Ambiente & Água - An Interdisciplinary Journal of Applied Science
ISSN 1980-993X – doi:10.4136/1980-993X
www.ambi-agua.net
E-mail: ambi.agua@gmail.com

Physical and chemical indicators of soil quality in a mountain environment in the Atlantic Forest biome

ARTICLES doi:10.4136/ambi-agua.3054

Received: 30 Dec. 2024; Accepted: 14 May 2025

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Editor-in-Chief: Nelson Wellausen Dias

ABSTRACT

Agricultural sustainability is the ability of a system to produce food properly without damaging environmental conditions. Assessing the quality of the soil and its attributes informs its proper use without compromising ecosystems. This study analyzes the chemical and physical properties of soil at sites under different management in the mountainous region of the state of Rio de Janeiro, Brazil. Two cultivation areas were selected: tomato (*Solanum lycopersicum* L.) and corn (*Zea mays* L.) production and; secondary forest. Four samples were taken at a depth of 0-10 cm to assess pH in water, Al^{+3}, Ca^{+2}, Mg^{+2}, P, K^{+}, Na^{+}, H+Al, carbon (C), particulate organic carbon (COP), organic carbon associated with minerals (COMA), total nitrogen content, carbon stock (SCS), carbon in the free light fraction (FLFC) and intra-aggregate light fraction (ILFC). The apparent density (AD), particle density (PD) and weighted average diameter (WAD) of the aggregates were characterized. High P contents were observed in the tomato area (125.78 to 502.03 mg kg^{-1}) and in the corn area (127.80 to 253.14 mg kg^{-1}), indicating excessive fertilization. As for BD, values of 1.25 Mg m^{-3} and 1.60 Mg m^{-3} were observed in the tomato and corn areas, respectively, which were higher than those observed in the forest area. It was noted that the management carried out in the cultivated areas is not promoting the accumulation of organic matter in the soil. Monitoring soil properties can help identify changes that impact on productivity and environmental quality.

Keywords: agricultural sustainability, environmental fragility, soil conservation.

Indicadores físicos e químicos da qualidade do solo em ambiente de montanha no bioma Mata Atlântica

RESUMO

Sustentabilidade agrícola é a capacidade do sistema de produzir alimentos de forma adequada sem prejudicar as condições ambientais. A avaliação da qualidade do solo e seus atributos auxiliam na recomendação do uso sem comprometer os ecossistemas. O objetivo deste estudo foi analisar propriedades químicas e físicas do solo em locais com diferentes manejos na região serrana do estado do Rio de Janeiro, Brasil. Foram selecionadas duas áreas de cultivo:

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Produção de tomate (*Solanum lycopersicum* L.) e milho (*Zea mays* L.) e; Floresta secundária. Quatro amostras foram coletadas na profundidade 0-10 cm para avaliação do pH em água, Al^{+3}, Ca^{+2}, Mg^{+2}, P, K^{+}, Na^{+}, H+Al, carbono (C), carbono orgânico particulado (COP), carbono orgânico associado aos minerais (COMA), teores de nitrogênio total, estoque de carbono (SCS), carbono nas frações leve livre (FLFC) e leve intra-agregado (ILFC). Caracterizou-se a densidade aparente (DA), a densidade de partículas (DP) e diâmetro médio ponderado (DPM) dos agregados. Elevados teores de P foram observados na área de tomate (125,78 a 502,03 mg kg^{-1}) e na área de milho (127,80 a 253,14 mg kg^{-1}), indicando adubação excessiva. Quanto ao BD, observou-se valores de 1,25 Mg m^{-3} e 1,60 Mg m^{-3} nas áreas de tomate e milho, respetivamente, superiores aos observados na área de floresta. Notou-se que o manejo realizado nas áreas de cultivo não está promovendo acúmulo de matéria orgânica no solo. O monitoramento das propriedades do solo pode auxiliar na identificação de alterações que impactam na produtividade e na qualidade ambiental.

Palavras-chave: degradação de poliestireno, microbioma intestinal, técnicas biotecnológicas.

1. INTRODUCTION

The peculiarities of mountain regions, such as rugged relief, susceptibility to climatic variations, the presence of shallow soils, intensive use, and the intensification of processes of environmental degradation affect the productivity of these areas, must all be considered when defining public policies that promote sustainable development. Additionally, these modifications can cause social vulnerability (Assis *et al.*, 2019; Pinheiro Junior *et al.*, 2019; Amorim and Assis, 2023; Gomes *et al.*, 2023).

