Gorostiaga et al., 1995), and its initial chemical properties, determined before the experiment installation, are detailed in Table 1.

Obtaining and characterization of organic fertilizer

The organic fertilizer used in this study was obtained from Cooperativa Manduvira Ltda., located in the city of Arroyos y Esteros. This cooperative produces organic fertilizers from solid waste derived from sugarcane processing, through a composting process without the use of chemical inputs. Raw materials include filter cake (58%), sugarcane bagasse (5%), ash (10%), vegetable protein (10%), minerals (1%), cattle manure (6%), poultry manure (1%), and liquid ecological decomposer inoculants (9%).

Composting is carried out in vertical piles with inoculation of native microorganisms and control of temperature (<70 °C), pH and humidity (20-30%), using mechanical turning to ensure adequate aeration until material maturity is reached. In the final stage, beneficial microorganisms are added to improve the biological quality of the compost.

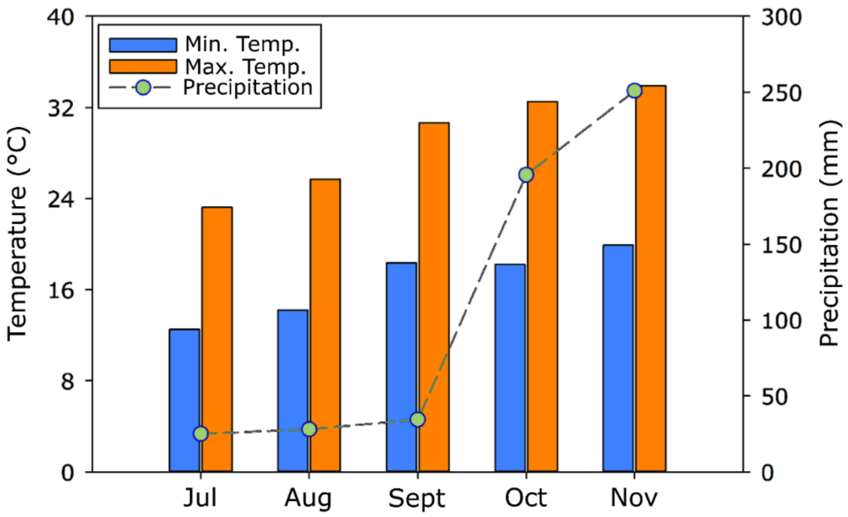

Figure 1. Monthly climatic behavior (minimum, maximum temperature and precipitation) during the experimental period at the Hernando Bertoni Research Center of the Paraguayan Institute of Agricultural Technology, Caacupé, Paraguay, 2021.

Table 1. Chemical characteristics of soil in the experimental area before the start of the experiment

Depth	**pH**	SOM	**P**	**Al^{+3}**	**Ca^{+2}**	**Mg^{+2}**	**K^{+}**
cm		%	mg dm^{-3}	..............$cmol_c$ dm^{-3}................			
0-20	6,40	0,82	30,87	0,0	2,86	0,33	0,03

Note: pH (H_2O); SOM (Soil Organic Matter, modified Walkley-Black); P and K^+(Mehlich); Al^{3+}, Ca^{2+} and Mg^{2+} (KCl 1 mol·L^{-1})

The result is a stable and biologically active product, ready for agricultural use. The main nutritional characteristics of the compost indicate that it possesses 7.45 g/100 g of organic carbon, 4.4 g/100 g of nitrogen, 0.4 g/100 g of phosphorus, 0.3 g/100 g of potassium, 1.7 g/100 g of calcium, and 0.47 g/100 g of magnesium. Chemical characterization of the organic fertilizer was performed through routine analysis in the laboratory at the Hernando Bertoni Research Center of the Paraguayan Institute of Agricultural Technology, Caacupé, Paraguay.

Treatments and experimental design

This study evaluated five treatments consisting of four doses of composted organic fertilizer from sugar industry waste and a control treatment without fertilization. The evaluated levels were: F0 (control, without fertilization), F1 (2 t ha^{-1}), F2 (4 t ha^{-1}), F3 (6 t ha^{-1}), and F4 (8 t ha^{-1}).

