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MULTIVARIATE ANALYSIS OF LATOSOL ATTRIBUTES IN THE AMAZON-CAATINGA TRANSITION ZONE UNDER AN AGROPASTORAL SYSTEM

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Conservation
Latosol
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ABSTRACT

This study aims to analyze the dynamic relationship between the physicochemical attributes of a Yellow Dystrophic Latosol, which a particular focus on their direct and indirect influences on soil electrical conductivity. Soil samples were collected from 50 georeferenced points within the municipality of Brejo – MA, Brazil, to evaluate these interactions using multivariate stastistical approaches. The path analysis process was conducted using the GENES software, a statistical tool essential for estimate linear correlation values and decomposing the data. The evaluated soil attributes included electrical conductivity, altitude, humidity, soil density, porosity, organic matter, pH, clay, silt, total sand, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, aggregates larger than 2.00 mm³, aggregates larger than 1.00 mm³, aggregates larger than 1.00 mm³, aggregates larger than 0.10 mm³, weighted mean diameter, and mean internal diameter. The approach was adopted due to the high occurrence of multicollinearity, which can lead to interpretative misunderstanding. For this purpose, data decomposition was performed, using electrical conductivity as primary variable - to mitigate the mutual influence among soil attributes. The analysis revealed that pH is the most influential attribute in determining the electrical conductivity of the studied Latosol.

Palavras-chave:
Agropastoril
Agroecologia
Conservação
Latossol
Sustentabilidade

ANÁLISE MULTIVARIADA DE ATRIBUTOS DE UM LATOSSOLO NA ZONA DE TRANSIÇÃO AMAZÔNIA-CAATINGA SOB SISTEMA AGROPASTORIL

RESUMO

O objetivo deste trabalho é apresentar dados sobre a respectiva dinâmica entre atributos de um Latossolo, bem como as influências diretas e indiretas destas propriedades sob a principal variável condutividade elétrica do solo. Foram avaliadas amostras de solo de 50 pontos da malha georreferenciada, em um Latossolo Amarelo Distroférrico, no município de Brejo - MA. O processo de análise de traços foi realizado no software de estatística descritiva GENES – aplicação técnica necessária para tangenciar os valores de correlação linear e, consequentemente, decompor os dados. Foram avaliados: condutividade elétrica, altitude, umidade, densidade do solo, porosidade, matéria orgânica, pH, argila, silte, areia total, areia muito grossa, areia grossa, areia média, areia fina, areia muito fina, agregados com mais superiores a 2,00 mm³, agregados com mais de 1,00 mm³, agregados com mais de 1,00 mm³, agregados com mais de 0,10 mm³, diâmetro médio ponderado e diâmetro interno médio. A abordagem resulta da elevada ocorrência e possibilidade de mal-entendidos interpretativos impostos pela multicolinearidade. Para tanto, sugere-se a decomposição dos dados - a partir da variável básica condutividade elétrica - para mitigar os efeitos das influências exercidas mutuamente entre os atributos. Concluiu-se que o pH é o atributo que melhor determina a condutividade elétrica no latossolo em análise.

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INTRODUCTION

The increasing demand for food requires the occupation and utilization of arable land to ensure food production and nutritional accessibility – thereby contributing to global food security. Food scarcity remains a growing problem, highlighting the need for comprehensive analyses and studies focus on sustainable production, nutritional diversification and equitable food access. As emphasized by Arsyad and Basunanda (2020), such research is essential for fostering a resilient and secure food system.

According to Embrapa (2022), the simultaneous growth of the global population and expected income increases in the coming years will lead to greater demand for food, fiber, and biofuel productions. Thus, it will be necessary to enhance productivity per hectare through sustainable and environmentally responsible practices. International trends emphasize the adoption of more intensive production models that incorporate integrated systems while minimizing environmental degradation. These approaches align with the global objective of expanding of agricultural production efficiently and sustainably, without further increasing the extent of agricultural areas.

According to IBGE (2020), agricultural area occupies approximately 7.6% of Brazil's national territory, with a high concentration of Latosols,, the most common soil types in the country, accounting for 31.6% of the mapping units in the Brazilian Soil Map. In particular, yellow latosols are highly weathered and aluminum-saturated , characterized by cohesive horizons — dense subsurface pedogenetic layers, with a hard to extremely hard consistency when dry and friable when wet (Embrapa, 2022). Despite their natural fertility limitations, these soils exhibit favorable agronomic properties, including considerable depth, stable structure, good porosity, and high permeability, rendering them suitable for agricultural use.

The Crop-Livestock Integration (ILP) has emerged as a strategic production model that integrates various agricultural and livestock systems within a single area. According to EMBRAPA (2022), this expanding model provides economic and environmental benefits, as it promotes production diversification and contributes to the recovery of degraded pastures.

Understanding the correlation between the variables is crucial in soil science and path analysis serves as a valuable tool for evaluating these relationships, allowing for the identification of correlations among the soil's physical and chemical attributes. This technique facilitates the partitioning of the correlation coefficient into direct and indirect effects, specifically quantified by path coefficients (Teodoro *et al*., 2024). The effectiveness of path analysis is based on the cause-effect dynamics among the variables (Olawamide and Fayeun, 2020; Santos Nogueira *et al*., 2024).

