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Organic fertilization increases yield and affects the postharvest quality of *Nopalea cochenillifera* cladodes

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Abstract

Organic fertilization can promote greater production of cladodes as well as increase phytomass production and the quality and content of bioactive compounds. Thus, the aim of this study was to evaluate the sources and doses of organic fertilizer on the production and quality of forage palm cladodes. A completely randomized experimental design in a 3 × 3 factorial scheme with five replications was used. Three sources of organic fertilizer (chicken manure, cattle manure, and goat manure) and three concentrations of each source (0, 10, and 20%) were studied. Cladodes fresh mass, pH, soluble solids, titratable acidity, soluble solids/titratable acidity ratio, ascorbic acid, chlorophyll, carotenoids, phenolic compounds, flavonoids, and anthocyanins were evaluated. Palm cladodes fertilized with 20% chicken manure produce the highest biomass, while cladodes fertilized with 10% chicken manure have the highest palatability and content of bioactive compounds. Thus, fertilization with 10% chicken manure is the most promising and economically viable way to increase the production and quality of palm cladodes. The research demonstrated that fertilization with chicken, cattle, and goat manure increases the productivity, nutritional quality, and palatability of the cladodes intended for human consumption, providing a sustainable and healthy alternative for the region.

Keywords: forage palm; manure; palatability; bioactive compounds.

Practical Application: The knowledge acquired made it possible to define the animal species and percentage of organic fertilizer capable of increasing productivity, nutritional quality, and palatability of the cladodes intended for human consumption.

1 INTRODUCTION

The Cactaceae family comprises approximately 94 genera and 1.150 species, with 26 genera and 113 species of cacti identified in northeastern Brazil (Guerrero et al., 2019). Forage palm, which is a member of this family, has versatile uses as a food source for both humans and animals, as well as in dye production. It is extensively cultivated in several countries, including Mexico (3 million ha), Brazil (500,000 ha), Peru (10,000 ha), Argentina (1,650 ha), and Chile (1,000 ha) (Inglese et al., 2017; Silva et al., 2023b). In Brazil, Opuntia ficus-indica and Nopalea cochenillifera are the most cultivated species (Cardoso et al., 2019). The productivity of forage palm ranges from 6.3 to 17.8 tons of dry matter per hectare every 2 years after planting, depending on factors such as variety, plant density, and fertilization levels (Souza et al., 2017).

Forage palm plays a significant role as a food source for humans, valued for its appealing taste and juiciness (Kahramanoğlu et al., 2020). Palm cladodes, which are rich in fiber (Inglese, 2018), minerals, phenolic compounds, vitamins, proteins, and antioxidant compounds such as carotenoids, chlorophylls, and betaines, are consumed in the form of juices or dried powders (Iqbal et al., 2020; Silva et al., 2023a). These cladodes contain pectin, mucilage, proteins, carbohydrates, fiber, and minerals, offering a wide range of nutritional benefits (Iqbal et al., 2020; Silva et al., 2023a). Furthermore, palm cladodes have been reported to have various health benefits. They have shown efficacy in reducing body weight and lowering blood glucose levels in diabetic patients (Carreira et al., 2014), as well as providing protection against fatty liver disease (Ribeiro et al., 2010). Additionally, they have been used to alleviate conditions such as constipation (Andrade-Cetto & Wiedenfeld, 2011), dermatitis, and conjunctivitis (Zhao et al., 2011). The positive impact of cladodes on human health is primarily attributed to their fiber content and antioxidant properties (Msaddak et al., 2017).

The limited productivity of forage palm in the Brazilian semi-arid region can be attributed to the misconception that it is a crop capable of tolerating environmental constraints without the need for improved agricultural practices, including fertilization and crop management (Matos et al., 2021). However, it

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is important to recognize that forage palm has specific requirements concerning its growing environment and management. By taking these factors into account, it is possible to enhance productivity and promote greater sustainability in both the environmental and agricultural aspects of its cultivation (Silva et al., 2012).

The application of fertilizers is a crucial management practice for enhancing the productivity of forage palm. Harvesting the forage palm removes significant amounts of nutrients from the soil, necessitating their replenishment to maintain productivity and prevent soil fertility depletion (Silva et al., 2016a). Organic fertilizers, such as manure from various sources (e.g., goat, sheep, pig, and cattle), offer different rates of nutrient release and can contribute to improving the physical, chemical, and biological properties of the soil (Saraiva et al., 2021). This, in turn, can enhance the productivity and quality characteristics of forage palm. Among the macronutrients, potassium (K) is the most essential nutrient absorbed by forage palm and plays a crucial role in its development (Silva et al., 2012).

The potential for innovation lies in the development and implementation of sustainable and cost-effective methods for improving crop productivity and nutritional value. By utilizing organic fertilizers, such as chicken, cattle, and goat manures, farmers can not only increase biomass production but also enhance the palatability and bioactive compound contents of the harvested cladodes. This innovation has several practical applications. First, it offers a solution for maximizing yield and meeting the increasing demand for forage palm cladodes, which are utilized in both human and animal consumption. Second, the higher palatability and enriched bioactive compound content can lead to the development of novel value-added products derived from forage palm cladodes, catering to the growing market demand for functional foods and nutraceuticals.

