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Multivariate analysis of physico-chemical data of soil cultivated with cactus pear varieties intercropped with legumes in Brazilian semi-arid region

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R E S U M O

Nas regiões semiáridas, a disponibilidade hídrica é um fator limitante para a agricultura, exigindo a adoção de estratégias eficientes para aproveitar ao máximo esse recurso. A utilização de águas residuais tratadas provenientes de esgotos domésticos representa uma alternativa viável, desde que sejam tomadas as devidas precauções. O objetivo desta pesquisa foi avaliar o efeito do efluente doméstico tratado na fertilidade do solo no cultivo de palma forrageira e leguminosas. O experimento foi conduzido em blocos casualizados (DBC), sendo as parcelas principais constituídas por variedades de palmeiras e as parcelas secundárias envolvendo diferentes sistemas de cultivo consorciado de leguminosas. Os solos foram avaliados nas profundidades de 0-10 e 10-20 cm. Os atributos do solo avaliados incluíram distribuição granulométrica, densidade do solo, pH, condutividade elétrica (CE), salinidade, sodicidade e macronutrientes primários. O delineamento experimental utilizado foi blocos completos casualizados (DBC) com 4 repetições. O planejamento fatorial utilizado na pesquisa foi 3 x 3 x 2, representado pelas três variedades de palmeiras forrageiras, três tipos de consórcios e duas profundidades. A redução nos teores de K^+ após a irrigação indica perdas por lixiviação e/ou absorção pelas culturas. A forte correlação entre Na^+, K+, Ca^{2+} e Mg^{2+} com silte e salinidade confirma o papel dos minerais primários e das reações de precipitação na disponibilidade desses elementos.

Palavras-chave: reúso agrícola, irrigação, sodicidade, salinização.

Multivariate analysis of physico-chemical data of soil cultivated with cactus pear varieties intercropped with legumes in Brazilian semi-arid region

A B S T R A C T

In semiarid regions, water availability is a limiting factor for agriculture, demanding the adoption of efficient strategies to make the most of this resource. The use of treated wastewater from domestic sewage represents a viable alternative, as long as appropriate precautions are taken. The objective of this research was to evaluate the effect of treated domestic effluent on soil fertility when cultivating forage palm and legumes. The experiment was conducted in randomized blocks (DBC), with the main plots consisting of palm varieties and the secondary plots involving different legume intercropping systems. The soils were evaluated at depths of 0-10 and 10-20 cm. The assessed soil attributes included particle size distribution, soil density, pH, electrical conductivity (CE), salinity, sodicity, and primary macronutrients. The experimental design used was randomized complete blocks (DBC) with 4 replications. The factorial design used in research was 3 x 3 x 2, represented by the three varieties of forage palms, three types of consortia, and two depths. Reduction in K^+ contents after irrigation indicates losses through leaching and/or uptake by crops. The strong correlation between Na^+, K^+, Ca^{2+} and Mg^{2+} with silt and salinity confirms the role of primary minerals and precipitation reactions in the availability of these elements.

Kay-words: Agricultural reuse water, Irrigation, Soil sodicity, salinization.

Introduction

In the midst of the arid scenario of the Brazilian semiarid region, where water scarcity and the search for sustainable solutions are constant challenges, the multivariate analysis of physicochemical data from soil cultivated with forage cactus under irrigation with agricultural reuse, intercropped with legumes, emerges (Obaideein et al., 2022).

The soil, once considered merely a substrate, reveals itself as a living matrix, whose fertility depends on the intelligent interaction between its intrinsic and extrinsic variables. By deciphering this intricate puzzle, researchers pave the way for a more efficient, sustainable, and resilient agriculture, offering promising solutions for agricultural development in the Brazilian semiarid region (Rodríguez et al., 2022).

A utilization of wastewater in agriculture emerges as an innovative and sustainable approach for cultivating forage cactus varieties in the Brazilian semiarid region. In this challenging scenario, where water scarcity is a constant reality, it becomes imperative to find solutions that maximize the efficient use of this precious resource. It is within this challenging context that wastewater, originating from human and industrial activities, reveals itself as a valuable catalyst for agricultural development (Obaideein et al., 2022).

When using wastewater for the irrigation of plants known as cacti, specifically forage cactus or different varieties of cacti, a double benefit occurs: on one hand, the negative environmental impact of this effluent is minimized, avoiding its discharge into water bodies and contributing to the preservation of water resources. On the other hand, an additional water source is provided for cultivation, acting as a source of both water and nutrients in the soil-plant-atmosphere system, thus expanding the productive possibilities in the semiarid region. This innovative approach, based on the reuse and valorization of wastewater, demonstrates an integrated and sustainable approach to agriculture in the region (Marinari et al., 2022).

The use of wastewater in agriculture, as an innovative way of cultivating forage cacti, promotes not only environmental sustainability but also the economic and social viability of the semiarid region. This practice boosts family farming, diversifies production, and generates income opportunities for local farmers, reducing their dependence on external water sources and inputs (Rodríguez et al., 2022).

