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Productive Performance of Carrot Under a Sustainable Cultivation System in the Semi-Arid Region Using Carnauba Straw and Sheep Manure Fertilization

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A B S T R A C T

Organic fertilization is essential for the sustainable management of soils in semi-arid regions, where climatic conditions and low natural fertility limit crop performance. In carrot (*Daucus carota* L.), studies on organic fertilization recommendations targeted to this region are still scarce. Therefore, the objective was to evaluate the effect of different rates of sheep manure, applied alone or in combination with carnauba straw, on the phytotechnical characteristics of carrot cultivation. The experiment was conducted in the semi-arid region of Piauí, using a randomized block design (5×2), with five levels of sheep manure (0, 10, 30, 50, and 80 t ha^{-1}), two levels of carnauba straw (with and without 15 t ha^{-1}), and four replications for each treatment. Plant height, number of leaves, fresh and dry shoot mass, total fresh and dry root mass, fresh and dry commercial root mass, total and commercial yield, and classification of the "Brasília" carrot were evaluated. Sheep manure significantly influenced all growth and yield variables, showing a quadratic response for most parameters, with an optimal technical dose between 50 and 55 t ha^{-1}, resulting in a maximum estimated yield of 62.1 t ha^{-1}. Carnauba straw, when applied alone, did not show a significant effect, possibly due to its slow decomposition. Moderate doses of sheep manure (±10 t ha^{-1}) promoted a greater proportion of commercial roots and uniformity, highlighting the agronomic potential of the input as an efficient and sustainable organic source for carrot production in semi-arid regions.

Keywords: Organic fertilizer, *Daucus carota* L., production, commercial classification.

Desempenho Produtivo da Cenoura em Sistema de Cultivo Sustentável no Semiárido sob Adubação com Palha de Carnaúba e Esterco Ovino

R E S U M O

A adubação orgânica é fundamental no manejo sustentável do solo em regiões semiáridas, onde as condições climáticas e a reduzida fertilidade natural limitam o desempenho das culturas. Em cenoura (Daucus carota L.), ainda são escassos estudos sobre recomendação de adubação orgânica direcionada a essa região. Portanto, objetivou-se avaliar o efeito de diferentes doses de esterco ovino, isoladas ou em associação com palha de carnaúba, sobre as características fitotécnicas da cultura da cenoura. O experimento foi conduzido na região semiárida do Piauí, com delineamento de blocos casualizados (5x2), cinco níveis de esterco ovino (0, 10, 30, 50 e 80 t ha^{-1}), dois níveis de palha de carnaúba (sem e com 15 t ha^{-1}) e quatro repetições para cada tratamento. Foram avaliados altura de planta, número de folhas, massa fresca e seca da parte aérea, massa fresca e seca total da raiz, massa fresca e seca da raiz comercial, produtividade total e comercial

e classificação da cenoura "Brasília". O esterco ovino influenciou significativamente todas as variáveis de crescimento e produtividade, com comportamento quadrático para a maioria dos parâmetros e dose ótima técnica entre 50 e 55 t ha^{-1}, resultando em produtividade máxima estimada de 62,1 t ha^{-1}. A palha de carnaúba, isoladamente, não apresentou efeito significativo, possivelmente devido à sua lenta decomposição. Doses moderadas de esterco ovino (±10 t ha^{-1}) proporcionaram maior proporção de raízes comerciais e padrão de uniformidade, evidenciando o potencial agronômico do insumo como fonte orgânica eficiente e sustentável para a produção de cenoura no semiárido.
Palavras-chave**:** Fertilização orgânica, *Daucus carota* L., produção, classificação comercial.

Introduction

Carrot (*Daucus carota* L.) belongs to the Apiaceae family and is classified among the tuberous-root vegetables (Deng et al., 2023). It originates from the temperate regions of Central Asia (India, Afghanistan, and Russia) and has been cultivated for more than two thousand years (Burkhonova et al, 2024). Its cultivation is widely distributed worldwide, being produced in more than 25 countries, and it is therefore considered one of the most economically important and most consumed vegetables globally. In addition, carrots contain nutraceutical compounds that act as promoters of human health (Suarez et al., 2020), including provitamin A and the carotenoids α- and β-carotene (Titcomb et al., 2019). In Brazil, carrot is consumed both fresh and processed, with 90% of national production concentrated in the states of Minas Gerais, Rio Grande do Sul, Bahia, Paraná, and São Paulo (Brazilian Horti&Fruti Yearbook, 2022).

To achieve high yields and the root quality demanded by the market, adequate nutrient supply is essential. Traditionally, this is achieved through mineral fertilization, which, when mismanaged, may negatively affect environmental quality and contribute to the degradation of soil and water resources (Filgueira, 2013). In contrast, organic fertilization represents a sustainable management alternative that promotes the recycling of plant and animal residues, contributing to the preservation of soil organic matter and enhancing soil resilience.

These organic inputs promote the gradual release of nutrients, stimulate microbial activity, and improve soil structure as well as water and nutrient availability. Thus, their use in horticultural production contributes to a more efficient use of resources and to improved soil conditions (Wang et al., 2024).

Vegetable cultivation in the Semi-arid region takes place in a naturally vulnerable environment characterized by high temperatures, intense solar radiation, and low water availability conditions that accelerate the decomposition of organic matter and compromise soil structure. In this context, the use of organic inputs goes beyond plant nutrition, acting as an essential practice for conserving and restoring the physical, chemical, and biological properties of the soil, enhancing its structure, water retention, and biological activity.