Moreover, the use of organic fertilizers aligns with sustainable agriculture practices, promoting soil health, minimizing environmental impact, and reducing reliance on synthetic fertilizers. This approach not only benefits farmers but also contributes to sustainable food production and ecosystem preservation. Overall, the identified optimal fertilization strategy presents a promising avenue for innovation in the agricultural sector. It opens opportunities for further research, technological advancements, and practical implementation, ultimately driving improvements in crop production, product development, and sustainability in the forage palm industry.

This study brought an important novelty by highlighting the production of forage palm not only for animal feed but also for human consumption in the context of the Brazilian semi-arid region. The results obtained revealed that the application of different sources and doses of organic fertilizer had significant impacts on the growth and composition of bioactive compounds in palm cladodes. This discovery is particularly relevant as forage palm is traditionally grown in the region for livestock purposes, but the study showed that it can also be a promising alternative to produce healthy food for human consumption. By improving the nutritional quality of the cladodes and increasing the concentration of beneficial compounds such as chlorophyll, carotenoids, flavonoids, and phenolic compounds, forage palm can play an important role in food security and combating malnutrition in the semi-arid region. This finding opens new perspectives and possibilities for the sustainable use of forage palm, contributing to crop diversification and the economic and social development of rural communities in the Brazilian semi-arid region.

A hypothesis for this study is that the application of organic fertilizers will result in increased yield and improved quality of forage palm cladodes compared to no fertilization. The hypothesis predicts that organic fertilization will enhance the biomass production, palatability, and content of bioactive compounds in the cladodes, leading to a more sustainable and valuable agricultural practice. Thus, the aim of this study was to evaluate the sources and doses of organic fertilizer (chicken, cattle, and goat manure) on the production and quality of forage palm cladodes (Nopalea cochenillifera Salm Dyck).

2 MATERIALS AND METHODS

2.1 Experiment location

The study was performed in the experimental area of the Center of Agrifood Sciences and Technology (CCTA) of the Universidade Federal de Campina Grande (UFCG), in Pombal, PB, Brazil (6° 48′ 16″ S and 37° 49′ 15″ W, altitude of 175 m). The predominant climate in the region according to the Köppen classification is of BSh type, i.e., semi-arid hot, with annual precipitation of 750 mm and rainfall in the months of December to April.

2.2 Experimental design and cultivation

A completely randomized experimental design was employed in a 3 × 3 factorial scheme with five replications. The study focused on investigating three sources of organic fertilizer (chicken manure, cattle manure, and goat manure) at three concentrations each (0, 10, and 20%).

The organic manures were procured from small herds in the rural area of the city where the experiment took place. These herds were fed contamination-free feed. The cladodes utilized in the experiment were collected from mature plants that were cultivated in the experimental field of CCTA/UFCG. Specifically, palm "Miúda" cladodes were planted in 20 dm3 buckets filled with 3 cm of number 1 gravel (with a 24-mm mesh) to enhance drainage. The spacing between rows and buckets was set at 1.0 m. The cladodes were inserted approximately two-thirds into the substrate. The plants were manually irrigated twice a week, with each plant receiving an approximate volume of 1 L of water. Weed control was carried out every 2 months through manual weeding. An analysis of the substrates (soil and the mixture of soil and manure) is provided in Table 1.

2.3 Plant material

Young secondary-order palm cladodes, which were approximately 15–25 days old and measured 10–15 cm in length, were carefully collected for analysis. The collection took place in the morning, specifically between 8:50 and 9:30 am, when the cladodes exhibited a fresh appearance and their characteristic color.

Table 1. Analysis of soil and substrates used in the experiment.

Manure	Conc	OM	EC	N	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}	SB	CEC	P	pH
	%	g kg^{-1}	dS m^{-1}	%	------------------ $cmol_c$ dm^{-3} ----------------						mg dm^{-3}	
Cattle	10	8	0.19	0.05	3.50	3.50	0.60	0.22	7.80	7.80	18	7.4
	20	9	0.29	0.10	4.20	2.80	1.04	0.42	8.50	8.50	19	7.5
Goat	10	5	0.29	0.08	3.10	3.50	0.91	0.33	7.80	7.80	19	7.3
	20	16	0.67	0.11	2.60	3.60	1.30	0.66	8.20	8.20	24	7.6
Chicken	10	13	0.41	0.04	2.60	3.60	1.04	0.73	7.90	7.90	18	7.7
	20	9	0.33	0.06	2.40	3.90	0.91	0.97	8.20	8.20	23	7.8
Soil	-	0	0.04	0.01	1.30	2.90	0.27	0.04	4.50	4.50	12	7.6

OM: organic matter; SB: sum of bases ($Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}$); CEC: cation exchange capacity - [$Ca^{2+}+Mg^{2+}+Na^{+}+K^{+}+(H^{+}+Al^{3+})$]; pH was measured in aqueous extract (1:2.5).

Following the harvesting process, the cladodes were visually inspected to ensure that they were free from any injuries. This step was crucial to obtaining uniform and high-quality samples. Subsequently, the cladodes were separated, thoroughly washed, and had their spines removed before further processing.

2.4 Variables analyzed

The cladodes were processed in a home blender (Philips, model Viva RI7632, Brazil) and stored in plastic containers protected from light for the analyses.

2.4.1 Cladodes fresh mass

The cladodes were collected and weighed on a semi-analytical scale (BEL, M214-AiH, Brazil) with 0.1 g precision. The values were expressed in g of fresh mass.