Using alternative statistical tools to understand the different behaviors and interactions within the various patterns of forage cactus cultivation, studying correlations, matrices, and principal components proves to be a challenging topic in the current context of a more comprehensive statistical study of soil fertility. By unraveling the secrets of the soil and the cactus, we pave the way for a more sustainable, efficient, and prosperous agriculture in the arid landscape of the Brazilian semiarid region (Scavo et al., 2022).

In the literature there are several methods to evaluate these relationships. However, we can apply multivariate analyses, such as principal component analysis – PCA, cluster analysis (Ramos et al., 2021) and canonical correlation analysis – ACC, as they allow the data to be grouped into a covariance matrix and identify more associated variables, thus reducing the set of information.

The study of multivariate analysis in the context of soil fertility, using reclaimed water as a form of sustainable agriculture, is of fundamental importance to understand the complex interactions among different physicochemical parameters of the soil and the effects of irrigation with reclaimed water on its fertility.

In light of the above, the objective of this work is to analyze the physical and chemical data of soil in a more comprehensive manner within the context of multivariate analysis of forage palm varieties in the Brazilian semiarid region.

Materials and Methods

Study area

The study area was conducted at the experimental unit of the National Institute of Semiarid (INSA), under field conditions from November 2019 to December 2022, using agricultural wastewater reuse from the municipality of São Fernando, state of Rio Grande do Norte, Brazil, located at geographic coordinates 6º22'45" S and 37º10'60" W, at an elevation of 131 meters above sea level according to the Köppen-Geiger classification.

The municipality of São Fernando, geographically located between the Seridó River, which originates in the Cariris Mountains, and the Piranhas Açu River, which flows through a large part of its rural area (Fig. 1). The predominant vegetation in the municipality is Caatinga Hipoxerófila, or Caatinga Shrubland. This vegetation formation covers the entire central-southern portion of the state.

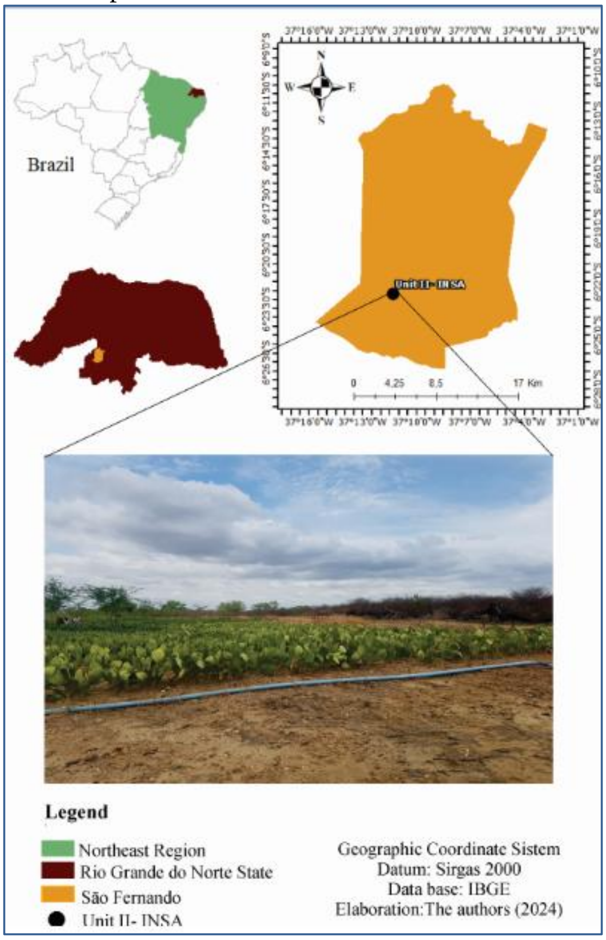

Figure 1. Geographic location of the study area referring to the application of treated domestic effluent located in the municipality of São Fernandes-RN. Figure 1 which is \label{fig1}.

Soil types in the region

The predominant soils in the region are Eutrophic Fluvic Neosols formed from Holocene alluvial deposits, which can also occur in association with Eutrophic Litholic Neosols resulting from weathering of dioritic orthogneisses (BELTRÃO et al., 2005). According to the Köppen classification, the local climate is characterized as a low-altitude and low-latitude semiarid climate (BS'h), with a rainy season between February and April. The average annual precipitation is 693 mm, with an average annual temperature of 25.5ºC.

Experimental design

The experimental design used was a completely randomized design (CRD). The agricultural wastewater reuse treatment unit consisted of a 1 ha area cultivated with three varieties of forage palm consorted with three leguminous species suitable for timber. The cultivated palm varieties were sweet small prickly pear (*Nopalea cochenillifera* Salm-Dick); Mexican prickly pear (*Opuntia stricta* L. Mill); and Bahian sweet palm (*Nopalea* sp.). The leguminous species were sabiá (*Mimosa caesalpiniifolia*); algaroba (*Prosopis juliflora*) and gliricidia (*Gliricidia sepium*).