This article aims to identify, through path analysis, the variables that most effectively explain electrical conductivity in relation to other physical-chemical attributes of a Red-Yellow Latosol within the Crop-Livestock Integration system in the Amazon-Caatinga transition zone.

MATERIALS AND METHODS

The present study involved soil samplings conducted in the municipality of Brejo - MA, Brazil, specifically at Fazenda Barbosa, located in the eastern mesoregion of Maranhão, within the Chapadinha microregion. The sampling site is situated at coordinates 3° 42'10.4 "S and 42° 57'09.8 "W. According to the Köppen-Geiger climate classification, the region experiences a tropical climate with a distinct dry season, transitioning towards the Aw climate (tropical summer rain). The municipality of Brejo - MA, along with other municipalities within the Chapadinha microregion, is classified under FFc10, which is characterized by the presence of Yellow Dystrophic Latosols, Concrete Plintosols, and Dystrophic Haplastic Plintosols (Santos *et al*. 2018).

The experiment was conducted in a soybean production area within the Crop-Livestock Integration system, where corn, brachiaria, and soybeans were cultivated, with corn and brachiaria planted together. Following corn harvest, brachiaria was utilized for cattle fattening. A georeferenced grid consisting of 50 regularly spaced points was established within the production area, with points spaced 30 meters apart. The grid consisted of five lines, each containg 10 points, covering a total area of 32,400 m^2 (Figure 1). Soil samples were collected at each point at a depth of 0.00 - 0.20 m. The studied soil was classified as Yellow Dystrophic Latosol, derived from sandy-clayey sediments of the Barreiras Group, characteristic of the Tabuleiros Costeiros geomorphological unit (GEPLAN, 2002).

The analyzed variables included electrical conductivity (CE), altitude (AL), soil moisture (U), soil density (DS), porosity (PO), organic matter content (MO), pH (PH), clay content (ARG), silt content (SI), total sand content (ARE), very coarse sand (AMG), coarse sand (AG), medium sand (AM), fine sand (AF), very fine sand (AMF), the percentage of aggregates greater than 2.00 mm^3 (A2), 1.00 mm^3 (A1), 0.50 mm^3 (A05), 0.25 mm^3 (A02), and 0. 10 mm^3, as well as the weighted mean diameter (DMP) and geometric mean diameter (DMG) of soil aggregates.

Electrical conductivity (CE) refers to the relationship between soil texture and water storage capacity, serving as an indicator of correlations with other physical characteristics. Altitude (AL) represents the vertical distance of the sample point relative to sea level; soil moisture (U) indicates the water content in the sampled soil portions; soil density (DS) represents the mass per unit volume, including pore spaces within the sample; porosity (PO) refers to the volumetric fraction of empty spaces between solid particles; organic matter (MO) comprises decomposed plant and animal residues, contributing to soil carbon (C) content; pH (PH) indicates the concentration of hydronium ions, representing the soil's hydrogen ion potential.

Additional soil attributes analyzed included: clay (ARG), which consists of sediments composed of fine particles approximately 4 micrometers in diameter; silt (SI), representing particles smaller than sand but larger than clay; and total sand (ARE), which comprises particles derived from the disintegration of rocks, originating from mineral granules. Sand fractions were further classified based on particle size: very coarse sand (AMG) includes grains with a diameter greater than 500 µm; coarse sand (AG) consists of grains approximately 500 µm in diameter; medium sand (AM) includes grains of 250 µm; fine sand (AF) consists of grains of 125 µm, while very fine sand (MFA) comprises grains with diameters of approximately 50 µm.

The percentage of aggregates greater than 2.00 mm^3 (A2) represents clusters of mineral particles surrounded by an organic matter of the same size. Similarly, the percentage of aggregates greater than 1.00 mm^3 is denoted as A1; those greater than 0.50 mm^3 as A05, those greater than 0.25 mm^3 as A02, those greater than 0.10 mm^2 as A01. The weighted mean indicates the predominance of large aggregates, serving as a key parameter for assessing aggregate stability. Conversely, the geometric mean diameter (DMG) provides an estimate of the aggregates size class with the highest occurrence in the studied soil.