2.4.2 Potential of hydrogen (pH)

The pH was determined in the cell extract of the forage palm cladodes using a bench-top digital potentiometer (Digimed, model DM-22).

2.4.3 Soluble solids

The soluble solids (SS) were determined through the cell extract of the young palm cladodes, which was read in a digital refractometer with automatic temperature compensation (model ITREFD65) and expressed in percentage.

2.4.4 Titratable acidity

Titratable acidity (TA) was measured in 1 mL of the cell extract of the palm cladodes and homogenized in 50 mL of distilled water. The solution containing the sample was titrated with 0.1 M NaOH until the turning point of the phenolphthalein indicator was reached. TA was expressed as the percentage of malic acid abundant in the palm, equivalent to the amount of 0.1 M NaOH spent in the titration (AOAC, 1990).

2.4.5 SS/TA ratio

The soluble solids/titratable acidity (SS/TA) ratio was obtained by dividing the SS values by the TA values.

2.4.6 Ascorbic acid

The ascorbic acid (AA) (vitamin C) content was estimated by titration, using 1 mL of the cell extract of the palm cladodes plus 49 mL of 0.5% oxalic acid and titrated with Tillman's solution until it reached pink coloration, according to the method described by AOAC (1990).

2.4.7 Chlorophyll and carotenoid content

Chlorophyll and carotenoid contents were determined according to Lichtenthaler (1987). The cell extract of palm cladodes was macerated in mortar with 0.2 g of calcium carbonate (CaC3) and 5 mL of acetone (80%) in a dark environment. The samples were then centrifuged (CT-500R) at 10°C and 3,000 rpm for 10 min, and the supernatants were read in a spectrophotometer (Spectrum SP-1105) at 470, 646, and 663 nm.

2.4.8 Phenolic compound content

The estimation of phenolic compounds was conducted using the Folin-Ciocalteu method (Waterhouse, 2017) with certain modifications. To prepare the extracts, 1 mL of the sample was mixed with 50 mL of distilled water and left to stand for 30 min. An 800 μL portion of the extract was then transferred to a test tube containing 1.325 μL of water and 125 μL of Folin-Ciocalteu reagent. The mixture was allowed to stand for 5 min before adding 250 μL of 20% sodium carbonate. The solution was thoroughly stirred and left to rest in a thermostatic bath at 40°C for 30 min. For the creation of a standard curve, gallic acid was employed, and readings were taken at 765 nm using a spectrophotometer (Spectrum SP-1105).

2.4.9 Flavonoid and anthocyanin contents

Flavonoid and anthocyanin contents were determined according to the methodology proposed by Francis (1982). About 1.5 g of fresh sample was macerated in a mortar with 10 mL of ethanol-HCl (85:15) in a dark environment and left to stand for 24 h in the refrigerator. Then, the samples were centrifuged at 10°C and 8.8 × 103 g for 10 min in a refrigerated centrifuge (CT-500R), and the supernatant was separated for reading in a spectrophotometer at 374 nm for flavonoids and 553 nm for anthocyanins.

2.5 Statistical analysis

The data obtained were subjected to analysis of variance (ANOVA), and when significant differences were observed, means were compared using the Tukey test ($p \leq 0.05$). These statistical analyses were conducted using the ExpDes package (Ferreira et al., 2021). Additionally, a principal components analysis (PCA) and Pearson correlation analysis were performed to explore relationships between variables. The correlation analysis was carried out using the PerformanceAnalytics package (Peterson & Carl, 2020). All statistical analyses were performed using the R software (R Core Team, 2022).

3 RESULTS

Palm plants treated with 20% chicken manure (13.57%) and goat manure (17.54%) exhibited the highest cladode biomass compared to other treatments. However, the application of cattle manure did not significantly influence this variable. Notably, no significant difference was observed between the effects of 20% chicken manure and 20% cattle manure on cladode biomass (Figure 1A). Regarding pH levels, the application of 10 and 20% cattle manure resulted in an increase of 6.37 and 6.44%, respectively. Conversely, the application of 20% chicken manure and goat manure led to a decrease in pH of 17.11 and 18.40%, respectively. Furthermore, cattle manure demonstrated superior effects compared to other fertilization treatments in terms of pH levels (Figure 1B).

The application of 10 and 20% chicken manure resulted in significant increases in the SS content of palm cladodes, with values of 46.08 and 47.87%, respectively. Similarly, fertilization with 10 and 20% goat manure also led to notable increases in SS content, with values of 42.11 and 42.71%, respectively (Figure 1C). Interestingly, there was no significant difference between the effects of chicken manure and cattle manure at the evaluated doses. Regarding TA, cladodes grown with 20% goat manure exhibited the highest value, reaching 49.54% (Figure 1D). In terms of the SS/TA ratio of palm cladodes, fertilization with 10% cattle manure (48.58%) and 10% goat manure (41.71%) resulted in notable increases compared to the control. However, these two treatments did not differ significantly from each other. On the contrary, they both differed significantly from fertilization with chicken manure (Figure 1E).