In the Northeastern Brazilian Semi-arid region, studies involving organic fertilization with native plant species have been conducted, highlighting the use of carnauba straw (*Copernicia prunifera*), silk flower (*Calotropis procera*), and jitirana (*Merremia aegyptia*). Carnauba palms occur naturally in the Northeast region of Brazil, with greater concentration in the states of Piauí, Ceará, Maranhão, and Rio Grande do Norte (Carvalho e Gomes, 2016). They are widely used for powder and wax extraction, with regional production reaching 18,541 tons of powder and 645 tons of wax, of which Piauí stands out with 10,252 tons (IBGE, 2022).

The use of shredded carnauba straw has been widely adopted by farmers as mulch, primarily to facilitate carrot seedling emergence while ensuring prolonged soil moisture retention (Linhares et al., 2014), in addition to presenting lower acquisition costs (Oliveira et al., 2011).

Carnauba straw has shown positive effects on vegetable production (Linhares et al., 2012), promoting rapid nutrient cycling, enhancing soil biological activity, increasing soil nitrogen content, improving water-holding capacity, reducing soil temperature, and contributing to soil loosening (Padovan, 2018). When applied together with manure, carnauba straw reduces production costs, as it is readily available in cultivation areas and aligns with ecological production principles (Melo et al., 2014).

Sheep manure is another example of organic fertilizer that stands out as an especially effective option due to its balanced nutrient composition and favorable decomposition kinetics. Its application can modify soil chemical properties by increasing calcium and organic matter contents, as well as enhancing cation exchange capacity (Xing et al., 2025).

Given the above, this study aimed to evaluate the effect of different sheep manure (SM) doses, applied alone or in combination with carnauba straw, on sustainable carrot cultivation and on the crop's growth and productive characteristics.

Materials and methods

The experiment was carried out in an area located at Chácara Viver Agropecuária, in Oeiras, Piauí State, Brazil, at latitude 7°00'44" S, longitude 42°09'39" W, and an altitude of 167 m. The region has a hot and dry climate, classified as Aw according to Köppen (high temperatures with a dry winter and summer rainfall). No precipitation occurred during the experimental period. Air temperature ranged from approximately 27 to 36°C, and relative humidity varied between 28 and 46% (INMET, 2017) (Figure 1).

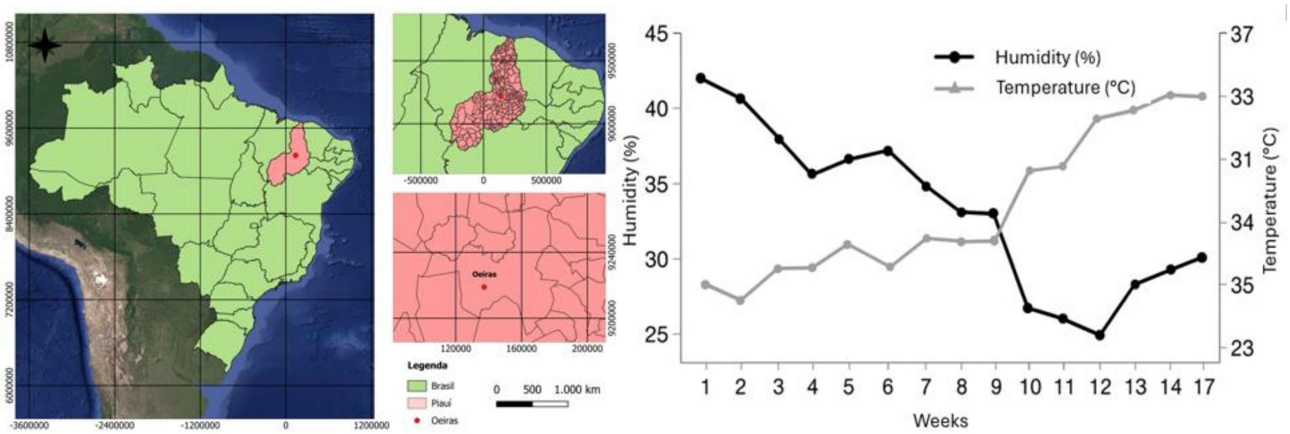

Figure 1. Location of the experimental area in Oeiras, Piauí State (Brazil), and weekly variation in air temperature (°C) and relative humidity (%) during carrot cultivation in 2018.

The study was conducted between July and October 2017. The soil in the experimental area is classified as a Yellow Latosol (Latossolo Amarelo Distrófico) (EMBRAPA, 2013), sampled from the 0–40 cm layer. The chemical and granulometric properties of this soil were determined prior to the experiment (Table 1), as well as the chemical composition of the carnauba straw and sheep manure (Table 2).

Table 1. Chemical and physical attributes of the Yellow Latosol in the experimental area at a depth of 0–40 cm.

Features soil chemistry								
pH	Ca	Mg	Al	H+Al	T	T	P	K
H_2O	-------------------------- cmolc dm^{-3} ----------------------------						mg dm^{-3}	
5.4	0.35	0.5	0.0	4.46	1.07	5.52	7.82	85.3
Cu	Zn	Faith	Mn	V	M	OM		
------------------mg dm^{-3} -----------------				---------%---------		g kg $^{-1}$		
0.83	0.34	73.7	5.96	19.3	0.0	7.2		

Particle size		
--- g kg $^{-1}$ ---		
Clay	Silt	Sand
90	45	864

P, K, Cu, Fe, Mn, and Zn - Mehlich1 extractor ; Ca, Mg, and Al - 1 mol L^{-1} KCl extractor; H + Al - Calcium Acetate extractor at pH 7.0; Organic Matter (OM) - Walkley -Black method; CEC (t) - Effective Cation

Exchange Capacity; CEC (T) - Cation Exchange Capacity at pH 7.0; V = Base Saturation Index; m = Aluminum Saturation Index. The CPCE/UFPI soil laboratory is not responsible for sample collection.