The values for electrical conductivity (CE) were determined using the method described by

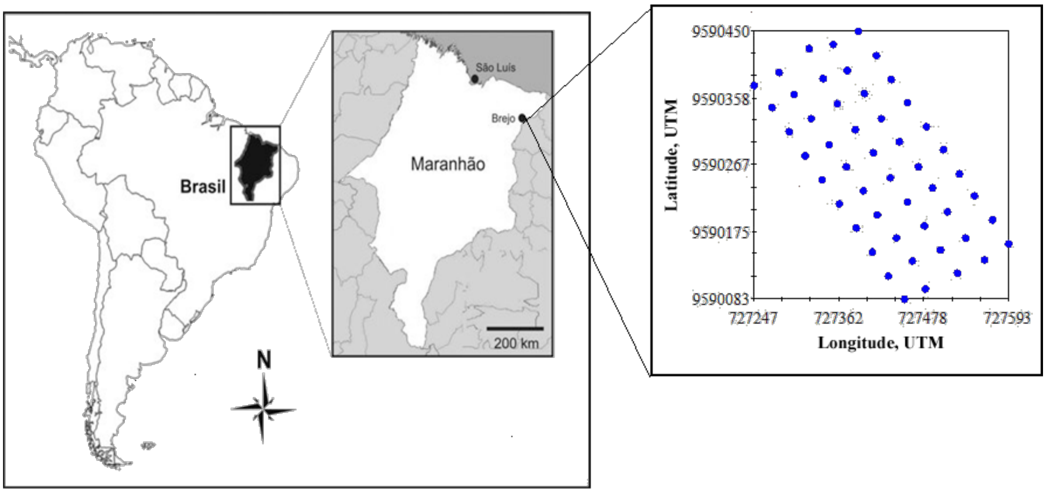


Figure 1. Location of the experimental area

Embrapa (2017). The assessments of soil texture components - clay (ARG), sand (ARE), and silt (SIL), along with measurements of moisture (U), density (D), and porosity (PO) were conducted following the same methodology.

For each soil sample, aggregate stability was assessed using wet sieving method, employing sieves with mesh sizes of 2.0 mm; 1.0 mm; 0.5 mm and 0.25 mm, following the procedure described by Yoder (1936), and later modified by Kemper and Chepil (1965).

The organic matter (MO) content was determined using the wet oxidation method, in which excess potassium dichromate was titrated with ammoniacal ferrous sulfate, following the protocol outlined by Embrapa (2017).

Each attribute was analyzed using descriptive statistics, a preliminary exploratory approach designed to characterize statistical parameters. This analysis facilitates the identification of data trends, dispersion patterns, and distribution characteristics, including homogeneity and normality.

The results are presented through descriptive statistical parameters, including minimum, mean, maximum and standard deviation values. Following data partitioning, the direct and indirect effects of the chemical attributes were determined using path analysis. To visually represent the functional relationship between the correlation estimates among attributes, a correlation network was constructed, where the proximity between the nodes (variables) is proportional to the absolute value of their correlation.

The degree of multicollinearity in the matrix was assessed based on the condition number (NC), defined as the ratio between the largest and smallest eigenvalues of the correlation matrix (Montgomery *et al*., 2012). Multicollinearity is classified as weak (NC < 100), indicating no significant impact on the analysis; moderate to strong (100 ≤ NC ≤ 1,000); or severe (NC > 1,000), which may compromise the reliability of the results. All statistical analyses were conducted using the GENES software (Cruz, 2013).

Such an application is essential for understanding the nature of the linear relationship between specific soil characteristics, facilitating the identification of variables and their respective contributions to the primary variable, which in this study was electrical conductivity (CE).

RESULTS AND DISCUSSION

Descriptive statistics of the soil data obtained in the study are presented in Table 1. The pH (PH) values ranged from 4.76 to 6.59 among the 50 samples, indicating an overall acidic nature (Table 1). The mean pH was 5.59, which is higher than the value reported by Lira Júnior *et al*. (2020), who examined nitrogen (N) and carbon (C) stocks in a system associated with legumes in a tropical environment. In their study, after four years of implementing the crop-livestock integration, the mean pH was 5.36. When comparing the pH values from the first two years of the system, the pH observed in the present study (5.59) is lower than the value of 5.74 reported in the research with legumes. The mean pH (PH) content in this study was also higher than that found by Longo *et al*. (2020), who examined chemical attributes and heavy metals in soils from urban forest remnants, where pH values ranged from 4.60 to 6.10. In areas near sugarcane plantation, Longo *et al*. (2020) found pH values close to 5.00 at both extremes, indicating higher acidity. Similar pH values to those observed in the Latosol analyzed in this study have also been reported in the scientific literature. For instance, Almeida *et al*. (2021) examined an Agro-silvopastoral system in the Brazilian Cerrado and found a mean pH of 5.40, both in native vegetation and in an integrated system with eucalyptus and marandu grass, while studying carbon (C) stocks, nitrogen (N), and organic matter (MO) quality.