The application of all studied doses and sources of fertilizer resulted in a decrease in the AA content of palm cladodes. The most significant decrease of 61.35% was observed in plants fertilized with 10% chicken manure (Figure 2A). In terms of total chlorophyll content, fertilization with 20% chicken manure and goat manure led to increases of 55.25 and 34.47%, respectively. Furthermore, the 10% chicken manure and cattle manure fertilization resulted in higher increases of 41.00 and 22.13%, respectively, compared to the 10% goat manure fertilization. It is noteworthy that the chicken manure fertilization, across all concentrations, demonstrated the highest impact on total chlorophyll content (Figure 2B). Regarding carotenoid content, cladodes from plants fertilized with chicken manure exhibited higher values both at 10% (21.85% increase) and 20% (37.43% increase) fertilization. However, the application of cattle and goat manure did not significantly influence this variable (Figure 2C).

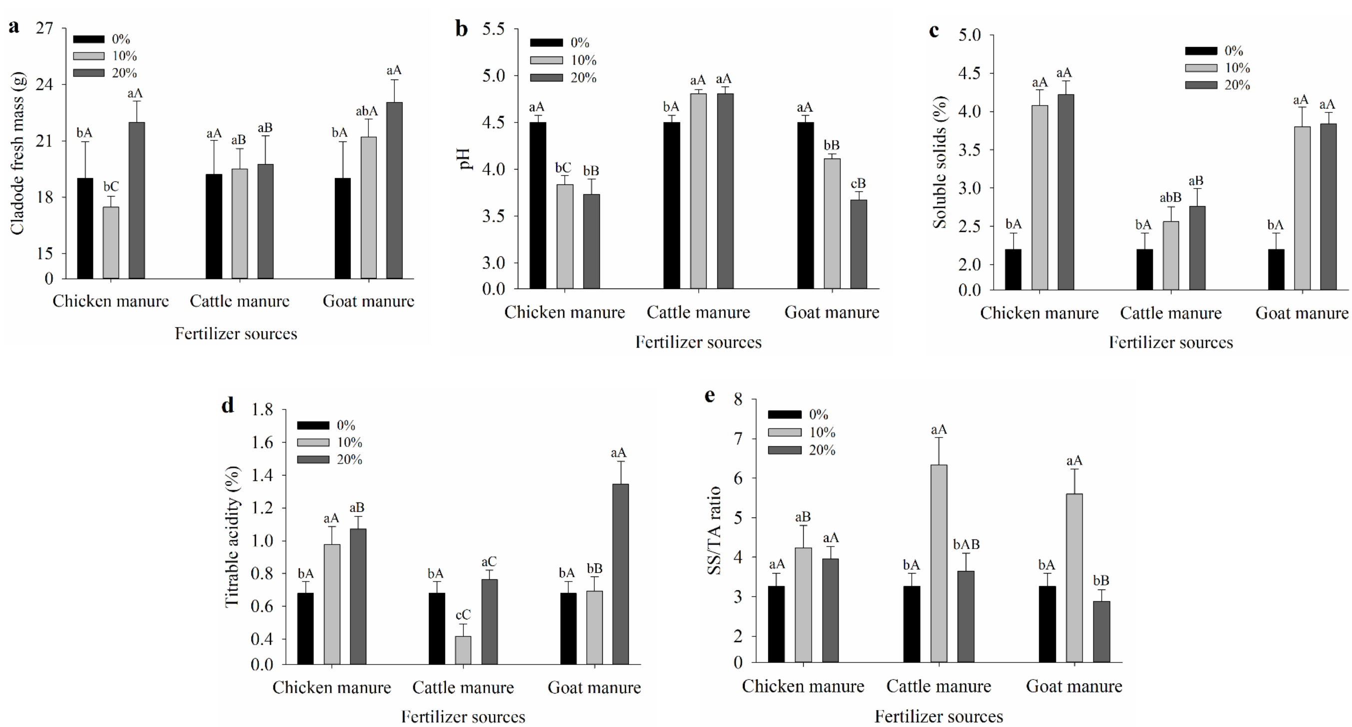

Figure 1. (A) Cladodes fresh mass, (B) pH, (C) soluble solids, (D) titratable acidity, and (E) soluble solids/titratable acidity ratio (SS/TA) of forage palm (*Nopalea cochenillifera*) cladodes grown under doses and sources of organic fertilization. Means followed by the same capital letters do not differ for sources, and means followed by the same lowercase letters do not differ for fertilizer doses by the Tukey test ($p \leq 0.05$).

The application of 20% chicken, cattle, and goat manure resulted in increased flavonoid content, with increases of 24.06, 30.48, and 13.58%, respectively. Additionally, the application of 10% chicken and cattle manure also led to significant increases in flavonoid content, with increases of 19.12 and 24.85%, respectively. Notably, the effect of applying 20% chicken manure was similar to that of applying the same concentration of cattle manure (Figure 3A). In terms of anthocyanin content, fertilization with 10 and 20% chicken manure resulted in significant increases of 59.78 and 43.36%, respectively. However, the application of cattle and goat manure did not influence this variable (Figure 3B). The content of phenolic compounds increased with the application of 10 and 20% chicken, cattle, and goat manure. The increases observed were 70.86 and 76.44% for chicken manure, 73.80 and 78.50% for cattle manure, and 78.92 and 73.17% for goat manure. It is worth noting that the 10% dose resulted in a higher increase in phenolic compounds for goat manure, while the 20% dose yielded a higher increase for cattle manure (Figure 3C).