Soil analysis laboratory of CPCE-UFPI.

The experimental design was a randomized block design with four replications and ten treatments, totaling 40 plots. The treatments were arranged in a 5 × 2 factorial scheme, consisting of five sheep manure levels (0, 10, 30, 50, and 80 t ha⁻¹) and two carnauba straw levels (0 and 15 t ha⁻¹).

Table 2. Chemical attributes of carnauba straw and sheep manure.

Chemical characteristics of carnauba straw (CS) and sheep manure (SM)									
	pH	Ca	Mg	In	CO	K	N	P	S
	H_2O	--------	--------	--------	------%------	--------	--------	--------	--------
CS	5.6	0.36	0.26	0.006	37.28	1.4	2.5	0.20	0.38
SM	9.0	3.92	0.76	0.164	25.11	2.10	2.70	0.97	0.40
	Cu	Zn	Fe	W	B	C/N	Moisture Content		
	--------	--------	ppm	--------	--------		On air	Oven 75 °C	
CS	17	23	271	49	23.3	14.91	0.00	3.76	
SM	19	136	283	19	42.4	9.30	66.91	70.13	

Total contents, determined in the acid extract (citric acid with perchloric acid)
N - Kjeldahl Method
CO - Walkley -Black Method

Soil Analysis Laboratory Viçosa Ltda.

Liming was performed using the base saturation method, aiming to raise it to 70%, with dolomitic limestone presenting a relative neutralizing power (RNP) of 97%. Consequently, soil correction was applied throughout the entire experimental area according to the soil analysis. The beds were constructed manually using hoes, measuring 1 × 1 m and 0.25 m in height. Sheep manure (SM) and carnauba straw (CS) were weighed separately, applied to each bed according to the treatments, and incorporated into the soil at a depth of 30 cm.

Carnauba straw was previously shredded using a forage cutter, and the sheep manure was composted before application; both materials were sourced from the municipality where the study was carried out. Ten days after incorporation, seeds of the summer carrot cultivar Brasília were sown in furrows at a depth of 2.0 cm, with 20 cm spacing between rows. This cultivar was selected because it is the most recommended for the Semi-arid region of Northeastern Brazil (Lopes et al., 2008).

Thinning was performed at 30 days after sowing (DAS), maintaining a spacing of 0.05 m between plants. The useful area consisted of the three central rows, excluding the lateral rows as well as the first two and last two plants of each row within the useful area. Manual weeding was carried out for weed control, and no pest or disease incidence was observed throughout the crop cycle. Irrigation was applied using micro-sprinklers twice a day, according to the crop's water requirements.

Harvesting was performed manually at 120 DAS, in a single operation. For each bed, 18 plants were randomly selected and used for the phytotechnical evaluations, assessing both shoot and root components. The following phytotechnical assessments were conducted:

To quantify shoot biomass, Fresh Shoot Mass (FSM) was determined immediately after harvest using an analytical balance with a precision of 0.0001 g, with results expressed in grams (g). Subsequently, the material was oven-dried in a forced-air circulation chamber at 65 °C until constant weight was achieved, obtaining the Dry Shoot Mass (DSM), also expressed in grams (g).

Similarly, root development was evaluated by determining the Total Fresh Root Mass (TFRM), obtained from the weight of the roots within the useful area and expressed in grams (g). The Total Dry Root Mass (TDRM) was determined after drying in a forced-air oven at 65 °C until constant weight. Productive efficiency was expressed in tons per hectare (t ha^{-1}). Total Yield (TY), corresponding to the gross root production, was calculated from the TFRM of the useful area and converted using a factor of 10^{-6}, according to the following formula:

$$TY\ (t\ ha^{-1}) = \frac{\text{Total Fresh Root Mass (kg)} \times 10{,}000}{\text{Harvest useful area (m}^2) \times 1{,}000}$$

The main market indicator, Commercial Yield (CY), included only roots free from injuries (cracks, mechanical damage), morphological defects (bifurcation, green or purple shoulders), and phytopathological problems (nematode damage) that met the commercial classification standards. Commercial Yield (CY) and Fresh Mass of Commercial Roots (FMCR) were calculated analogously to Total Yield and TFRM.

For the assessment of commercial quality, root classification was performed according to the standards established by CEAGESP (2015). Root length was measured using a digital caliper, and based on these measurements, samples were distributed into size classes: class 10 (>10 cm and <14 cm), class 14 (>14 cm and <18 cm), class 18 (>18 cm and <22 cm), class 22 (>22 cm and <26 cm), class 26 (>26 cm), and discard (roots that did not fit into any of the previous size categories). The proportion of roots in each class was expressed as a percentage (%) of the total harvested roots, according to the following equation:

$$\text{Class (\%)} = \left(\frac{\text{Number of roots in the specific class}}{\text{Total number of harvested roots}}\right) \times 100$$

The data obtained for all phytotechnical parameters were subjected to Analysis of Variance (ANOVA). Statistical significance was evaluated using the F-test at the 5% probability level. When significance was detected, regression analysis was performed. The model showing the best fit and statistical significance was adopted to describe the behavior of the dependent variables in response to the treatments. All statistical analyses were performed using Sisvar 5.0 software (Ferreira, 2011).