The mean value for soil density (DS) observed in the multivariate analysis of the latosol was 1.66, classifying it as sandy loam. In a similar context, Tezolin *et al*. (2021) reported a higher value of 1.74 when describing the physical attributes of soils in different agricultural production systems. High soil density values may suggest prolonged machine traffic, which contributes to compaction and increased soil density, subsenquently limiting root growth, particularly in latosols. The soil density values for the latosol ranged from a maximum of 1.86 and a mean of 1.66, which are higher than those reported in the scientific

Table 1. Descriptive statistics of the chemical and physical attributes of soil samples

Attribute	Minimum	Average	Maximum	SD*
Height	104.00	111.40	121.00	3.09
Electric conductivity (mS cm)	0.48	0.56	0.65	0.01
Moisture (%)	10.03	12.96	15.18	1.04
Soil density (kg dm^{-3})	1.46	1.66	1.86	0.08
Porosity (%)	25.92	33.80	41.97	3.22
Organic matter (mg dm^{-3})	44.69	58.28	72.35	5.55
pH	4.76	5.59	6.59	0.50
Clay (g kg^{-1})	119.00	152.49	190.50	18.36
Silt (g kg^{-1})	37.30	66.07	90.00	11.33
Total sand (g kg^{-1})	731.50	781.43	820.40	19.83
Very coarse sand (g kg^{-1})	4.80	14.46	34.90	7.99
Coarse sand (g kg^{-1})	39.20	69.77	121.10	18.21
Medium sand (g kg^{-1})	195.20	249.06	293.80	22.55
Thin sand (g kg^{-1})	221.50	339.22	394.40	31.27
Very fine sand (g kg^{-1})	80.70	108.91	197.10	18.13
% aggregates greater than 2.00 mm^3	1.14	20.01	61.61	15.62
% aggregates greater than 1.00 mm^3	5.24	30.05	69.48	16.17
% aggregates greater than 0.50 mm^3	1.14	20.01	61.61	15.62
% aggregates greater than 0.25 mm^3	1.14	20.00	61.60	15.62
% aggregates greater than 0.10 mm^3	59.86	96.60	99.70	5.45
Weighted average diameter	0.56	1.46	3.30	0.69
Geometric mean diameter	0.30	0.80	1.99	0.36

*SD – standard deviation

literature. For instance, Lira Júnior *et al*. (2020) observed a lower soil density of 1.40 during the first two years and 1.39 by the fourth year in a system incorporating legumes in a tropical environment. Lower soil density values have also been reported in other studies. Polanía-Hincapié *et al*. (2021), in an analysis of soil physical quality dynamics following the implementation of an integrated system in the Colombian Amazon, observed a value of 1.16. These findings suggest that, regardless of the predominant soil class, land use and management practices significantly influence soil physical properties, particularly soil density and the characteristics of surface layers (Panini *et al*., 2024).

The analysis of total sand content (ARE) in the studied Latosol revealed a mean of 781.43, with values ranging from 731.50 to 820.40. This mean value was higher than the 524.00 reported by Lira Júnior *et al*. (2020) in an agricultural system within a tropical ecosystem, where grass was present. The total sand content also exceeded values reported for the Cerrado region in northern Minas Gerais. This discrepancy may be attributed to the significant soil diversity within the Cerrado biome, where certain areas exhibit higher total sand content due to a combination of geological, climatic and environmental factors. According to Almeida *et al*. (2021), the mean total sand content in this Cerrado region was 420.00 in native vegetation, 520.00 in an integrated system with Eucalyptus, 530.00 in an integrated system with *Eucalyptus urograndis* and Marandu grass, and 530.00 in a regenerating stratum.

The claycontent (ARG) in the analyzed Oxisol ranged from 119.00 to 190.50, with a mean of 152.49. Higher and more divergent values were reported by Lira Júnior *et al*. (2020) and Almeida *et al*. (2021). In the agricultural system within a tropical environment studied by Lira Júnior *et al*. (2020), the mean clay content was 259.00, increasing to 321.00 when intercropped with *Gliricídia sepium*. Almeida *et al*. (2021) recorded a mean clay content of 280.00 in native vegetation, 210.00 in an integrated system with eucalyptus, 220.00 in a system integrating *Eucalyptus urograndis* with Marandu grass, and 240.00 in the regenerating portion of the system. Clay content is particularly influenced by various factors that contribute to soil formation, including geological and pedological processes, climate and weathering conditions, as well as topography.

The mean organic matter (MO) content in the studied Latosol was 58.28, with values ranging from 44.69 to 72.35. In urban forest remnants of Campinas - SP, Brazil, Longo *et al*. (2020) reported a lower mean MO content of 48.50, compared to the multivariate analysis of the latosol in this study. The presence of organic matter (MO) is crucial for sustaining arboreal vegetation and enhancing ecological interactions. Furthermore, Longo *et al*. (2020) observed variations in MO content at the edges of Cerrado forest remnants, directly influencing seed availability and the natural regeneration process of the ecosystem. It is important to highlight that the organic matter content in this study refers to a transitional zone between the Cerrado and the Amazon rainforest. In natural ecosystems, soil organic matter remains stable in a humification stage (Ferreira *et al*., 2022). These authors further emphasize that agricultural land use contributes to carbon loss by reducing soil organic matter levels, thereby impacting soil quality.