A PCA with clusters was conducted to examine the relationships among the factors and variables studied. The results revealed that the first principal component accounted for 50.5% of the total variation, while the second principal component explained 22.2% of the variation. Together, these two components explained 72.2% of the total variance. Based on the PCA results, three distinct groups were identified (Figure 4). The first group comprised treatments with cattle manure at 10% (CM10) and 20% (CM20), as well as 10% goat manure (GM10). The second group consisted of the treatments with 10% (ChM10) and 20% (ChM20) chicken manure, along with 20% goat manure (GM20). Finally, the third group included the treatments without any manure application (GM0, ChM0, and CM0).

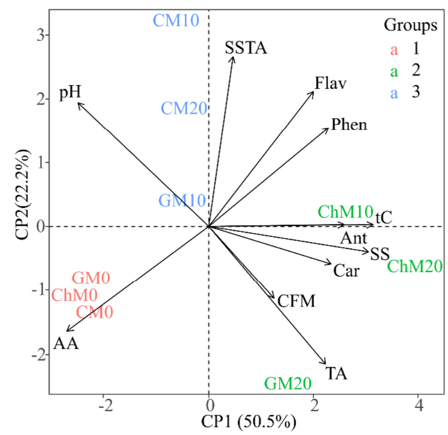

Figure 4. Principal component analysis for factors and analyzed variables of forage palm (*Nopalea cochenillifera*) cladodes grown under doses and sources of organic fertilization.

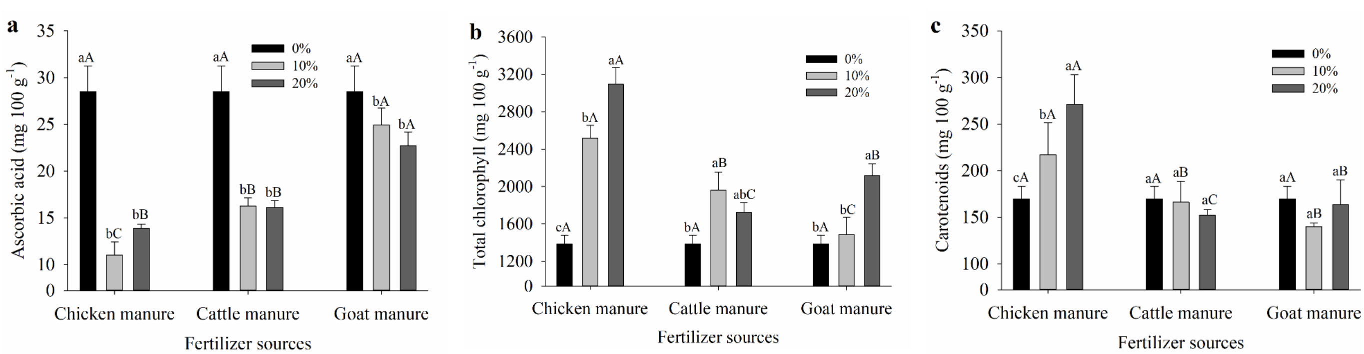

Figure 2. (A) Ascorbic acid, (B) total chlorophyll, and (C) carotenoids of forage palm (*Nopalea cochenillifera*) cladodes grown under doses and sources of organic fertilization. Means followed by the same capital letters do not differ for sources, and means followed by the same lowercase letters do not differ for fertilizer doses by the Tukey test ($p \leq 0.05$).

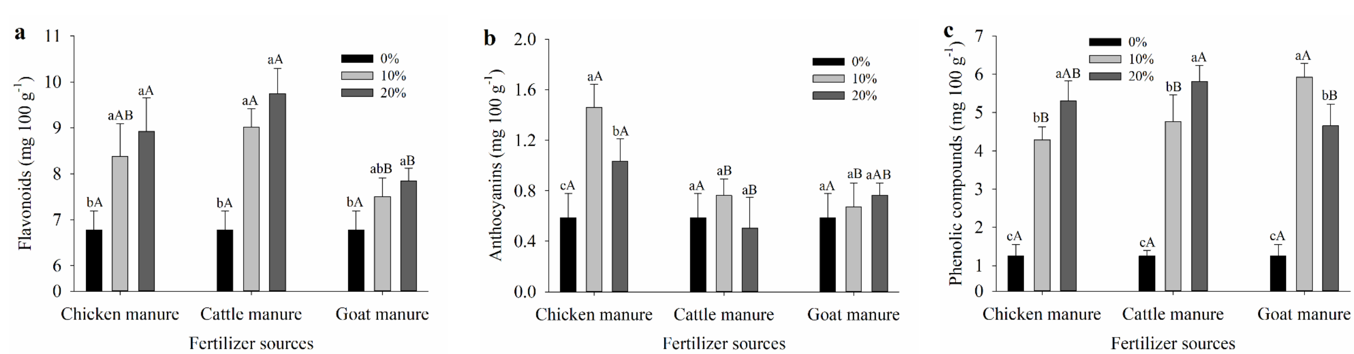

Figure 3. (A) Flavonoids, (B) anthocyanins, and (C) phenolic compounds of forage palm (*Nopalea cochenillifera*) cladodes grown under doses and sources of organic fertilization. Means followed by the same capital letters do not differ for sources, and means followed by the same lowercase letters do not differ for fertilizer doses by the Tukey test ($p \leq 0.05$).