The experimental design was organized under a randomized complete block scheme with three replications per treatment, resulting in a total of 15 experimental plots. Each experimental plot of 1.2 x 1.2 m contained four rows separated 0.25 m from each other and 0.08 m between plants, corresponding to a total of 48 plants per plot and 720 plants in the entire experiment. The useful area was considered to be the two central rows with a surface area of 0.816 m^2, discarding the lateral rows and 0.16 m at the ends due to border effect (Figure 2).

Crop establishment and evaluation methods

Soil sampling and analysis were performed at the beginning of July 2021. Fifteen days before sowing, the soil was prepared with the help of a rototiller and raised beds of 20 cm height were formed. Following this, the composted organic fertilizer dose, previously weighed according to assigned treatments, was applied and incorporated with a rake. Subsequently, the drip irrigation system was installed.

Carrot sowing, variety *Shin Kuroda*, was carried out at the end of July. Furrows were opened with a hoe and seeds were deposited manually at 1 cm depth. At 30 days after sowing (DAS), thinning was performed, leaving plant populations as described in the previous section. Throughout the entire crop cycle, periodic monitoring was conducted to ensure optimal irrigation and cleaning conditions. No phytosanitary products were applied at any stage of the crop.

Plant height (cm) was measured at three time points

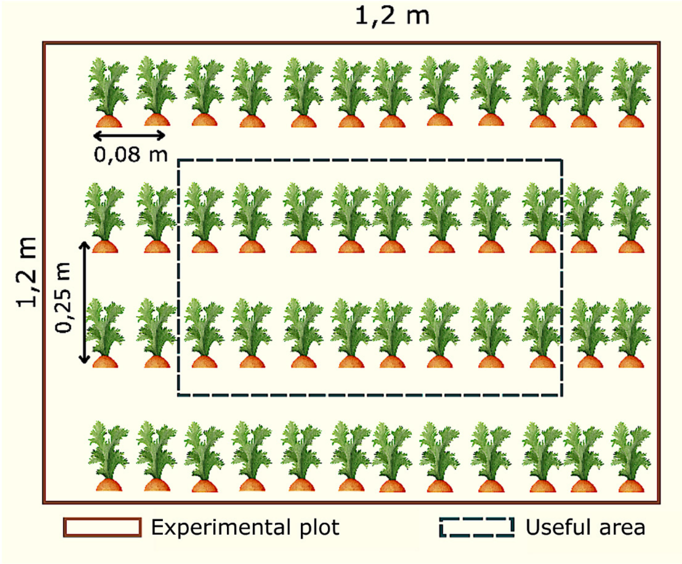

Figure 2. Schematic plan of the experimental plot, with dimensions and distances between rows and plants, highlighting the useful area. Caacupé, Paraguay, 2021.

after sowing (30, 60, and 110 DAS, respectively). For this purpose, six plants were randomly selected from the useful area of each plot. Height was measured from soil level to the apex of the aerial part using a measuring tape.

Harvest was performed immediately after the last plant height evaluation (110 DAS). At this stage, six roots were randomly selected from the useful area, and the following variables were measured: root length (cm), determined from the base of the crown to the longest distal extremity; root diameter (cm), measured 2 cm below the crown with a caliper; root weight (g), after washing the roots to remove soil residues and air drying, they were weighed on a precision digital scale; and yield (kg m^{-2}), calculated from the average weight of roots obtained in each treatment, extrapolated by multiplying the average weight by the population density established in the experiment.

Statistical analysis

Data were processed using R software (R Core Team, 2020). Normality of residuals was evaluated using the Shapiro-Wilk test. Once this assumption was confirmed, analysis of variance (ANOVA) was performed to determine the effect of treatments on carrot growth and yield variables. When significant differences were identified ($p \leq 0.05$), treatment means were compared using Duncan's test at the same significance level. Additionally, for significant variables, regression analysis corresponding to the evaluated doses was performed.