The experiment was conducted in a randomized block design (RBD), with a factorial scheme of 3 x 3 x 2, corresponding to three varieties of forage palms, three consortia, and two soil depths (0-10 and 10-20 cm), with four repetitions, totaling 72 sampled experimental units.

Composite soil samples were collected (24 soil samples) at two depths (0-10 and 10-20 cm) for the determination of physical and chemical attributes. The physical analyses were performed at the Soil and Mineralogy Laboratory of INSA according to the standards described per Teixeira et al. (2017). The particle size analysis and clay dispersion in water were conducted using the pipette method, with NaOH and H_2O as dispersing agents, respectively. Soil density (Sd) was obtained using the volumetric ring method.

Sampling and physical and chemical analysis of soils

Composite soil samples were collected (24 soil samples) at two depths (0-10 and 10-20 cm) for the determination of physical and chemical attributes. The physical analyses were performed at the Soil and Mineralogy Laboratory of INSA according to the standards described per Teixeira et al. (2017).

The particle size analysis and clay dispersion in water were conducted using the pipette method, with NaOH and H_2O as dispersing agents, respectively. Soil density (Sd) was obtained using the volumetric ring method.

The chemical analyses of the soils were conducted at the Soil Physics and Fertility Laboratory of the State University of Paraíba - UEPB, in partnership with INSA, following the guidelines described in Teixeira et al. (2017). The pH was determined in water (1:2.5 - TFSA:H_2O). Electrical conductivity (EC) was obtained using a direct reading conductivity meter (1:5.0 - TFSA:H_2O), where 10 cm³ of soil samples were collected and then 25 ml of distilled water was added. Each sample was stirred with a spatula and allowed to settle for a specified period of 1 hour to initiate the appropriate quantifications. The exchangeable contents of Ca^{2+}, Mg^{2+}, and Al^{3+}

were extracted with 1 mol L^{-1} KCl solution. The contents of P, K^+, and Na^+ were extracted with Mehlich 1 solution (0.05 mol L^{-1} HCl + 0.0125 mol L^{-1} H_2SO_4). The contents of Ca^{2+} and Mg^{2+} were determined by complexometry, K^+ and Na^+ by flame photometry, and P by colorimetry.

Statistical analysis

All data were parameterized through a script using the R software, as a statistical computer program to analyze the multivariate data in order to understand the relationships between the behavior of palm varieties in relation to soil quality and their respective intercrops according to Mesquita et al. (2023) and Abbott et al. (2019).

The statistical treatment was performed through analysis of variance, and the means of qualitative data were compared using Tukey's test at a 5% probability. All data and their respective multivariate analyzes were parameterized according to Abbott et al. (2019). All data decomposition, organization, analysis, and interpretation were done using the statistical software R version 4.2 (WEI T, SIMKO VR., 2017).

Results

Principal Component Analysis (PCA) is a statistical technique used to reduce the dimensionality of a dataset by transforming it into a set of orthogonal new variables, called Principal Components. Each principal component is a linear combination of the original variables, and together they explain most of the total variation in the soil fertility data regarding the study of forage palm varieties (*Mexican elephant ear*, *small*, and *Bahian*) and three types of consortium arrangements (*algaroba*, *sabiá* and *gliricidia*). PCA is often used in areas such as data analysis and pattern recognition.

A analysis of the two principal components (Figure 2A) refers to a study of nutrient balance in the soil-water-atmosphere system and its physical characteristics at a depth of 0-10 cm. In this sense, the first principal component, which explains 39.2% of the data variability, is related to the contribution of the soil's physical and chemical attributes directly associated with soil fertility through the application of agricultural reuse.