The SS/TA ratio (SSTA) exhibited the strongest relationship with CM10, indicating that this treatment had the most significant impact on this variable. The contents of flavonoids (Flav), phenolic compounds (Phen), total chlorophyll (tC), anthocyanins (Ant), soluble solids (SS), and carotenoids (Car) showed higher relationships and higher values in the treatments ChM10 and ChM20, suggesting that these two treatments had the greatest influence on these variables. Cladode fresh mass (CFM) was most closely related to GM20 and Ch2M20, indicating that these treatments had the highest effect on CFM. TA showed the strongest relationship with GM20, suggesting that this treatment had the most significant impact on TA. AA content exhibited the highest relationship with the third group, which comprised treatments without manure application (GM0, ChM0, and CM0), suggesting that the absence of manure application resulted in higher AA content. Finally, pH had the highest relationship with CM10 and CM20, indicating that these treatments had the most significant impact on pH levels.

A Pearson correlation analysis was conducted to examine the relationships between the variables studied (Figure 5). The analysis revealed several significant correlations. The highest positive correlations were observed between SS and total chlorophyll (tC) (r = 0.93), indicating a strong positive relationship between these two variables. Similarly, carotenoids (Car) showed a strong positive correlation with tC (r = 0.90), as well as anthocyanins (Ant) with tC (r = 0.87), indicating that higher levels of tC were associated with higher levels of Car and Ant. On the contrary, there were also significant negative correlations observed. The highest negative correlations were found between TA and pH (r = -0.95), indicating that higher TA values were associated with lower pH values. Additionally, SS showed a strong negative correlation with pH (r = -0.91), as well as with AA (r = -0.91), suggesting that higher SS values were associated with lower pH and AA levels. Furthermore, AA exhibited negative correlations with Car (r = -0.91) and Ant (r = -0.87), indicating that higher AA levels were associated with lower Car and Ant levels.

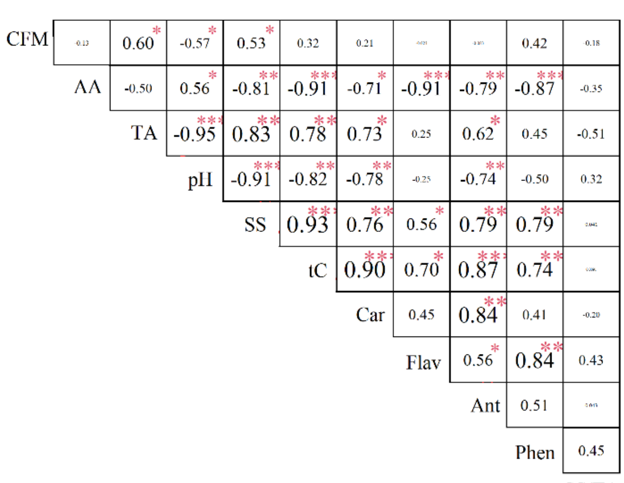

Figure 5. Person correlation between the analyzed variables of forage palm (*Nopalea cochenillifera*) cladodes grown under different doses and sources of organic fertilization.

According to the Pearson correlation analysis (Figure 5), the AA content exhibited negative correlations with all variables, except for CFM and the SS/TA ratio. This suggests that higher AA levels were associated with lower values of the other variables analyzed. Similarly, pH showed negative correlations with all variables, except for carotenoids (Car), phenolic compounds (Phen), and the SS/TA ratio. This indicates that higher pH values were associated with lower levels of the other variables. On the contrary, SS content demonstrated positive correlations with all variables except for pH, AA, and the SS/TA ratio. This implies that higher SS levels were associated with higher values of the other variables analyzed. Likewise, total chlorophyll (tC) content showed positive correlations with all variables, except for pH, AA, and the SS/TA ratio. This suggests that higher tC levels were associated with higher values of the other variables. In summary, the correlation analysis reveals complex relationships between the variables, with AA and pH displaying negative correlations with most variables, while SS and tC exhibit positive correlations with most variables. The CFM and SS/TA ratio show no significant correlations with the other variables.

4 DISCUSSION

Fertilization with chicken manure and goat manure resulted in increased fresh mass of the cladodes and SS. This effect can be attributed to the higher organic matter content as well as elevated levels of nitrogen (N), phosphorus (P), and potassium (K) in the substrate (Table 1). This response is likely due to the rapid decomposition of chicken and goat manure, which leads to the release of higher amounts of N, P, and K compared to cattle manure. This increased decomposition is attributed to the intense microbial activity on the components of these manures, which contain a larger proportion of easily biodegradable carbon compounds such as sugars, amino acids, and proteins (Silva et al., 2014). Moreover, chicken manure exhibits lower concentrations of complex organic compounds such as cellulose, lignin, and fats, which decompose at a slower rate (Saraiva et al., 2021).

Increasing phosphorus (P) fertilization has been found to result in greater uptake and accumulation of P in the dry matter of forage palm (O. ficus-indica Mill—Dubeaux Júnior, 2010). This increased availability of nutrients leads to higher yields and biomass, as well as an increase in SS content in palm cladodes. Consequently, the application of these two manures (chicken and goat) can be recommended to enhance both the yield (phytomass) and the SS content, which is a crucial factor for the palatability of oil palm cladodes for human and/or animal consumption. Fertilizing forage palm plants has been observed to elevate the SS content in comparison to unfertilized plants (Karim et al., 1998).