RESULTS AND DISCUSSION

Effect of organic fertilizer on carrot growth parameters

Carrot plant height measured at three stages of the growth cycle is presented in Table 2. Although the highest dose showed heights up to 17% higher at 30 DAS, 16% at 60 DAS, and 13% at 110 DAS compared to other treatments, vegetative growth was statistically similar for all treatments and evaluation stages. These results contrast with those of Hailu et al. (2024), who reported a significant increase in carrot plant height with vermicompost application, but coincide with those of Chillo Yupanqui, Peñafiel Rodríguez and Aruquipa Condori (2024), who observed no significant differences with poultry manure-based fertilizers.

The limited growth response observed in this study could be attributed to the low compost doses applied, which were insufficient to completely satisfy the nutritional needs of the crop, especially in terms of nitrogen (N) and potassium (K). Although the compost used contained considerable amounts of these nutrients, the concentrations present in the soil were relatively low, particularly for K (Table 1). This macronutrient is fundamental for various biochemical functions in plants and is known to improve the quality of horticultural products by participating in processes such as enzymatic metabolism and synthesis of defense compounds (Sustr, Soukup and Tylova, 2019).

Furthermore, the slow release of N in the compost may have restricted its immediate availability, limiting the growth of the crop's aerial part, which is crucial for sustaining high levels of photosynthesis and accumulating reserves for root development, directly impacting final yield (Guan, Zhang and Chu, 2025; Mishra, Levengood, Fan and Zhang, 2024; Zhou et al., 2022). This suggests that, in addition to increasing applied doses, it might be necessary to enrich the compost with rapid-release sources of N and K or combine it with mineral fertilizers to optimize the availability of these nutrients in degraded soils and satisfy crop demands more effectively.

Table 2. Carrot plant height at 30, 60, and 110 days after sowing (DAS) under different doses of composted organic fertilizer made from sugar industry waste.

Treatments	Plant height (cm)		
	30 DAS	**60 DAS**	**110 DAS**
F0	5,1 NS	23,8 NS	41,2 NS
F1	5,3	24,8	40,7
F2	4,8	23,0	37,3
F3	5,4	23,6	40,5
F4	5,6	26,7	42,3
p value	0,73	0,59	0,75
CV%	16,08	14,11	12,85

NS: no significant difference between treatments by Duncan's test ($p \leq 0.05$). CV: coefficient of variation.

Influence of organic fertilizer on crop yield parameters

Root length and diameter increased significantly with the applied organic fertilizer doses ($p < 0.05$). Regarding length, the treatment with the highest dose (F4) showed increases of up to 24.7% compared to the control (F0), reflecting the positive impact of higher concentrations on this variable (Figure 3a). This trend was confirmed by regression analysis, which showed a significant linear association between applied dose and root length ($y = 12.418 + 0.313x$; $R^2 = 0.73$; Figure 3b). When analyzing the equation, it is observed that for each ton of organic fertilizer applied, root length increases on average by 0.313 cm, with dose being responsible for explaining 73% of the observed variation.

Similarly, root diameter also increased with higher doses, with F4 being the treatment with the greatest increases: 34.9% compared to the control and 15.3% compared to F1 (Figure 3c). This positive relationship was supported by regression analysis, which showed a strong linear fit ($y = 2.590 + 0.104x$; $R^2 = 0.89$; Figure 3d). When interpreting the equation, it is observed that carrot diameter increased on average by 0.104 cm for each ton of fertilizer applied, and that 89% of the observed variation in this variable is explained by the dose used.

Both evaluated parameters suggest that higher doses are required to reach the optimum point in the response curve, highlighting the need to conduct local studies on degraded soils to maximize the agronomic potential of the crop. These results are consistent with previous research that has demonstrated positive effects of organic fertilizers on crop root development. For example, Hailu et al. (2024) reported increases of 63% in length and 146% in carrot root diameter with 3 t ha^{-1} of vermicompost, while Zerga Heterat & Tsegaye (2019) observed increases of 118% in