The soil porosity (PO) of the latosol under analysis showed an mean value of 33.80%, with observed variations among samples ranging from 25.92% to 41.97%. In contrast, the study conducted by Polanía-Hincapié *et al*. (2021) reported total porosity (PO) values in an integrated system located in the Colombian Amazon, with means of 54.00% in native vegetation and 55.00% in the crop-livestock integration system. Similarly, Tezolin *et al*. (2021), when evaluating soil attributes in several agricultural production systems, obtained higher porosity values for Latosols: 44.40% under no-tillage, 46.60% in oat cultivation, 46.19% in crop-livestock integration, and 40.95% in sugarcane cultivation. Among the values reported by Tezolin *et al*. (2021), only the mean porosity observed in the permanent pasture system (33.80%), closely approximates that obtained for the Latosol under the present study conditions. Additionally, Oliveira *et al*., 2023 highlighted that soil porosity is significantly influenced by machinery and implement traffic, with increased traffic leading to a reduction in soil porosity.

In the multivariate analysis of the Latosol, the weighted mean diameter (DMP) values ranged from 0.56 to 3.30, with a mean of 1.46. Notably, the values obtained using the path coefficient were lower than those reported in the scientific literature. For instance, Tezolin *et al*. (2021) recorded higher DMP values through different agricultural systems: 4.15 under no-tillage, 2.46 in oat cultivation, 4.51 in permanent pasture, 3.46 in crop-livestock integration, and 3.34 in sugarcane cultivation. The weighted mean diameter serve as a valuable indicator for assessing soil texture and structural stability, which are critical factors in agricultural management, soil conservation strategies, and ecological studies.

Soils with a weighted mean diameter (DMP) greater than 0.50, as observed in the Latosol of the present study, are considered highly stable and resistant to crushing and dispersion. The geometric mean diameter (DMG) exhibited a mean value of 0.80, with variations ranging from 0.30 to 1.99, which are lower than those reported in the literature. Tezolin *et al*. (2021) obtained higher DMG values through different agricultural systems: 3.15 under no-tillage, 1.45 in oat cultivation, 3.70 in permanent pasture, 2.27 in crop-livestock integration, 2.20 in sugarcane cultivation, and 2.91 in forested areas. The Pearson correlation network illustrating the relationship between the studied attributes is presented in Figure 2.

Pearson's linear correlation network reveals a significant, positive, and direct correlation electrical conductivity (CE) and pH (PH). Soils exhibit distinct characteristics influenced by prolonged and intensive use, which can lead to alterations in their physicochemical porperties, productivity, and and geographical distribution. These changes highlight the importance of studying the spatial variability of soil attributes such as pH and electrical conductivity, as such research is essential for understanding soil dynamics and optimizing management practices (Wijayanto *et al*., 2024).

Positive correlations were also observed among the percentage of aggregates greater than 1.00 mm^3 (A1), 0.25 mm^3 (A02), 0.50 mm^3 (A05), and 2.00 mm^3 (A2), as well as between geometric mean density (DMG) and weighted mean density (DMP).