Considering the primary challenges in these areas, knowledge of these environments is fundamental, as these ecosystems participate in important functions for ecosystem balance (Formoso, 2014). The utilization and management of soils in Rio de Janeiro's mountainous regions highlight the significance of agriculture within the state, as favorable climatic conditions allow for year-round production of a wide variety of foods (Pereira *et al.*, 2022). The agricultural landscape of the region is characterized by the use of agricultural machinery and implements, limited adoption of fallow periods and heavy reliance on fertilizers, as well as the widespread use of agrochemicals (Grisel and Assis, 2020; Osinuga *et al.*, 2023). Thus, harmonizing the expansion of agricultural activities with the ecosystem is an emerging challenge. In light of the above, soil quality is supported by diverse and complex processes in natural and agricultural ecosystems that can be compromised by intensified soil management (Hermans *et al.*, 2020; Souza *et al.*, 2024). Karlen *et al.* (1992) Soil quality is defined as the soil’s capacity to function within an ecosystem, sustaining productivity, enhancing water and air quality, and supporting human health, while emphasizing its variability based on land use, ecosystem type, and soil interactions. Although soil quality cannot be quantified directly, it can be studied through evaluations of indicators that include physical, chemical, and biological attributes of the soil, as essential tools to assess the agroecosystem (Silva *et al.*, 2020; Falcão, 2021; Lopes *et al.*, 2022). Soil quality is defined as the soil’s ability to perform functions within an ecosystem, sustaining productivity and varying according to land use, ecosystem type, and soil interactions (Karlen *et al.*, 1992). It is also understood as the capacity of soils to interact with the ecosystem to maintain biological productivity, preserve environmental quality, and promote plant and animal health (Doran and Parkin, 1994).

In this context, to assess soil fertility it is fundamental to have knowledge about the contents of nutrients present in the soil, as well as the derived variables, and it is essential for the producer to understand the importance of restoring the nutrients absorbed by crops to the soils (Silva *et al.*, 2022; Tavares *et al.*, 2024). Thus, soil chemical indicators are essential for the recommendation of adequate management, avoiding excessive fertilization, nutrient leaching, erosion, excessive liming, among other activities, helping in the recognition of the soil's capacity to sustain ecosystems through nutrient cycling (Silva *et al.*, 2021). Physical indicators are associated with several soil functions linked to crop and environmental quality, making it possible to analyze changes resulting from anthropogenic activities, besides helping to characterize the current situation, paying attention to future risks (Silva *et al.*, 2020; Khasi *et al.*, 2024).

In view of the importance of achieving more sustainable strategies for these environments, considering emerging issues, it is essential to make useful decisions for sustainable and appropriate agricultural practices to understand the long-term impact of agrochemicals on soil characteristics (Balsiger and Debarbieux, 2015; Dax, 2022; Osinuga *et al.*, 2023).

Therefore, systems are regularly being investigated to identify strategies to mitigate negative effects, and given the importance of soil chemical and physical attributes, the assessment of edaphic environment quality needs to include reference values to identify management effects (Bünemann *et al.*, 2018; Ozório *et al.*, 2024). Thus, rational use and utilization of soils must be supported by understanding their physical and mineral limitations and capacities (Lima Silva *et al.*, 2021), acting in the evaluation of agricultural productivity results and in environmental sustainability.

However, considering all the characteristics inherent to the region, as well as the management practices adopted by many farmers, the hypothesis of the present study is that conventional management in mountain environments results in major changes in the physical and chemical attributes of the soil. Therefore, the aim of this study is to assess the chemical and physical properties in different areas in a mountain environment in the mountainous region of the Rio de Janeiro state, Brazil.

2. MATERIAL AND METHODS

2.1. Location of study areas

The research was carried out in the mountainous region of the state of Rio de Janeiro in the municipality of Sumidouro. Three areas were selected, with approximately 1 hectare each, two of which were agricultural production, with tomato (*Solanum lycopersicum* L.) and maize (*Zea mays* L.), located at the geographic coordinates 22°09'38" S and 42°38'34" W, 22°09' 34" S and 42°38'22" W, respectively, and an area of secondary forest fragment with a low degree of anthropogenic intervention, located at the geographic coordinates 22° 09' 31" S and 42°38'32" W (Figure 1).

The production areas have been farmed for over 10 years in a conventional system with crop rotation. The area with tomato cultivation is alternated with Brassicaceae and Solanaceae crops, situated in the middle third of the landscape with undulating relief, whereas the area with maize cultivation is located in the lower third of the landscape, being alternated with Brassicaceae cultivation. Cover crops are not planted in these areas. Regarding the use of fertilizers, although they are constantly applied, there are no records by the producer of precise quantities used. Regarding irrigation, the sprinkler system is used.

The climate of the zone is Cfb type in Köppen's (1948) classification, with high humidity and mild summer. The prevailing average temperature is 18.1°C and the average yearly rainfall is 2,174 mm, with relative humidity ranging from 36 to 87% (INMET, 2024). The soils of the areas were classified as *Cambissolos Húmicos* (Santos *et al.*, 2018), equivalent to *Inceptisols* (Soil Survey Staff, 2014).