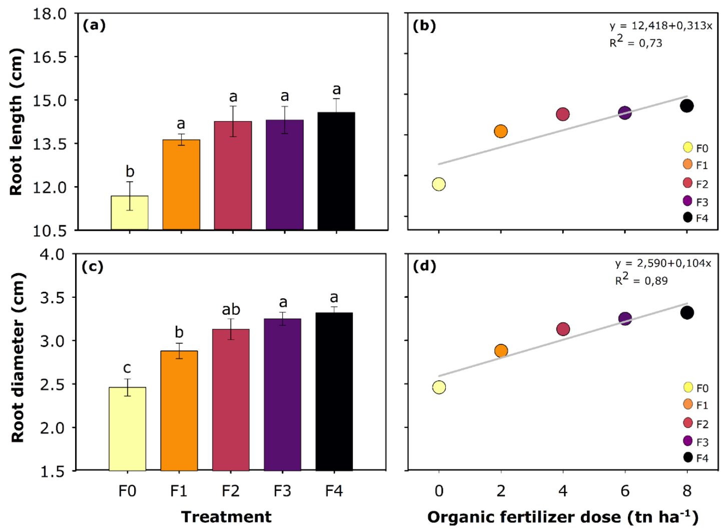

Figure 3. Root length (a-b) and root diameter (c-d) under different doses of composted organic fertilizer made from sugar industry waste. F0 (control, without fertilization), F1 (2 t ha^{-1}), F2 (4 t ha^{-1}), F3 (6 t ha^{-1}), and F4 (8 t ha^{-1}). Vertical lines above bars indicate standard error of means (n = 3). Different letters above bars indicate significant differences between treatments by Duncan's test ($p \leq 0.05$).

diameter with 75 t ha^{-1} of compost. These findings support the capacity of organic fertilizers derived from solid waste to significantly improve root structure.

Both root length and diameter are critical parameters for commercial quality and support of carrot plants (Chillo Yupanqui et al., 2024; Hailu et al., 2024). The positive effect observed with increasing doses of organic fertilizer may be related to the gradual supply of essential nutrients (Oyege and Balaji Bhaskar, 2023). Additionally, the incorporation of organic matter may have partially improved soil structure (Villalba Algarin, 2025), increasing moisture retention and aeration, conditions that favor root development and facilitate nutrient uptake in deeper layers of the soil profile (Salman et al., 2023; Tavali, 2020; Villalba Algarin, Ramírez Paniagua, Sanabria Franco and da Silva, 2024b). These benefits may have promoted more efficient root growth in treatments with increasing doses of organic fertilizer.

Although increases in root length and diameter were not significantly reflected in root weight and yield, both variables showed a positive linear response with increasing fertilizer doses (Figure 4). Regression analysis showed that, even at the highest doses, yield and root weight continued to increase proportionally (Figure 4b, d), confirming that the applied doses did not saturate the crop's response potential. This suggests that the crop could continue to respond positively to higher applications, possibly because critical thresholds for maximizing productivity have not yet been reached. This trend is consistent with the gradual nutrient release characteristic of organic fertilizers, which may require higher applications to sustain significant increases in biomass and yield, especially in crops with relatively short cycles (Bonanomi, Lorito, Vinale and Woo, 2018).

When analyzing root weight, it was observed that the lowest weight was recorded in F0 (46.6 g), while F4 reached the highest value with 59.3 g (Figure 4a). When interpreting the regression equation, a linear response is observed where for each ton of organic fertilizer applied there is an increase of 1.386 g in root weight (Figure 4b). Although this does not represent a statistically significant difference between means, it could suggest that the applied amounts of organic fertilizer have not been sufficient to completely cover the nutritional demands of the crop and fully activate its productive capacity.

Likewise, when analyzing root yield, it was observed that the lowest value was obtained in the control treatment (F0 = 2.23 kg m^{-2}) and reached its maximum point in F4 (2.85 kg m^{-2}) (Figure 4c). This linear response was supported by regression analysis, which showed that for each ton of fertilizer applied, the increase in yield was 0.066 kg per square meter ($y = 2.366 + 0.066x$; $R^2 = 0.79$; Figure 4d).

These results partially contrast with those reported in previous studies that found statistically significant increases in root yield with the use of organic fertilizers. For example, Hailu et al. (2024) and Zerga Heterat and Tsegaye (2019) documented substantial improvements in these variables with the highest applied doses. Although a gradual increase was observed here with the studied doses, the degraded soil conditions influenced the agronomic responses of the crop.