Fertilization with cattle manure resulted in an increase in the pH of palm cladodes (Figure 1B), which can be attributed to the rise in acid concentrations caused by this type of fertilization. Acidity and pH are inversely related. In this case, the use of cattle manure as fertilizer makes the fruit more acidic, potentially reducing its palatability for human consumption. On the contrary, fertilization with 20% goat manure led to an increase in TA (Figure 1D), indicating the production of organic acids through this fertilization. However, it is important to note that this higher acidity is undesirable as it affects the preservation and flavor of palm cladodes, ultimately impacting consumer acceptance of the product (Corrales-García et al., 2004). Therefore, the use of 20% goat manure as a fertilizer is not recommended due to the negative effects on acidity and flavor.

Fertilization with 10% cattle and goat manure resulted in an increased SS/TA ratio of palm cladodes (Figure 1E). The SS/TA ratio serves as a quality indicator that is associated with sweetness, meaning that cladodes with a higher ratio exhibit a more pronounced sweetness, leading to better consumer acceptance (Cunha et al., 2021). This ratio is considered a practical way to evaluate taste, as it follows a simple relationship: when acidity increases, the SS/TA ratio decreases, and when acidity decreases, the SS/TA ratio increases (Alexandre et al., 2018). Therefore, fertilization with 10% chicken and goat manure represents a viable strategy to enhance the quality and palatability of palm cladodes, improving their taste and desirability for consumers.

AA, also known as vitamin C, possesses strong antioxidant properties and is recognized as a valuable dietary and nutritional antioxidant (Kim et al., 2016). Interestingly, organic fertilization resulted in a decrease in the AA content of palm cladodes (Figure 2A). This reduction could potentially be attributed to an increased stress response caused by nutritional deficiencies, leading to an upregulation of secondary metabolism and consequently impacting the levels of AA. Plants often enhance their antioxidant metabolism as an adaptive mechanism to cope with adverse conditions and ensure their survival. It is important to note that even though the AA content decreased, all the applied treatments still exhibited vitamin C contents exceeding 10 mg 100 g-1 of cladodes. This amount is considered adequate to prevent symptoms of scurvy, a condition associated with vitamin C deficiency, particularly in infants (FAO, 2004). Incorporating small amounts of cladodes into food products has the potential to address vitamin C deficiencies due to the substantial vitamin C content in forage palm cladodes. These cladodes are considered an excellent and reliable source of vitamin C, with the added advantage of extended supply and preservation compared to the fruits of the palm plant (Mabotja et al., 2021). Furthermore, forage palm cladodes may contain higher levels of AA compared to apples, pears, grapes, and bananas and exhibit similar contents to citrus fruits, mangoes, and guava (Wit et al., 2019).

Palm cladodes naturally contain pigments such as chlorophylls and carotenoids, which possess notable antioxidant capabilities (El Kharrassi et al., 2016). Fertilization with 20% chicken manure and goat manure led to an increase in the total chlorophyll content of the cladodes (Figure 2B), while the carotenoid content was higher in plants fertilized with 10 and 20% chicken manure (Figure 2C). This response is linked to the higher nutrient content, particularly nitrogen (N), present in these fertilizers (Table 1). N plays a crucial role as the primary constituent of chlorophyll (Namvar & Khandan, 2015), and its availability in the soil is essential for the production and maintenance of photosynthetic pigments. Furthermore, the application of N in conditions where light is not limiting enhances antioxidant defense mechanisms, resulting in reduced photooxidation of chloroplast pigments (Namvar et al., 2013). Consequently, there is an increase in the content of photosynthetic pigments. Remarkably, the carotenoid content in palm cladodes surpasses that of baby carrots, beets, spinach, and lettuce (Medina-Torres et al., 2011), highlighting their richness in these valuable pigments.

Fertilization with both chicken and cattle manure resulted in an increased content of flavonoids in palm cladodes (Figure 3A). Furthermore, fertilization with chicken manure specifically led to an increase in anthocyanin content (Figure 3B). Additionally, all the studied manures demonstrated the ability to enhance the content of phenolic compounds in the cladodes (Figure 3C). These responses can be attributed to the greater availability of nitrogen (N) in plants that received organic manure as fertilizer (Table 1). The increased content of these antioxidant compounds may be attributed to the regulation of specific enzymes involved in their biosynthesis, such as phenylalanine ammonia-lyase (Tavarini et al., 2015). Moreover, nutrient deficiencies in plants can cause alterations in the content and composition of phenolic compounds across various crops (Ladd & Amato, 1986). The content of flavonoids, anthocyanins, and phenolic compounds in palm cladodes is dependent on the type and dosage of the fertilizer used, as the synthesis of these compounds is closely linked to nitrogen input and the plant's metabolism. This is because the precursor of phenolic compounds is the amino acid phenylalanine (Ortega-García et al., 2015).