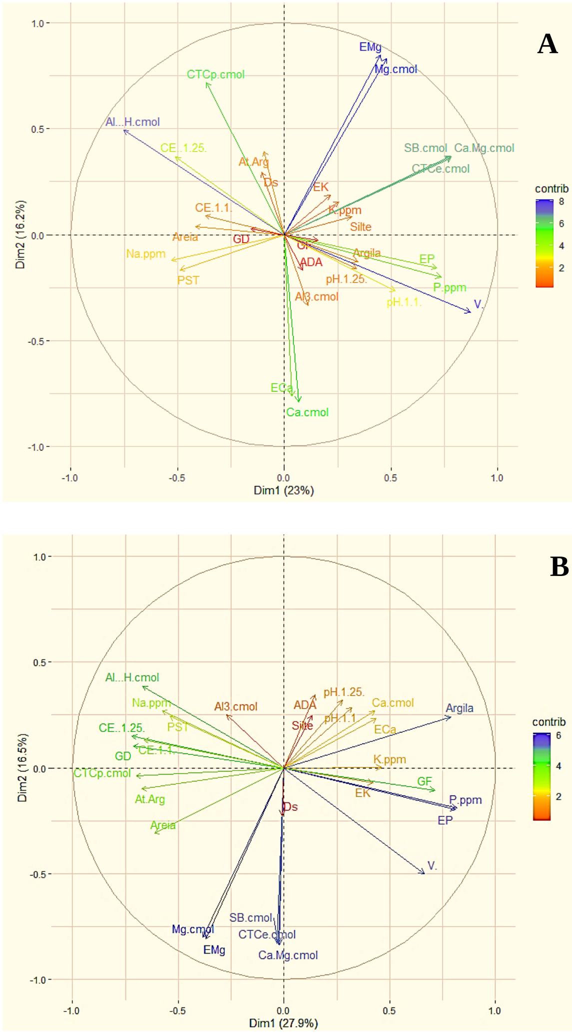

Figure 2. Principal component analysis (PCA) referring to all physical and chemical characteristics of the soil evaluated at a depth of 0-10 cm (A) and 10-20 cm (B) under cultivation of three varieties of cactus pear intercropped with native legumes and exotic in soil with treated domestic agricultural reuse (RAT), municipality of São Fernando-RN. Figure 2 which is \label{fig2}.

It represents a weighted combination of these characteristics that are directly related to soil fertility due to the application of treated domestic agricultural reuse. On the other hand, the second principal component (Figure 2A), which explains 44.4% of the data variability, is related to the contribution of these physical and chemical attributes for the assessment of soil fertility with agricultural reuse application. These data were studied at a depth of 10-20 cm, with 23% and 27.9% attributed to PCA1 and PCA2, respectively (Figure 2).

Physically, the positive dimension of PCA1 is constituted by soil density (Sd), silt, and clay activity, while the negative dimension is composed of sand, ADA, dispersion degree (DG), flocculation degree (FG), and clay, as these data are represented from the 0-10 cm layer (Figure 3A).

In the positive dimension, this means that these attributes are positively related to soil fertility after agricultural reuse application. In other words, the higher the values of these attributes, the higher the soil fertility tends to be. On the other hand, the negative dimension represents those physical attributes that are negatively related to soil fertility, meaning that lower values of these attributes indicate higher soil fertility after agricultural reuse application.

Chemically analyzing the soil at a depth of 0-10 cm, the positive dimension of PCA1 was grouped by the chemical attributes $H+Al^{3+}$, SEC, EC, potassium stock (PS), sum of bases (SB), magnesium stock (MS), and soil Mg. On the other hand, the negative dimension was statistically represented by Na^{+}, ESP, pH, Al^{3+}, and phosphorus stock (PS). These attributes are negatively related to soil fertility after agricultural reuse application.

When chemically analyzing the soil at a depth of 10-20 cm (Figure 2B), the positive dimension of PCA 2 was grouped by the chemical attributes P content, phosphorus stock (PS), base sum (SB), Mg, and magnesium stock (MS). In turn, the negative dimension chemically is statistically represented by the attributes aluminum (Al^{3+}), soil pH, calcium (Ca^{2+}), calcium stock (CS), potassium (K^{+}), and potassium stock (PS).

Regarding the physical parameters of the soil, at the same depth, it is observed from PCA 2 that the positive dimension was represented only by the clay fraction, however, the opposite behavior was observed in the negative dimension of PCA 2, represented by the attributes soil density (Sd), silt, and clay dispersed in water (CDW).

Soil fertility is a crucial aspect for agricultural development and environmental sustainability. In this context, elliptical PCA analysis stands out as a powerful tool for understanding the relationship between soil fertility data and agricultural reuse applications.

In this Figure 2, the type of behavior and its implications were explored, with a special focus on the Baiana variety and its representativeness in relation to other varieties, such as the Mexican Elephant Ear and the small variety.

These results indicate that the use of treated wastewater as a source of irrigation and fertilization can be an effective strategy to promote soil quality. The principal component explains 39.6% of the data variability regarding the study of forage palm varieties intercropped with different types of legumes, as shown in (Figure 3).

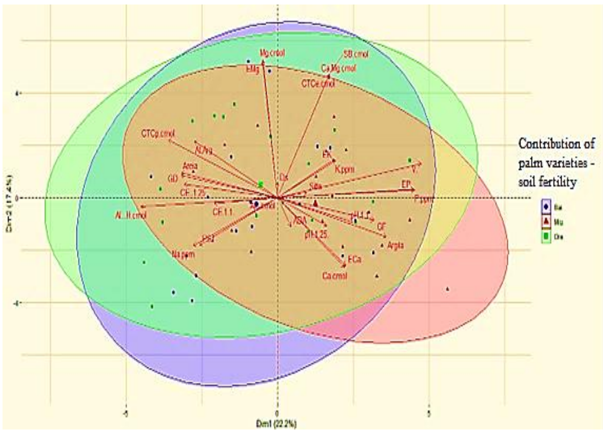

Figure 3. Principal component analysis (PCA) regarding the contributions of the palm varieties under study on soil fertility in soil with treated domestic agricultural reuse (RAT), municipality of São Fernando-RN. Figure3 which is \label{fig3}.