Results and discussion

Phytotechnical and yield variables such as plant height, fresh and dry shoot mass, yield, root length, and total fresh and dry root mass showed significant effects as a function of sheep manure (SM) doses, regardless of the addition of carnauba straw (CS) (Table 3). No significant interaction was observed between SM doses and CS application for any phytotechnical or carrot root production variables (Table 3).

It was verified that carrot did not respond to the use of carnauba straw as a nutrient source, since no significant effect was detected for any of the evaluated variables. This lack of response may be associated with a desynchronization between nutrient release from the straw and the period of greatest nutritional demand of the crop. According to Linhares et al. (2014), who evaluated the incorporation of carnauba straw combined with *jitirana* in coriander cultivation, the highest productivity occurred when organic material was incorporated 42 days after sowing, indicating that decomposition time is a determining factor for nutrient availability.

The chemical composition presented in Table 2 supports this interpretation. Carnauba straw exhibits a more acidic pH (5.6) and high organic carbon content (37.28%), with a C/N ratio of 14.91 characteristics indicative of slower decomposition and an initial tendency toward nitrogen immobilization in the soil. Although it contains 2.5% N and 1.4% K, its naturally high lignin content, combined with the elevated carbon/nitrogen ratio, lowers microbial mineralization rates (Silva et al., 2014). Consequently, nutrient release tends to occur later in the cycle, which may explain the lack of immediate response of carrot to the isolated use of carnauba straw.

Thus, this characteristic must be considered from the perspective of Carnauba Biome Residue Management, as the material is abundant and requires advance handling in order to be effectively integrated into nutrient cycling.

In contrast, sheep manure exhibited a higher pH (9.0) and greater contents of Ca (3.92%), Mg (0.76%), and P (0.97%), as well as higher N content (2.7%) and a lower C/N ratio (9.30). Beyond supplying nutrients, the application of SM may have contributed to a slight increase and buffering of soil pH, potentially improving the availability of certain micronutrients, such as Mo (molybdenum), and enhancing biological activity conditions that are beneficial for carrot development.

These attributes indicate a greater mineralization potential and faster nutrient release, contributing to its effective influence on plant growth and productivity. SM also presented expressive levels of micronutrients such as Zn (136 ppm) and Fe (283 ppm), which, although required in smaller quantities, are essential for key physiological and enzymatic processes in the crop.

Another relevant aspect concerns the high boron concentration (42.4 ppm) observed in sheep manure (SM), compared with carnauba straw (CS). Boron is an essential micronutrient for root growth, cell wall formation, and the development of meristematic tissues, playing a key role in cell elongation and differentiation. This characteristic may have contributed to the superior performance of plants fertilized with sheep manure compared with those receiving carnauba straw alone.

This behavior is consistent with the findings of Oliveira et al. (2018), who reported a reduction in soil boron concentrations over years of carnauba straw use, attributed to the naturally low levels of this element in the residue. This condition highlights the limitation of carnauba straw as a micronutrient source particularly boron reinforcing that, in addition to application timing, its composition is also a critical factor.

As highlighted by Pompeu et al. (2023), the application of 10 t ha^{-1} of carnauba straw may delay nutrient release due to its lignified structure. In the present study, carnauba straw was applied at 15 t ha^{-1}, ten days before sowing a period likely insufficient for substantial mineralization to occur. Conversely, Morais, Araújo Junior, and Farias (2017) observed that the incorporation of 14 t ha^{-1} of shredded carnauba straw at 15 and 30 days before carrot sowing increased root length and yield, demonstrating the importance of adequate application lead time.

Table 3. Summary of the analysis of variance for plant height (PH), number of leaves (NL), fresh shoot mass (FSM), dry shoot mass (DSM), total fresh root mass (TFRM), root length (RL), total dry root mass (TDRM), fresh mass of marketable roots (FMMR), dry mass of marketable roots (DMMR), total yield (TY), and commercial yield (CY) of carrot cv. Brasília subjected to different sheep manure doses and carnauba straw application under semi-arid conditions**.**

SV	DF	PH	NL	FSM	DSM	TFRM	RL
Carnauba straw (CS)	1	21.02 ^{ns}	0.22 ^{ns}	111.02 ^{ns}	13.95 ^{ns}	393.9 ^{ns}	0.986 ^{ns}
Sheep Manure (SM)	4	147.85 *	4.43 ^{ns}	842.73 *	35.18 *	2835.2 *	11,186 *
CS x SM	4	9.21 ^{ns}	2.48 ^{ns}	151.10 ^{ns}	11.83 ^{ns}	98.4 ^{ns}	6,380 ^{ns}
Block	3	6.7 ^{ns}	2.62 ^{ns}	551.65 *	21.83*	299.8 ^{ns}	6,374 ^{ns}
Error	27	31.4	2.38	179.19	6.04	218.6	3,386
CV(%)		12.59%	14.40%	35.91%	27.95%	20.03%	15.71%

SV	DF	TDRM	FMMR	DMMR	TY	CY
Carnauba straw (CS)	1	13.95 ^{ns}	448.0 ^{ns}	1.92 ^{ns}	175.1 ^{ns}	199.0 ^{ns}
Sheep Manure (SM)	4	35.11 *	471.8 ^{ns}	3.77 ^{ns}	1259.89 *	209.7 ^{ns}

CS x SM	4	11.83 ns	194.2 ns	1.81 ns	43.72 ns	86.2 ns
Block	3	21.83 *	1773.2 ns	18.59 ns	133.21 ns	788.0 *
Error	27	6.03	319.5	2,289	97.15	142.0
CV (%)		27.95%	46.12%	45.32%	20.03%	46.12%

NS - not significant. * significant at the 5% probability level.