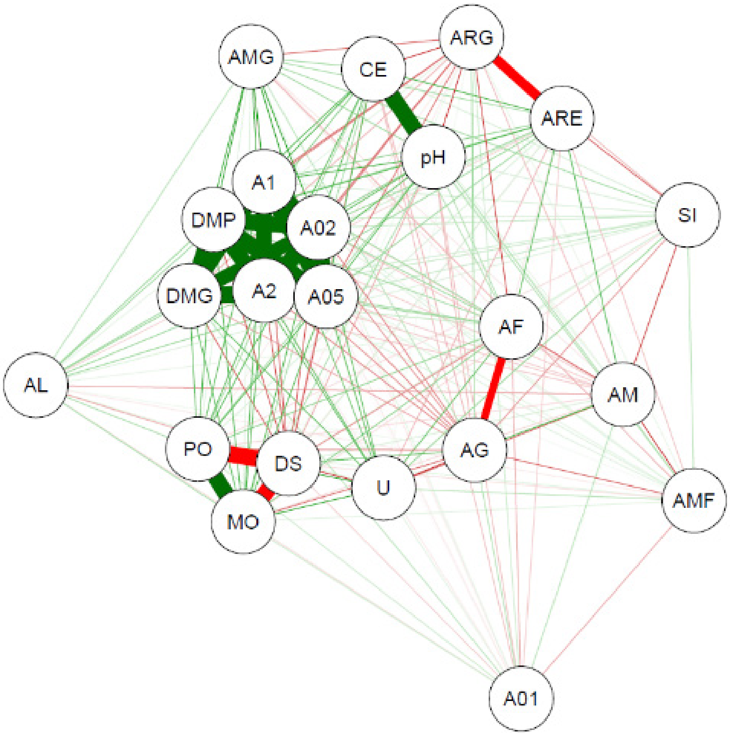


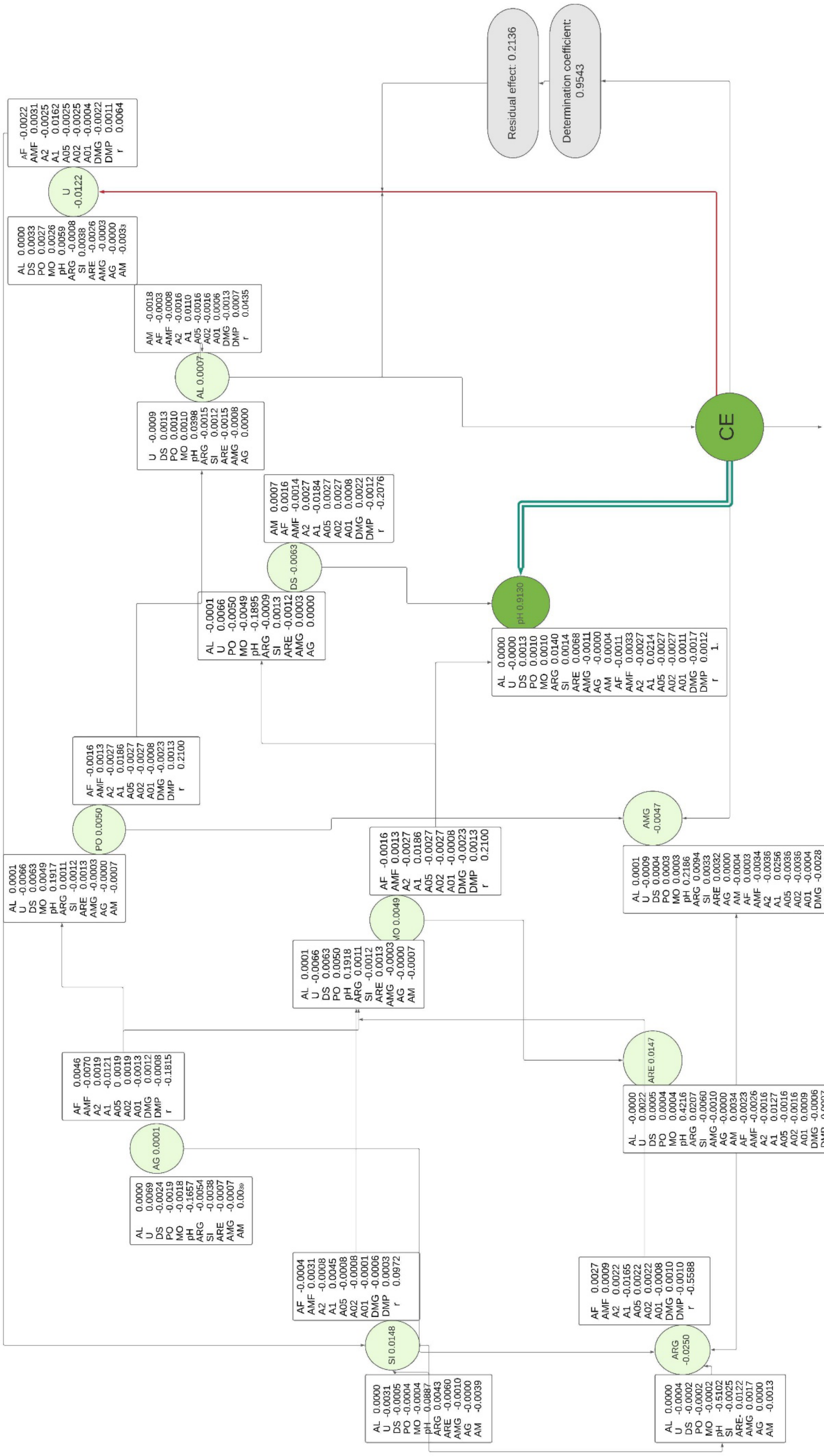
Figure 2. Pearson's correlation network among the studied soil attributes, including electrical conductivity (CE), altitude (AL), humidity (U), soil density (DS), porosity (PO), organic matter (MO), pH (PH), clay content (ARG), silt content (SI), total sand content (ARE), very coarse sand (AMG), coarse sand (AG), medium sand (AM), fine sand (AF), very fine sand (AMF). Additionally, the analysis includes aggregate size fractions: the percentage of aggregates greater than 2.00 mm³ (A2), 1.00 mm³ (A1), 0.50 mm³ (A05), 0.25 mm³ (A02), 0.10 mm³, along with the weighted mean diameter (DMP) and geometric mean diameter (DMG)

Additionally, a similar correlation was identified between porosity (PO) and organic matter (MO). Oliveira *et al*, 2023 highlighted the importance of studying the soil physical attributes to better understand soil dynamics and their impact on crop productivity. These authors further reported that well-structured soils with adequate porosity enhance crop management and overall agricultural efficiency.

Thus, the network configuration reveals a system in which components mutually exerts direct and more pronounced positive influences on the overall structure. According to Dash *et al*. (2020), the association of these variables helps to analyze the interdependence between connector components and the final yield, as such correlations may exhibit an inherent degree of association. On the negative spectrum, a strong and direct inverse relationship is observed between clay content (ARG) and total sand content (ARE). Similarly, soil density (DS) it inversely related to both porosity (PO) and organic matter (MO).