The positive dimension (contribution) of PCA is composed of the attributes silt, clay, Sd, EC, $H+Al^{3+}$, Ni, Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, TOC, ETOC, SOM, SEC, CE, Clay, and ESP, while the negative dimension is composed of sand, EC, CECp, Na, and V%. In the positive dimension of PCA, the attributes sand, clay, TOC, ETOC, SOM, $H+Al^{3+}$, and Sd were grouped, while in the negative dimension, the attributes sand, pH, EC, DP, EMg, SB, CDW, CEClay, V%, and ESP were grouped. From the data analysis, it can be observed that the Baiana variety has a greater representativeness compared to the other varieties, followed by the Mexican Elephant Ear variety, and finally the small variety. When analyzing the data related to soil fertility, it can be noticed that the Baiana variety stands out for its greater representativeness compared to the others. This indicates that this variety plays a fundamental role in improving soil fertility when subjected to agricultural reuse applications. Through the analysis of elliptical PCA, it is possible to identify the significant contribution of the Baiana variety to soil quality, which directly impacts crop health and agricultural productivity.

The applications of agricultural reuse have proven to be an efficient strategy for the sustainable use of water resources and soil fertility improvement. In the case of the Baiana variety, these applications have shown a positive influence on its representativeness and contribution to soil fertility. This can be attributed to the presence of essential nutrients from agricultural reuse, which are absorbed by the plants and enrich the soil, increasing its capacity to sustain the healthy growth of crops.

In addition to agricultural reuse applications, plant consortia play an important role in improving soil fertility in the context of the Baiana variety. The interaction between the plants present in the consortium, including legumes, provides a favorable environment for nitrogen fixation and nutrient cycling, further enriching the soil. This positive interaction between plants contributes to chemical parameters such as Mg, Ca+Mg, SB, and K^+ levels, as well as physical attributes such as silt content, clay dispersal in water, and soil density. Thus, the application of elliptical PCA in legume intercropping studies can provide valuable behaviors to optimize soil fertility, promoting more efficient and environmentally friendly agricultural systems.

Elliptical PCA analysis is a powerful tool for understanding the complexity of soil fertility data, especially in agricultural systems where legume intercrops are used (Mahiran et al., 2023). This type of analysis makes it possible to identify patterns and relationships between multiple variables that influence soil fertility, such as nutrients, organic matter, pH, among others.

The elliptical PCA analysis of the soil fertility data in association with legume consortium plots and their interactions in soil under agricultural reuse applications reveals valuable information about the behavior of these variables (Figure 4).

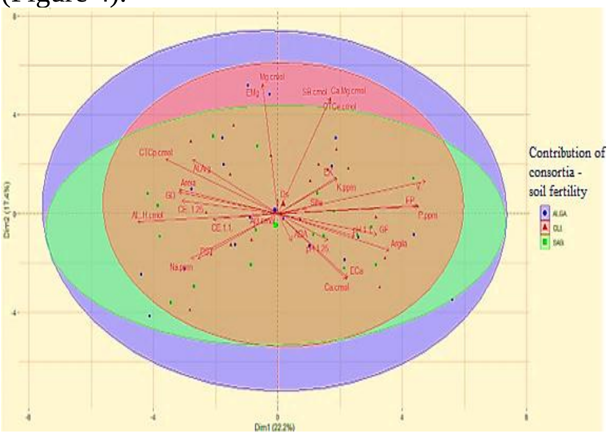

Figure 4. Principal component analysis (PCA) referring to the contributions of leguminous intercrops for the study of soil fertility in soil irrigated with treated domestic agricultural reuse (RAT), municipality of São Fernando-RN. Figure 4 which is \label{fig4}.

Through the analysis of the principal component, represented in Figure 5, it was possible to observe that PCA explains 39.6% of the variability of the data related to the different types of legume consortia and their contribution to soil fertility, considering the analyzed physical and chemical attributes. This indicates that the characteristics of the consortia have a significant impact on soil fertility.