In the analysis of plant height (Figure 2A), a quadratic model was fitted as a function of sheep manure (SM) doses, with a strong correlation between the data and the regression equation (R^2 = 0.81). The estimated optimal dose was approximately 53.8 t ha⁻¹ of SM, at which maximum plant height was estimated at 48.47 cm. Considering that the control (0 t ha⁻¹) reached 37.2 cm, this represents an increase of 30.3%. This gain demonstrates that SM application promotes vegetative growth in carrot, likely by improving soil physical structure (aeration, water retention) and providing gradual release of nitrogen and other nutrients. As previously reported, plants with greater height and larger leaf area provide advantages for root filling in carrots (Oliveira et al., 2011).

For fresh shoot mass (FSM) (Figure 2B), the data fitted a linear model (R^2 = 0.93), indicating that for every ton of SM applied, there was an average increase of 0.309 g plant⁻¹, equivalent to approximately 0.31 t ha⁻¹ of FSM per t ha⁻¹ of SM. At the highest dose, 80 t ha⁻¹ of SM, the estimated FSM was 52.13 g plant⁻¹ (52.1 t ha⁻¹), compared with 27.41 g plant⁻¹ (27.41 t ha⁻¹) in the control an increase of 90%. This linear response indicates that, within the evaluated range, no saturation effect of organic input supply occurred for shoot biomass. This result suggests that the increase in organic matter and nutrient availability provided by SM favored shoot biomass accumulation, an important condition for root yield, since greater shoot biomass is associated with enhanced photosynthetic capacity and the translocation of assimilates to the root system.

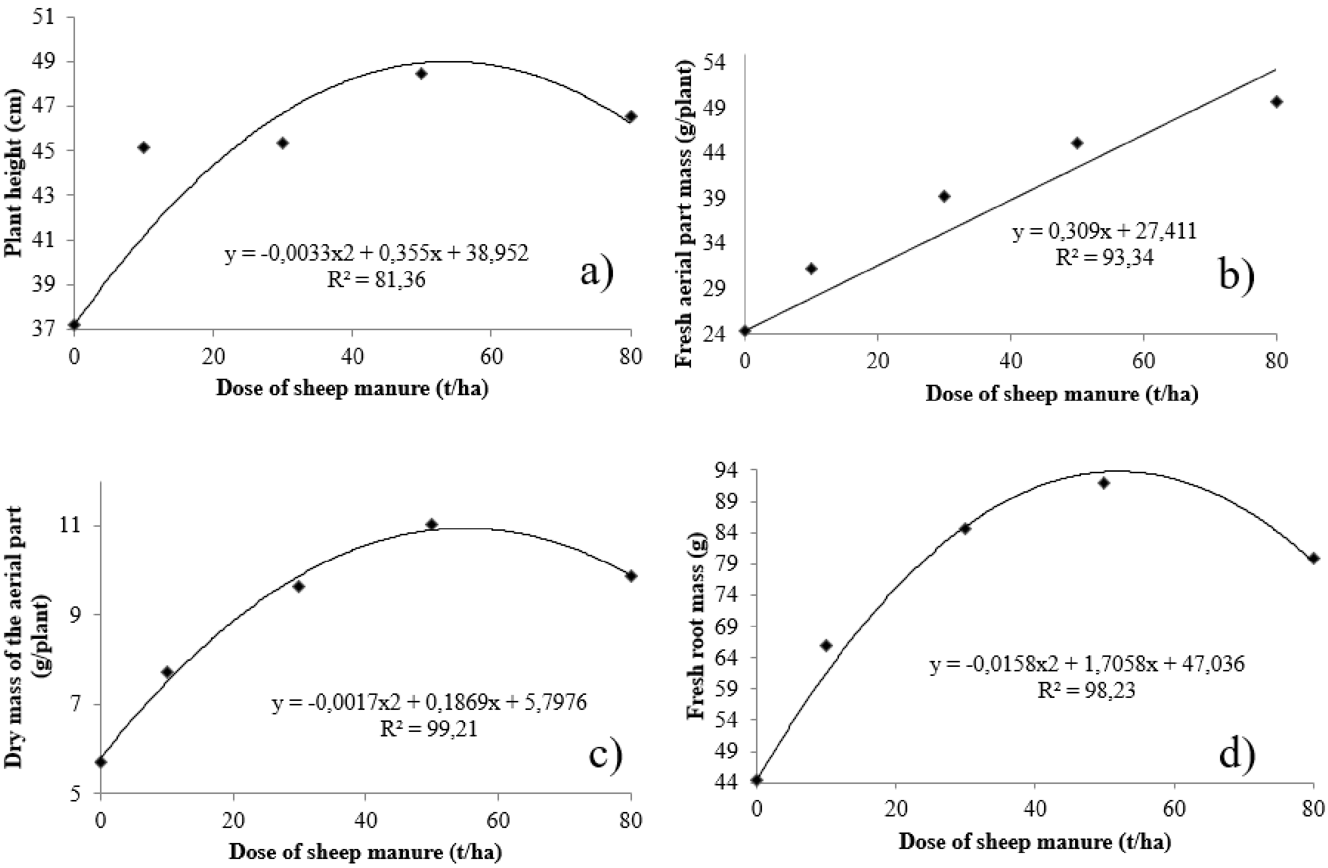

Figura 2. Respostas de variáveis de fitotécnicas e produtividade da cultivar de cenoura 'Brasília' em função de doses de adubação com esterco ovino no semiárido: (a) altura de planta (cm); (b) massa fresca da parte aérea (g planta⁻¹); (c) massa seca da parte aérea (g planta⁻¹); e (d) massa fresca da raiz (g).