The approach shows that, within a correlation network, multicollinearity frequently occurs, as different variables exert mutual influences. This interdependence increases the likelihood of data interpretation errors. To mitigate this issue, it is essential to apply the path analysis with the inclusion of a correction factor (K = 0.05) to eliminate multicollinearity, thereby ensuring data reliability without interference from interdependent attributes. Several studies have also emphasized the importance of this correction technique to enhance result accuracy and reliability (Oliveira *et al*., 2022; Machado *et al*., 2024).

The data obtained through the path analysis technique (path coefficient) are presented in Figure 3. For this analysis, the variables used were those previously identified in the Pearson's linear correlation, corresponding to the physical and chemical attributes of the Latosol under investigation.


Residual effect: 0.2136
Determination coefficient: 0.9543
CE
pH 0.9130
U -0.0122
AL 0.0007
DS -0.0063
PO 0.0050
MO 0.0049
AMG -0.0047
ARE 0.0147
AG 0.0001
SI 0.0148
ARG -0.0250

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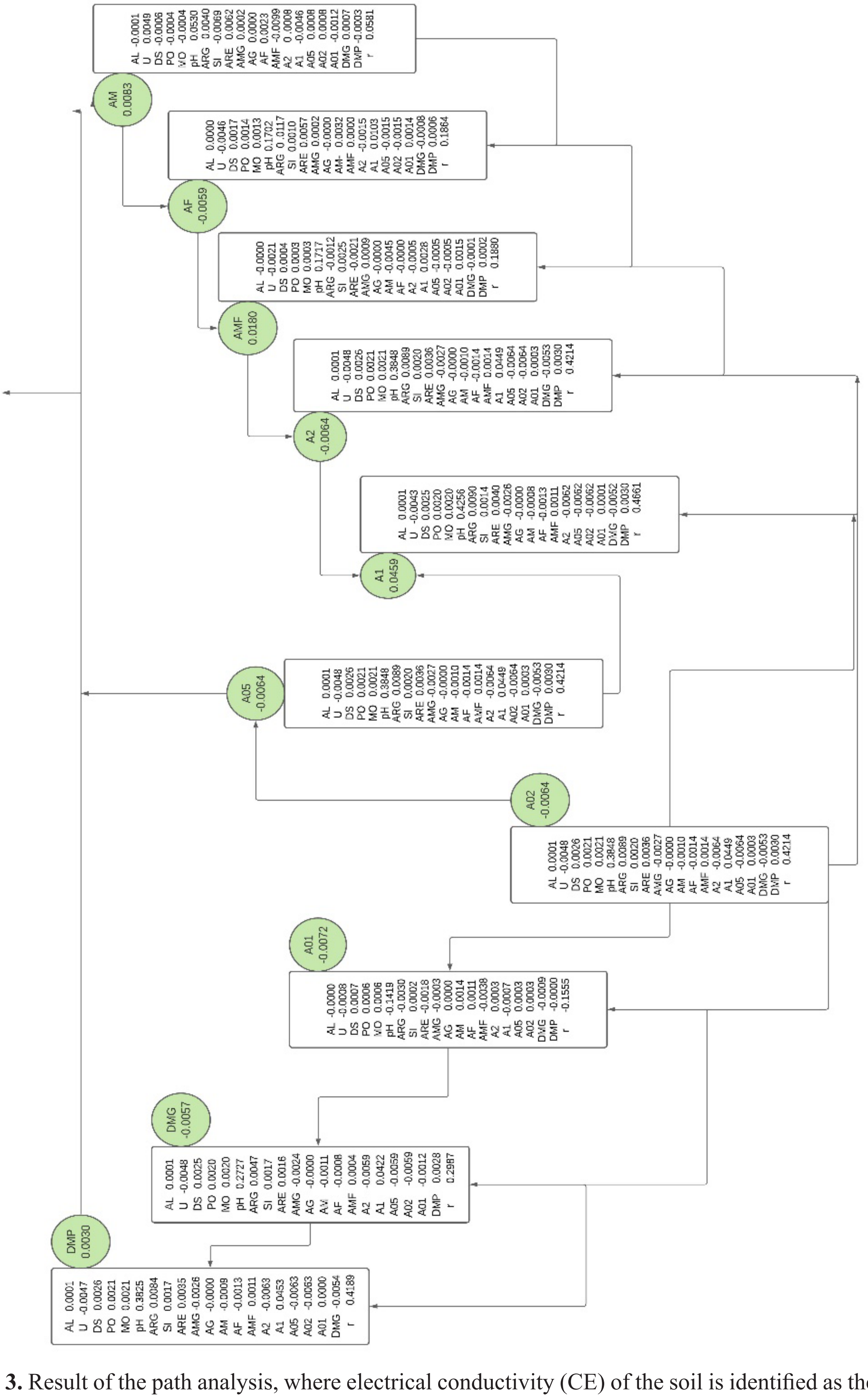

Figure 3. Result of the path analysis, where electrical conductivity (CE) of the soil is identified as the main variable

The path analysis enable the removal of multicollinearity influences from the expressions of direct and indirect variables. Other studies have similarly presented the relationships between variables in the form of a flowchart (Oliveira *et al*., 2022; Machado *et al*,. 2024), which enhances the understanding and visualization of these relationships. To minimize the inflation factor in the matrix, factor K = 0.05 was added diagonally. The final rearrangement of the expressions detailing the relationships between direct and indirect variables after the application of the analysis was significant. As a result, some values in Pearson's linear correlation had their holistic representations modified. The correlations of the direct variables and their influences are shown in Table 4.