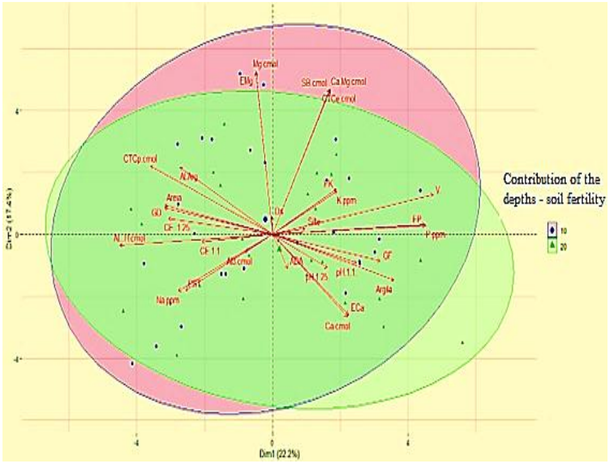

Figure 5. Principal component analysis (PCA) referring to the contributions of soil depth for the study of soil fertility in soil irrigated with treated domestic agricultural reuse (RAT), municipality of São Fernando-RN. Figure 5 which is \label{fig5}.

When observing (Figure 5) of the PCA, it is notable the subdivision into three ellipses or ellipsoids, representing the contributions of the different legume consortium arrangements. In this context, the consortium with algaroba stands out, as it presented the highest contribution to soil fertility. This can be attributed to the fact that this consortium increases nutrient availability in the soil and promotes greater nutrient cycling. It is also important to highlight the influence of agricultural reuse irrigation, which contributes to these positive results.

On the other hand, it was observed that the consortium with gliricidia had the second highest representativeness among the legume consortium arrangements, while the consortium with sabiá showed a lower contribution and representativeness in the study area. These results can be attributed to specific interactions between the legumes and the soil, as well as the individual characteristics of each consortium. Further investigation is needed to better understand these processes and interactions in order to comprehend this type of behavior. These elliptical PCA analyses provide a comprehensive view of the relationship between legume consortia, agricultural reuse, and soil fertility. Understanding these interactions is crucial for the development of more efficient and sustainable agricultural practices, aiming at better utilization of available resources and continuous improvement of soil quality in the semiarid region.

Through the analysis of the principal component, represented in (Figure 5), it was found that PCA explains 39.65% of the variability of the data concerning the different soil depths, specifically 0-10 cm and 10-20 cm, and their relation to the contribution to soil fertility. This means that the physical and chemical characteristics of the soil in these depth ranges play an important role in soil fertility.

By observing (Figure 5) of the PCA, we can highlight that the analysis was subdivided into two ellipses or ellipsoids, representing the two soil depths. It became evident that the depth of 0-10 cm showed a greater contribution and positive dimension of the physical and chemical soil attributes, indicating higher fertility in this superficial soil layer. This can be explained by the fact that in this layer, there is a greater input of nutrients from successive agricultural reuse applications, which favor the growth and development of forage palm varieties. It is important to mention that processes such as leaching or nutrient transport throughout the soil can influence this distribution and interaction of nutrients.

On the other hand, at the depth of 10-20 cm, a lower representativeness of the data regarding soil fertility study was evident. This phenomenon can be attributed to various interactions and processes. Nutrient losses through leaching, which is the movement of nutrients to deeper soil layers where plant roots have more limited access, may occur. Additionally, factors such as lower biological activity in this soil layer and lower availability of nutrients from agricultural reuse applications can contribute to this lower representativeness.

This elliptical PCA analysis allows us to understand the interactions between different soil depths, agricultural reuse applications, and soil fertility. It is important to consider these results when planning agricultural practices and management strategies, aiming to optimize nutrient availability in layers that are more favorable for the development of forage plants. Understanding these processes and interactions is crucial to ensure better utilization of resources and continuous improvement of soil quality.

The correlation matrix of soil physical and chemical characteristics is fundamental to understanding soil fertility. By evaluating these correlations at different depths, it is possible to identify which attributes are interconnected, such as organic matter and water retention capacity. Correlation patterns can indicate areas that require specific interventions, helping to optimize the use of fertilizers and other management practices. This detailed understanding allows us to improve soil health and agricultural productivity in a sustainable way. The analysis makes it easier to identify practices that promote long-term fertility.

The use of the correlation matrix of soil physical and chemical characteristics is especially relevant to understand fertility in intercrops with cactus pear in semi-arid regions. In these areas, cactus is a strategic crop due to its resistance to drought and ability to improve soil quality. Correlation analysis makes it possible to identify how forage cactus influences nutrient availability and water retention in the soil, essential for agricultural sustainability in these regions. Furthermore, it can reveal beneficial interactions with other intercropped crops, optimizing the production and resilience of semi-arid agricultural systems. This helps to develop more efficient management practices adapted to the challenging conditions of these areas.

The correlation matrix of the physical and chemical soil characteristics evaluated at two depths is presented in Figure 6. This matrix allows us to visualize the relationships between different soil attributes and identify correlation patterns.