Regarding dry shoot mass (DSM) (Figure 2C), a strong fit to the quadratic regression model was again observed (R^2 = 99.21). The estimated sheep manure (SM) dose for maximum DSM accumulation was approximately 55.0 t ha^{-1}, resulting in an estimated peak value of 10.95 g $plant^{-1}$. This optimal dose is remarkably consistent with that determined for plant height and fresh root mass, indicating an optimization of vegetative growth and assimilate translocation within a narrow range of SM application.

The average dry mass to fresh mass ratio (DM/FM) at the optimal dose was 21% (comparing 10.95 g DSM with 52 g FSM), indicating that the DM/FM ratio remains within the physiological range expected for full crop development. This stability is positively influenced by the optimal SM dose, which may have helped mitigate water stress effects, allowing high efficiency in the conversion to dry biomass (DSM).

The quadratic behavior of DSM is critical, as it signals an inflection point in the crop's response: beyond the optimal dose, the marginal benefit of SM decreases. This inefficiency may be attributed to deleterious effects at high concentrations, such as: (i) nutritional imbalances caused by excess of one or more nutrients (e.g., N), antagonizing the uptake of others; (ii) delayed mineralization of organic matter, which, in large quantities, may induce temporary N immobilization, compromising growth during critical stages; or (iii) potential osmotic effects due to the high concentration of undecomposed organic compounds, impairing water absorption. This dynamic confirms that the optimal SM dose is essential to maximizing dry biomass gains before such deleterious effects occur (Sun et al., 2020; Zhang et al., 2022; Ning et al., 2022).

Finally, fresh root mass (Figure 2D) also showed a quadratic fit (R^2 = 98.23). The estimated optimal dose was approximately 54.0 t ha^{-1} (calculated as 53.98 t ha^{-1}), with a corresponding estimated fresh root mass of 93.2 g $root^{-1}$. Compared with the control (47.0 g $root^{-1}$), this represents an increase of approximately 98.3%. This result confirms that the positive effect of SM fertilization is not restricted to the aerial part but strongly influences root production. However, as pointed out by Brito et al. (2005), excessive doses of organic residues must be avoided to prevent adverse effects, reinforcing the need to estimate an optimal dose (54 t ha^{-1} in the present study).

Total dry root mass (TDRM) (Figure 3A) also showed a quadratic response to sheep manure (SM) doses, with an excellent level of agreement between observed and estimated values (R^2 = 0.974). The dose of maximum technical efficiency was estimated at 51.66 t ha^{-1}, corresponding to a maximum dry mass of 11.98 g $plant^{-1}$, whereas the minimum value was 6.12 g $plant^{-1}$ in the absence of fertilization. This relative increase of approximately 96% demonstrates the expressive effect of SM on root dry biomass accumulation.

Teófilo et al. (2009) found mean values of 10.7 g $plant^{-1}$ for carrot 'Brasília' cultivated with cattle manure, whereas Silva et al. (2013) reported values of 8.4 g $plant^{-1}$ of TDRM in plants fertilized with silk flower. Thus, the results obtained in this study exceed the values reported for different organic sources, evidencing the potential of sheep manure as an alternative input with high agronomic efficiency. Accordingly, the average TDRM content observed (12.5 to 14% of TFRM) lies within the expected range for the crop, indicating good efficiency in converting fresh biomass into dry biomass, a characteristic typical of nutritionally balanced systems.