Table 4. Direct correlations between the key variables influencing electrical conductivity (CE)

Correlation	r
pH x CE	1.0000
A1 x CE	0.4661
ARE x CE	0.4617
A2 x CE	0.4214
AO5 x CE	0.4214
AO2 x CE	0.4214
DMP x CE	0.4189
DMG x CE	0.2987
AMG x CE	0.2394
MO x CE	0.2100
PO x CE	0.2100
AMF x CE	0.1880
AF x CE	0.1864
SI x CE	0.0972
AM x CE	0.0581
AL x CE	0.0435
U x CE	0.0064
AO1 x CE	-0.1555
AG x CE	-0.1815
DS x CE	-0.2076
ARG x CE	-0.5588

The explanatory correlation analysis for the electrical conductivity (CE) variable revealed a significant positive relationship with pH (PH) variable (1.000). Additionally, strong positive correlations were observed with other soil attributes including the percentage of aggregates greater than 1.00 mm³ (A1) (0.4661), total sand content (ARE) (0.4617), percentage of aggregates greater than 2.00 mm³ (A2) (0.4214), percentage of aggregates greater than 0.50 mm³ (A05) (0.4214), percentage of aggregates greater than 0.25 mm³ (A02) (0.4214), weighted mean diameter (DMP) (0.4189), and geometric mean diameter (DMG) (0.2987). Weaker yet still notable correlations were observed with very coarse sand (AMG) (0.2394), organic matter (MO) (0.2100), porosity (PO) (0.2100), very fine sand (MFA) (0.1880) and fine sand (AF) (0.1864).

A negative correlation was observed between electrical conductivity (EC) and clay content (ARG) (-0.5588), indicating that higher clay content is associated with lower EC values. Additional negative correlations were identified for soil density (DS) (- 0.2076); coarse sand (AG) (-0.1815) and the percentage of aggregates smaller than 1.00 mm³ (A01) (-0.1555). These findings highlight the diverse indirect relationships between soil properties and EC. A comprehensive understanding of soil attributes, their interrelationships, plant characteristics, and crop dynamics is essential for optimizing site-specific management practices and enhancing both crop yield and soil quality (Plazas *et al*., 2024).

The need for comprehensive data and advanced analytical tools to enhance the understanding of ecosystem conservation, and its interactions with the environment is evident. This is consistent with the findings of Holanda *et al*. (2017), who, in their evaluation of litter and nutrients dynamics, highlighted the crucial role of biogeochemical cycling in forest ecosystems in enhancing soil chemical attributes. These processes are intrinsically influenced by both biotic and abiotic factors, which have direct effects on nutrient cycling and overall functioning of ecosystems.

The coefficient of determination obtained from the path analysis demonstrated a 95% validity, indicating the robustness of the results in the present study. Strong correlation coefficients, exceeding 90% in path analysis, were similarly reported in other soil-related studies, such as those by Pinheiro *et al*, (2024) and Machado *et al*, (2024). This analytical approach, as supported by Ubi *et al*. (2019), enables the identification of correlations and simplify the interpretation of associative relationships among the overall system and its constituent variables. Through the evaluation of path coefficients, it is possible to distinguish between direct and indirect effects, thereby enriching the analytical framework.

CONCLUSION

- Multivariate analysis, specifically path analysis, revealed that pH (PH) is the attribute most strongly associated with electrical conductivity (CE) in Latosol, demonstrating a direct and significant relationship among the variables examined. This primary association was followed by others, including percentage of aggregates greater than 1.00 mm³ (A1), total sand content (ARE), percentage of aggregates greater than 2.00 mm³ (A2), percentage of aggregates greater than 0.50 mm³ (A05), percentage of aggregates greater than 0.25 mm³ (A02), and weighted mean diameter (WMD). All of these correlations exceeded 41%.
- These findings highlight the significance of studying soil physical attributes, as they exhibit a strong and positive correlation with soil electrical conductivity.

AUTHORSHIP CONTRIBUTION STATEMENT

OLIVEIRA, I. R.: Conceptualization, Data curation, Methodology, Supervision, Writing – review & editing; **VIEIRA, M. M.:** Data curation, Project administration, Writing – review & editing; **CUNHA, F. F.:** Formal Analysis, Methodology, Software, Supervision, Writing – review & editing; **ROQUE, C. G.:** Funding acquisition, Methodology, Writing – review & editing; **CASTRO, T. R.:** Formal Analysis, Funding acquisition, Writing – review & editing; **OLIVEIRA, J. T.:** Data curation, Project administration, Supervision, Visualization, Writing – review & editing.

DECLARATION OF INTEREST

The authors declare that they have no financial or personal interests that could influence the work reported in this article.

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