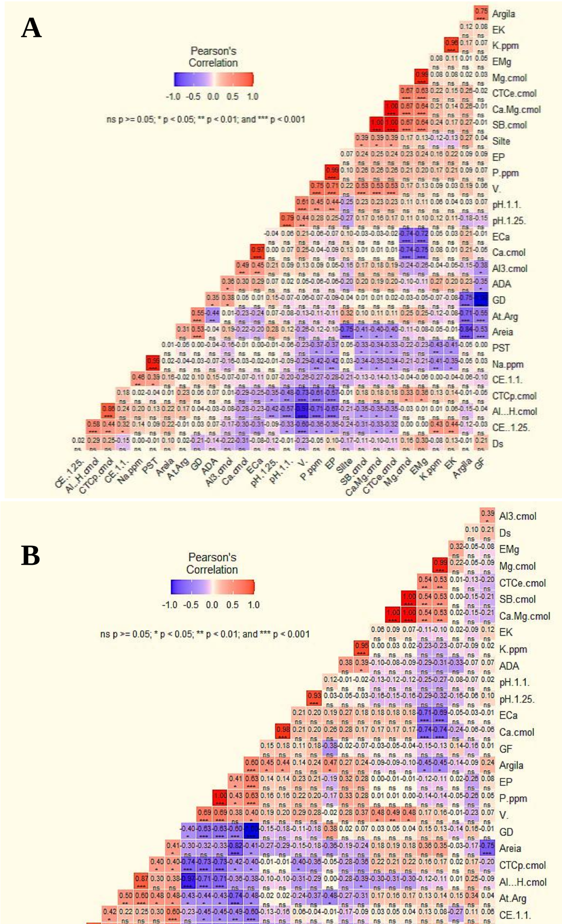

Figure 6. Pearson Correlation Coefficients (PCC) referring to the main physical and chemical

characteristics of the soil evaluated at a depth of 0-10 cm (A) and 10-20 cm (B) under cultivation of three varieties of cactus pear intercropped with native legumes and exotic in soil with treated domestic agricultural reuse (RAT), municipality of São Fernando-RN. Figure 6 which is \label{fig6}.

At the depth of 0-10 cm, strong and positive correlations ($p < 0.001$) were found between pH x $H+Al^{3+}$ ($r = 0.90$), Na^+ x ESP ($r = 0.85$), pH x V% ($r = 0.61$), SB x CTCe ($r = 1.0$), and Clay x DF (0.75). Significant positive correlation at the 1% level ($p < 0.01$) also occurred between SB x Mg ($r = 0.67$), V% x Mg^{2+} ($r = 0.53$), and Clay Activity x DP ($r = 0.55$).

Furthermore, significant positive correlations at the 1% level ($p < 0.01$) were also observed between SB x Mg2+ ($r = 0.67$), V% x Mg2+ ($r = 0.53$), and Clay Activity x DF ($r = 0.55$). These results indicate the relationships between the physical and chemical soil attributes at the depth of 0-10 cm under agricultural reuse application. The strong positive correlation between pH and $H+Al^{3+}$ suggests that the increase in soil pH is related to a reduction in acidity, represented by a decrease in the concentration of hydrogen and aluminum ions. The positive correlation between Na^+ and ESP indicates that sodium is related to the exchangeable sodium percentage, which can influence the availability of this nutrient for plants. The positive correlation between pH and V% suggests that soils with higher pH may have a higher base saturation, indicating a better capacity to retain nutrients. The strong positive correlation between SB and CECe indicates a direct relationship between effective cation exchange capacity and soil base sum, meaning soils with greater capacity to retain and provide nutrients.

The positive correlation between clay and GF suggests that soils with higher clay content may have a finer particle size, which influences their physical properties such as water and nutrient retention. On the other hand, the negative correlations between Ca^{2+} and Mg^{2+}, DF and clay, Clay Activity and Clay, $H+Al^{3+}$ and V%, and sand and silt indicate inverse relationships between the mentioned attributes. This means that when one attribute increases, the other tends to decrease.

On the other hand, strong negative correlations were identified between Ca^{2+} x Mg^{2+} ($r = -0.74$; $p < 0.001$), DP x clay ($r = -0.75$; $p < 0.01$), Clay Activity x Clay ($r = -0.71$; $p < 0.01$), $H+Al^{3+}$ x V% ($r = -0.97$; $p < 0.01$), and sand x silt ($r = -0.75$; $p < 0.01$). The negative correlation between GD (coarse particle size) and clay suggests that soils with higher clay content tend to have a lower coarse particle size, meaning they have a lower quantity of larger particles. This can influence the soil's drainage capacity and water retention capacity.

The negative correlation between Clay Activity and Clay indicates that soils with higher clay activity tend to have a lower clay content. Clay activity is related to the soil's capacity to retain nutrients and interact with plant roots. The negative correlation between $H+Al^{3+}$ and V% indicates an inverse relationship between soil acidity (represented by the concentration of hydrogen and aluminum ions) and soil base saturation. More acidic soils tend to have lower base saturation, which can affect nutrient availability for plants.

Lastly, the negative correlation between sand and silt suggests an inverse relationship between these two soil fractions. Soils with higher sand content tend to have lower silt content and vice versa. This relationship is related to the soil's physical characteristics such as texture and water retention capacity.