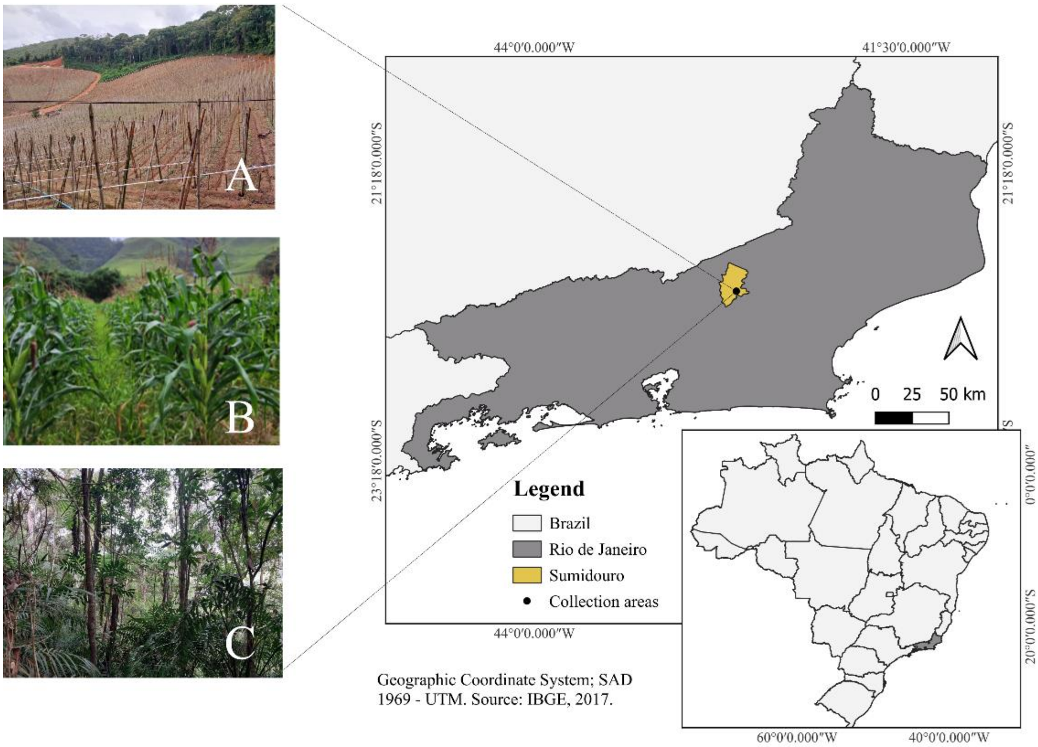

Figure 1. Location of the study areas, Sumidouro – Rio de Janeiro. (A) tomato, (B) corn and (C) forest.

2.2. Chemical analysis

Mini soil pits were opened in each respective area, and four composite samples were obtained, consisting of the homogenization of five single samples, randomly distributed, for better representativeness of the area, in the 0-10, 10-20 and 20-40 cm layers, with four replicates per area. After collection, the samples were sent to the laboratory to be air-dried, crushed to break up clumps and passed through a 2-mm-mesh sieve to obtain air-dried fine earth (ADFE).

ADFE was then used for analysis of: pH in water at ratio of 1:2.5 (soil:water); exchangeable Ca^{+2}, Mg^{+2} and Al^{+3}, extracted with 1 mol L^{-1} KCl and analyzed by titrimetry; P, K and Na, extracted with the Mehlich-1 extractant and analyzed by colorimetry and flame photometry, respectively; H+Al, evaluated by means of 0.025 mol L^{-1} calcium acetate solution, all procedures in the methods carried out according to Teixeira *et al.* (2017); and total organic carbon (C_{org}) determined according to Yeomans and Bremner (1988).

2.3. Physical analysis

For particle-size analysis, the ADFE samples were dispersed with 1 mol L^{-1} NaOH solution and shaken for 16 hours at low rotation.

Total clay content was assessed by suspension, using the pipette method (Teixeira *et al.*, 2017). Sand fractions (coarse and fine) were separated by sieving, in 0.20- and 0.053-mm meshes, respectively, and silt fraction was calculated by difference according to the other fractions, sand and clay.

Bulk density (BD) and particle density (PD) were determined according to Teixeira *et al.* (2017). Aggregate stability was evaluated in undisturbed samples (clods) from the 0-10 cm layer. To separate the aggregates, the collected samples were passed through 8.00- and 4.00-mm-mesh sieves. Subsequently, from the aggregates that were retained in the 4.00-mm-mesh sieve, 25 g were weighed and transferred to a 2.00-mm-mesh sieve, which comprises a set of sieves with increasing meshes (2.00, 1.00, 0.50, 0.25 and 0.105 mm). Aggregates were exposed to vertical wet sieving for 15 minutes at 42 oscillations per minute in the Yoder apparatus

(Yoder, 1936). After the time had elapsed, the material retained in each sieve was separated and dried in the oven until reaching constant mass, and the mean weight diameter (MWD) of the aggregates was calculated (Teixeira *et al.*, 2017).