The use of organic fertilizers in vegetable production has shown mixed results. Some studies reported positive effects on crop productivity and soil quality, while others found limited effects. For example, Núñez Sosa, Liriano González, and López Ceballos (2005) observed that the efficiency of organic amendments can increase when soil organic matter levels are lower. Similarly, Juárez-Rodríguez, Hidalgo-Moreno, Hernández-López, Padilla Cuevas and Etchevers (2024) found that organic fertilizers improved

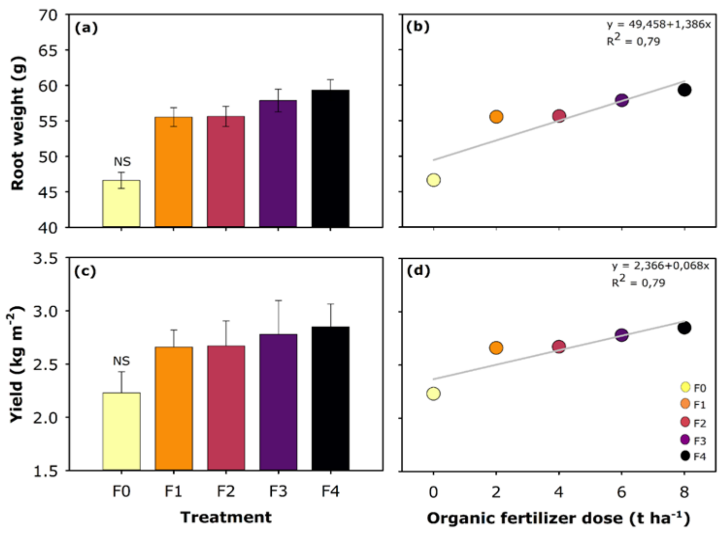

Figure 4. Root weight (a-b) and yield (c-d) of carrot under different doses of composted organic fertilizer made from sugar industry waste. F0 (control, without fertilization), F1 (2 t ha^{-1}), F2 (4 t ha^{-1}), F3 (6 t ha^{-1}), and F4 (8 t ha^{-1}). Vertical lines above bars indicate standard error of means (n = 4). NS: no significant difference between treatments by Duncan's test ($p \leq 0.05$).

or maintained soil fertility and increased commercial productivity of vegetables, although these effects appear to depend on initial nutrient availability and specific soil characteristics.

The original soil conditions where this study was developed are challenging. Like all highly weathered soils in the region, they present fertility limitations (Table 1), a characteristic normally observed on Paraguayan farms, especially in family farming systems that frequently face limited resources, inputs and implements, in addition to scarce knowledge about good agricultural practices (Derpsch, Lange, Birbaumer and Moriya, 2016). This represents a significant challenge for restoring soil health and closing production gaps.

In this context, the results of this study revealed promising findings: organic fertilizers derived from solid waste from the sugar industry showed clear potential to improve carrot production, supported by the positive linear response in all evaluated variables with increasing applied doses. This trend suggests that, with more adequate management strategies, these fertilizers can offer substantial economic and environmental benefits for producers and the country.

Based on these results, it is suggested that future research evaluate crop response to higher doses, especially considering soil nutrient availability and specific plant requirements. This is fundamental to ensure that applications are precise and effective, maximizing fertilizer benefits. Additionally, combinations with rapid-release sources or the use of additives that accelerate compost mineralization could be explored, promoting more efficient nutrient uptake and higher yields. These approaches could optimize the use of organic fertilizers derived from solid waste and strengthen the sustainability of agricultural systems.

CONCLUSIONS

The use of sugar industry waste converted into organic fertilizers through composting favors carrot root development (length and diameter). However, under the experimental area conditions, the doses used do not influence carrot height, weight, and yield parameters.

In addition to the use of organic waste, highly weathered soils require strategies that synchronize nutrient release with crop demands. These strategies can improve the efficiency of organic fertilizer use derived from sugar industry waste and contribute to more sustainable and productive agricultural systems.

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