At the depth of 10-20 cm, a strong positive correlation ($p < 0.001$) was observed between Ca+Mg x CTC ($r = 1.0$), indicating that soils with higher calcium and magnesium content have a greater cation exchange capacity, which favors nutrient availability for plants. CE x ESP ($r = 0.72$), indicating that soil electrical conductivity is related to the percentage of exchangeable sodium content, which can indicate the presence of salts and soluble nutrients. Positive correlation between EC x Na ($r = 0.73$), indicating a relationship between electrical conductivity and sodium content in the soil, which may be associated with salinity and/or sodicity. DF x EC ($r = 0.60$) and Clay x DF ($r = 0.60$), this type of correlation suggests that soils with higher degree of flocculation have higher electrical conductivity, indicating the influence of soil aggregation characteristics on its electrical conductivity.

Comparatively, a significance level of 1% also found a positive correlation between Clay x CDW ($r = 0.47$), SB x V% ($r = 0.49$), and Na^+ x ESP ($r = 1.00$). This behavior demonstrates that soils with higher clay content exhibit a higher degree of flocculation, which affects the soil's physical properties such as water retention and soil aggregation.

On the other hand, a strong negative correlation was observed between DP x DF ($r = -1.00$, $p < 0.001$), V x Al + H ($r = -0.97$; $p < 0.001$), Clay Activity x Clay ($r = -0.74$; $p < 0.01$), and Sand x Silt ($r = -0.75$; $p < 0.001$). This indicates an inverse relationship between soil dispersion and soil flocculation, which is related to the stability of soil aggregates. It also reveals an inverse relationship between base saturation and the presence of aluminum and hydrogen in the soil. Soils with higher base saturation tend to have lower levels of these toxic elements. Regarding Clay Activity and Clay, this phenomenon shows an inverse relationship between clay activity and clay content in the soil, which may indicate differences in the adsorption and nutrient retention properties of the clay.

Discussion

The data presented are similar to those compiled by (Mesquita et al., 2023), which show that the cultivation of forage palm together with the application of treated domestic sewage resulted in improvements in the physical and chemical attributes of the soil. These results indicate that the use of treated wastewater as a source of irrigation and fertilization can be an effective strategy to promote soil quality.

Principal Component Analysis (PCA) was also used by (Mesquita et al., 2023), to assess the effect of different forage palm varieties and consortium types on soil physical and chemical attributes. The results indicated that forage palm cultivation and the application of treated domestic sewage contributed to soil improvement.

These findings were also supported by (Mesquita et al., 2023), when evaluating the behavior of different varieties of forage palm and different consortium arrangements on the physical and chemical parameters of the soil. The results regarding soil quality data assessed by PCA indicated that the cultivation of forage palm and the application of treated domestic wastewater contributed to soil improvement. Similar to soil and climate conditions, the data presented by (Mesquita et al., 2022), confirm that the soil was improved in terms of physical and chemical attributes under forage palm cultivation and application of treated domestic wastewater.

The correlation between Sand and Silt reflects an inverse relationship between the quantity of sand and silt in the soil, reflecting differences in soil texture characteristics such as porosity and water retention capacity. The Pearson correlation matrix was used by (Mesquita et al., 2022), to assess the relationship between soil physical and chemical parameters and soil fertility in different varieties of forage palm and consortium types. The results indicated that the cultivation of forage palm and the application of treated domestic sewage contributed to the improvement of soil physical and chemical attributes, resulting in higher soil fertility.

The Pearson correlation matrix revealed significant associations between soil physical parameters such as texture, density, and porosity, and soil fertility, represented by nutrient levels and pH. These correlations indicate that soil physical characteristics play an important role in nutrient availability and water retention capacity, directly influencing soil fertility.

Conclusions

Irrigation with reclaimed water causes significant changes in the physical and chemical properties of the soil. The changes in the physical attributes reflect the entry of dissolved solids through reclaimed water, as well as the loss of silt-sized particles due to erosion.

Leaching processes or losses of K^+ and Mg^{2+} were detected after irrigation with reclaimed water in palm cultivation associated with different leguminous crops, or possibly the absorption by palm varieties associated with different legume consortia.

The detailed study of multivariate analyses showed that irrigation with reclaimed agricultural water affected the physical and chemical properties of the soil, including particle erosion, changes in nutrient levels, and increased salinity and sodicity. Therefore, it is essential to adopt appropriate management practices, such as monitoring the applied water depth, to minimize these negative effects and adopt appropriate management practices, such as monitoring the water depth applied, to minimize these negative effects and ensure the conservation of soil structure and fertility. Multivariate analysis thus becomes an indispensable tool for identifying and mitigating the impacts of irrigation with reused water, promoting more sustainable agricultural management and the preservation of natural resources.

Disclosure statement

No potential conflict of interest was reported by the authors.

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