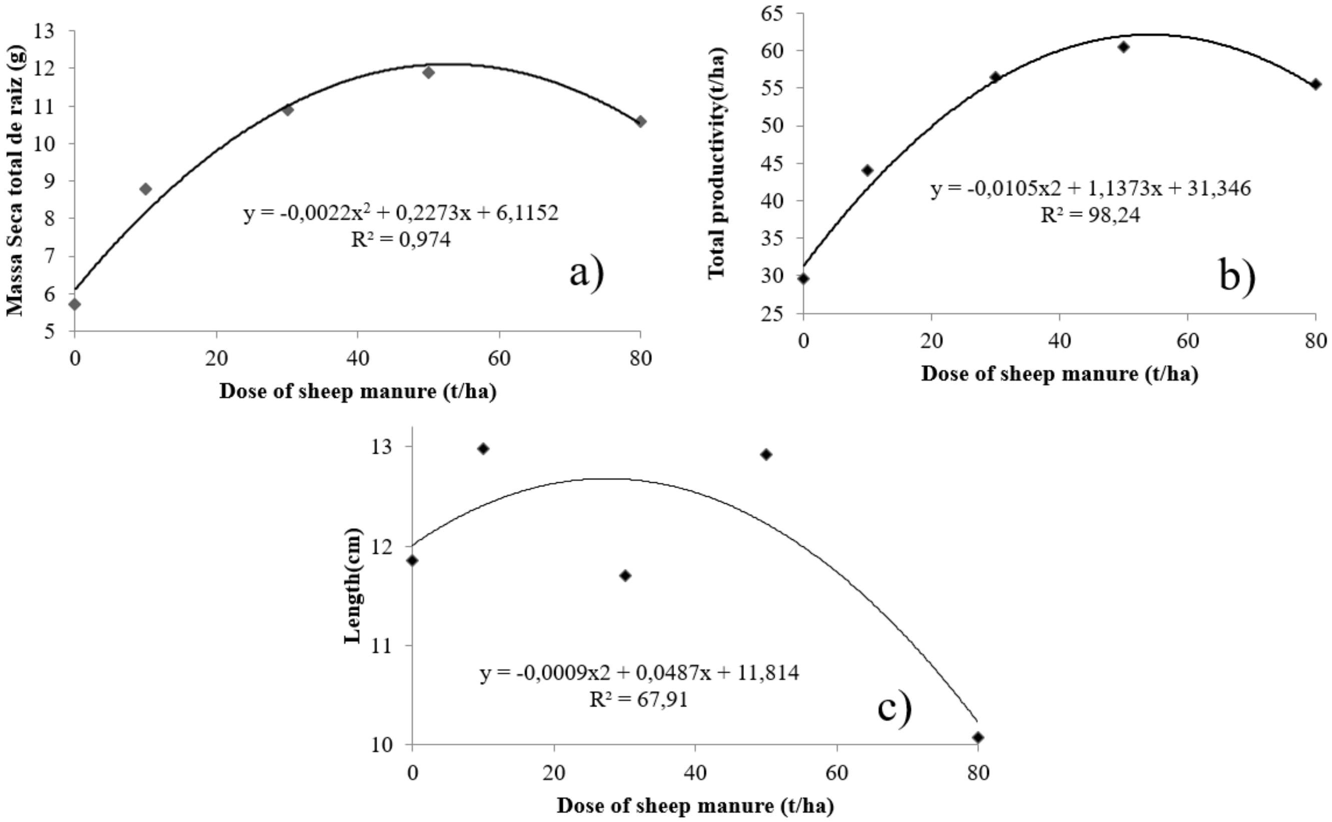

Figure 3**.** Relationship between sheep manure doses and phytotechnical and yield variables of the carrot cultivar ‘Brasília’ grown under semi-arid conditions in Oeiras, PI: (a) total dry root mass, (b) total yield, and (c) root length.

Total root yield (Figure 3B) showed a quadratic response, demonstrating a strong relationship between sheep manure (SM) doses and crop performance (R^2 = 98.24). The dose of maximum technical efficiency was estimated at 54.14 t ha^{-1}, resulting in a maximum yield of 62.1 t ha^{-1}, whereas the absence of fertilization (0 t ha^{-1}) produced 31.35 t ha^{-1}. This expressive increase highlights the role of SM in enhancing nutrient availability, promoting greater root growth and physiological efficiency in water and mineral uptake. However, doses above 54 t ha^{-1} reduced yield. A similar trend was reported by Resende et al. (2015), who observed a quadratic response for the cultivar ‘Brasília’ under organic fertilization, confirming both the agronomic efficiency and the positive residual effect of animal-derived organic inputs.

Although the maximum observed yield (62.1 t ha^{-1}) is lower than the 70–71 t ha^{-1} reported for high-technology conventional systems (2023 season), according to the Hortifruti Brazil Yearbook 2024 (Cepea/Hortifruti, 2024), it represents a remarkable performance for an organic production system, considering the restrictions on mineral fertilization and the sustainable nature of the management approach. These results reinforce the high productive potential of the ‘Brasília’ cultivar under organic management with SM and demonstrate that moderate doses of this input provide the best balance between yield and productive sustainability.

The variable commercial root length (Figure 3C) showed a quadratic fit, with a determination coefficient of 67.91%, indicating a moderately consistent response to SM doses. The dose of maximum technical efficiency was estimated at 27.06 t ha^{-1}, corresponding to a maximum length of 12.47 cm. In the absence of fertilization, roots measured 10.12 cm, while the highest dose (80 t ha^{-1}) reduced root length to 9.95 cm, evidencing a decreasing trend at higher doses.

The wider variation range and the lower R^2 value (67.91%) compared with the other evaluated variables indicate that, for root length, the model explains only a moderate portion of the observed variation. This behavior suggests that this variable may have been influenced by external factors such as soil physical conditions, moisture content, and microenvironmental variations, which affect root elongation independently of SM fertilization.

Despite this variability, the results obtained remain consistent with the literature and are comparable to those reported by Paulus et al. (2012), who observed mean lengths of 15.9 cm in summer cultivars under chicken-litter fertilization, and by Zanatta et al. (2012), who, when testing different cultivars fertilized with cattle manure, found no significant differences between 'Brasília' (15.41 cm) and 'Alvorada' (13.75 cm). Although the absolute values observed in this study are slightly lower, they reflect adaptation to the local edaphoclimatic conditions and to the nutrient-release dynamics of sheep manure, highlighting its agronomic efficiency as an alternative and sustainable organic source for carrot production.

Sheep manure (SM) doses significantly influenced the commercial classification of roots of the carrot cultivar Brasília (Figure 4), based on root length determined according to CEAGESP (2015) standards. It is observed that increasing SM doses altered the percentage distribution across commercial classes, reflecting the effect of organic management on root growth and conformation.

In the control treatment (0 t ha^{-1}), there was a predominance of discarded roots, around 55%, and Class 10 roots (10 to 14 cm), with approximately 44% (Figure 4), indicating deficient root development in the absence of fertilization. This limitation is associated with the reduced availability of essential nutrients, especially nitrogen and phosphorus, which play fundamental roles in root elongation and thickening.