The PCA (Figure 4) revealed distinct relationships between the different fertilizers and various parameters. The SS/TA ratio and pH were found to be more closely associated with cattle manure fertilization. On the contrary, the content of bioactive compounds (flavonoids, anthocyanins, phenolic compounds, chlorophyll, and carotenoids) and SS showed stronger relationships with plants fertilized with chicken manure. The fresh mass of the cladodes exhibited a closer relationship with goat and chicken manure fertilization. TA was predominantly associated with cattle manure, while the content of AA was linked to plants grown without fertilization. This pattern of behavior could be attributed to the gradual release of a higher nutrient flow to the plants, particularly at higher doses of organic fertilization. Furthermore, organic fertilization likely led to soil improvements, including enhanced moisture retention and improved nutrient utilization (Silva et al., 2016b). Overall, the PCA highlights the specific effects of different fertilizers on various parameters, demonstrating the diverse impacts of organic fertilization on the overall performance and composition of palm cladodes.

Antioxidants play a crucial role in reducing, slowing, or inhibiting the oxidation process of molecules, even at low levels, thereby offering protection against various diseases (Gülcin, 2012). In recent studies, palm cladodes have emerged as a potential source of these valuable compounds (Wit et al., 2019). The contents of bioactive compounds in the cladodes exhibited strong correlations with each other, except for AA (Figure 5). This observation can be attributed to the role of organic fertilizers in stimulating biosynthetic pathways, particularly the shikimate acetate pathway, which results in increased production of flavonoids and phenolic compounds (Salama et al., 2015). These findings are highly promising, as phenolic compounds are known to possess significant antioxidant capacity owing to their redox properties, enabling them to effectively neutralize free radicals (Haile et al., 2016).

Furthermore, organic fertilization proves to be an interesting practice for enhancing the levels of bioactive compounds and improving the palatability characteristics of forage palm cladodes. Organic fertilizers can enhance nutrient availability, physiological functions, and various metabolic pathways, including those involved in the synthesis of secondary compounds. These pathways are closely interconnected with the photosynthetic cycle, which provides carbohydrates as raw materials for the formation of diverse substances (Onofrei et al., 2017). Therefore, organic fertilization holds promise as a means to increase the levels of bioactive compounds and improve the overall quality of forage palm cladodes.

This study mentioned the potential of organic fertilizers in improving the quality and composition of forage palm cladodes. The results demonstrated that fertilization with different types of animal manure, such as chicken, cattle, and goat manure, had significant impacts on cladode characteristics. Fertilization with chicken and cattle manure led to an increase in cladode fresh mass as well as higher SS content and a higher SS/TA ratio, indicating increased sweetness and consumer acceptance. This fertilization also positively influenced the levels of bioactive compounds such as flavonoids, anthocyanins, and phenolic compounds, as well as chlorophyll and carotenoids, which are pigments with antioxidant properties.

On the contrary, fertilization with goat manure resulted in increased TA, which may negatively affect cladode preservation and flavor. However, this fertilization did not have a significant impact on the levels of bioactive compounds. Furthermore, it was observed that organic fertilization may decrease the content of AA (vitamin C) in cladodes, but the levels found were still adequate to prevent vitamin C deficiencies.

These studies emphasize the importance of organic fertilizers in improving the nutritional and antioxidant quality of forage palm cladodes. These fertilizers enhance nutrient availability, stimulate the biosynthesis of bioactive compounds, and improve various metabolic pathways. Therefore, the use of organic fertilizers can be an interesting practice to increase the nutritional value and palatability of forage palm cladodes, providing benefits for both human and animal consumption.

The novelty of the study regarding the cultivation of forage palm with organic fertilization in the Brazilian semiarid region lies in the confirmation of the benefits of these agricultural practices for improving productivity and crop quality. In the context of the semiarid region, where environmental conditions are adverse and water resources are limited, finding sustainable and efficient management alternatives becomes crucial. The study highlights that there is often a mistaken understanding that forage palm is a crop tolerant to environmental limitations and does not require specific care, such as proper fertilization and management. However, the results demonstrate that organic fertilization, particularly with chicken, cattle, and goat manure, can increase the productivity of forage palm in the semiarid region.

By using these organic fertilizers, there was an increase in the fresh mass of the cladodes and the content of SS, indicating better nutritional quality and greater palatability. Additionally, organic fertilization promotes the accumulation of bioactive compounds such as flavonoids, anthocyanins, and phenolic compounds, which have beneficial antioxidant properties for human health. These findings are relevant to forage palm producers in the Brazilian semiarid region, as they indicate that organic fertilization can be a viable and sustainable strategy to improve productivity and crop quality. Furthermore, the study emphasizes the importance of considering the environmental and management specificities of forage palm to optimize results and promote sustainability in both cultivation and the environment.

5 CONCLUSION

Forage palm cladodes fertilized with 20% chicken manure produce the highest biomass, while cladodes fertilized with 10% chicken manure have the highest palatability and bioactive compound contents. With this, fertilization with 10% chicken manure is the most promising and economically feasible for increasing the yield and quality of forage palm cladodes. The novelty of the study lies in the confirmation of the benefits of organic fertilization, using chicken, cattle, and goat manure, for the cultivation of forage cactus intended for human consumption in the Brazilian semiarid region. The results demonstrate that this agricultural practice improves the productivity and nutritional quality of the cladodes, increasing their fresh weight and SS content. Additionally, organic fertilization promotes the accumulation of bioactive compounds, such as flavonoids, anthocyanins, and phenolic compounds, which have beneficial antioxidant properties for human health. These findings indicate that organic fertilization can be a viable and sustainable strategy to enhance the productivity and quality of forage cactus cultivated for human consumption in the challenging context of the Brazilian semiarid region.

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