With the application of 10 t ha^{-1} of SM, the best qualitative performance was observed: 72% of the roots were classified as Class 10 (10 to 14 cm), 11% as Class 14 (14.01 to 18 cm), and approximately 6% as Class 18 (18.01 to 22 cm). This dose presented the highest proportion of uniform and marketable roots, indicating that moderate levels of manure favor balanced growth and the commercially desirable shape of carrots (Figure 4).

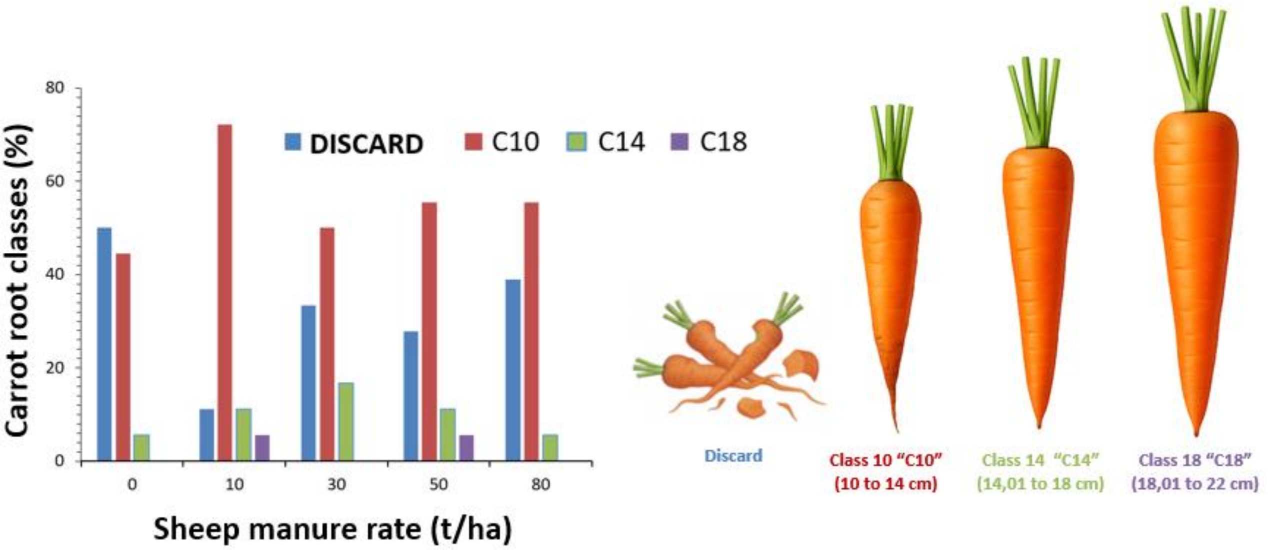

Figure 4. Classification of roots of the carrot cultivar 'Brasília' as a function of sheep manure doses, grown under semi-arid conditions in Oeiras, PI: Class 10 (10–14 cm), Class 14 (14.01–18 cm), and Class 18 (18.01–22 cm).

Starting at 30 t ha^{-1}, a gradual reduction in the higher commercial classes (Class 14 and Class 18) was observed, along with an increase in discarded roots, especially at the 80 t ha^{-1} dose, in which the proportion of discarded roots exceeded 40% (Figure 4). This behavior may be related to the excessive application of organic matter, which can alter soil physical structure by increasing density and moisture, thereby hindering root penetration and straight growth, and favoring deformities and bifurcations. This result highlights the environmental cost of excessive input use, where a high rejection rate represents a loss of resources and reduced system efficiency.

Similar results were reported by Oliveira et al. (2011), who, using jack bean as green manure, observed a predominance of short roots (Class 10) and low discard rates (4.2%), similar to the pattern observed at the 10 t ha⁻¹ dose in the present study. Here, the longest roots (Class 18) represented only 2% of the total, indicating that root elongation is not directly proportional to increasing SM doses, as soil physical and moisture conditions begin to impose greater limitations on root growth.

Overall, considering all doses, approximately 56% of the roots were classified as short (Class 10), 12% as medium to long (Class 14 + Class 18), and 32% as discard. These results contrast with those of Silva et al. (2013), who reported 53.3% medium-sized roots and only 11% discard in 'Brasília' carrots fertilized with silk flower, emphasizing that the type and degree of organic residue decomposition strongly influence final root conformation. Although sheep manure is rich in nutrients and fast mineralizing, it may exert adverse physical effects at high doses, particularly due to surface compaction after drying.

Therefore, the evidence suggests that moderate SM doses (around 10 t ha⁻¹) provide the best balance between yield and commercial root quality, maximizing the proportion of Class 10 carrots and reducing the occurrence of deformities and discard. This fertilization range offers agronomic and economic advantages, as it promotes uniformity and market standards without compromising soil physical structure.

Conclusions

Organic fertilization with sheep manure significantly influenced the phytotechnical and yield variables of the carrot cultivar 'Brasília', demonstrating the high potential of this input for sustainable management and agronomic performance under semi-arid conditions. Most variables responded to an optimal technical dose between 50 and 55 t ha⁻¹, above which productive gains tended to stabilize or decline.

In contrast, moderate doses around 10 t ha⁻¹ resulted in a higher proportion of marketable roots (approximately 89%) and better uniformity, with a predominance of Class 10 roots (10–14 cm). This application range provides the best balance between yield and root conformation, minimizing discard and thereby maximizing the environmental and economic efficiency of production.

Carnauba straw, when applied alone, did not show significant effects on the evaluated variables, likely due to its slow decomposition and initial nitrogen immobilization. This reinforces the importance of managing incorporation timing (advance application) so that its nutrient-recycling function becomes effective and can contribute to sustainable soil management.

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