Particle-size physical fractionation was performed using ADFE. 20 g of soil was weighed and transferred to tubes, followed by addition of 60 mL of sodium hexametaphosphate solution (5 g L^{-1}), and homogenized with a horizontal shaker for 15 hours (Cambardella and Elliot, 1992). Then, the material was passed through a 53-μm-mesh sieve. Particulate organic carbon (POC) related with the sand fraction corresponds to the material that was retained in the sieve, which was then dried in an oven at 65ºC with quantification of its mass and total organic carbon (TOC) content was analyzed according to Yeomans and Bremner (1988). The material that passed through the 53-μm-mesh sieve represents the mineral-associated organic carbon (MAOC) of the silt and clay fractions, calculated by the difference between total organic carbon (TOC) and particulate organic carbon (POC).

Light fractions of SOM (densimetric physical fractionation) were obtained using the technique proposed by Sohi *et al.* (2001). Light fractions were extracted using 35 mL of sodium iodide (NaI) solution with density of 1.8 g cm^{-3} (± 0.02) and 5 g of ADFE. The supernatant, which corresponds to the organic fraction present in the solution (free light fraction) was suctioned and separated with the aid of a glass fiber filter (Sterifil Aseptic System, 47 mm – Millipore) (47 mm diameter; 2 microns - Whatman type GF/A), which was previously weighed. The collected fractions were washed with distilled water to eliminate the excess NaI present in the fraction and in the filter. Then, together with the filter, the organic fraction was dried at 65°C, weighed and macerated in mortar.

After removing the free light fraction (FLF), the intra-aggregate light fraction (ILF) or occluded fraction was extracted by vibration using a Hielscher device (UP400S Model) for 60 seconds, at an energy of ± 1036 J mL^{-1} in the NaI solution. Organic carbon contents of the free light fractions (FLFC) and intra-aggregate light fractions (ILFC) of SOM were determined according to Yeomans and Bremner (1988).

2.4. Carbon, nitrogen and soil carbon stock contents

Total carbon and total nitrogen contents were determined by the dry combustion technique, in a Perkin Elmer 2400 CHN elemental analyzer at the Laboratory of Research in Carbon and Nitrogen Biotransformations (LABCEN), Santa Maria, Brazil. The analyses were conducted using 1.0 (± 0.1) mg of soil sample macerated in a mortar and passed through a 100 mesh (149 μm) sieve (Nelson and Sommers, 1996; Sato *et al.*, 2014). Subsequently, the C/N stoichiometric ratio was calculated.

From the information on organic carbon contents and organic matter fractions and BD, the carbon stocks (SCS) were calculated by the equivalent mass method (Ellert and Bettany, 1995), based on the Equation 1 below.

$$\mathrm{SCS} = (\mathrm{TOC} \times \mathrm{BD} \times \mathrm{h})/10 \quad (1)$$

Where: SCS is soil carbon stock (MgC ha^{-1}); TOC is total organic carbon content (g kg^{-1}); BD is bulk density (Mg m^{-3}); h is the depth of the evaluated layer (cm).

2.5. Data analysis

The data were assessed for the normality of residuals and homoscedasticity of variances using the Shapiro-Wilk and Bartlett tests, respectively. Then, with the ANOVA assumptions met, the F test at 5% probability level was applied using R software (RStudio, 2023). A multivariate analysis, principal component analysis (PCA), was performed to assess the distribution of the chemical and physical attributes evaluated in the different zones, using R software (RStudio, 2023).

3. RESULTS

3.1. Chemical analysis

According to the soil chemical analyses, pH values did not differ between the cultivation areas in the 0–10 cm layer (Table 1). In the 10–20 cm and 20–40 cm layers, pH was higher in the tomato area (6.36–6.43) than the maize area (5.75–5.87). In the forest, pH ranged from 3.97 (0–10 cm) to 4.21 (20–40 cm), reflecting natural acidity. No significant differences in Al^{3+} and H+Al, were observed between the cultivation areas, with null values for Al^{3+}. In the forest, Al^{3+} ranged from 1.07 to 1.58 cmolc dm^{-3}, confirming high natural acidity.

Table 1. Characterization of chemical attributes, at depths of 0-10 cm, 10-20 cm and 20-40 cm, of tomato and corn areas, Sumidouro, RJ.

Areas	pH	Al^{3+}	H+Al	Ca^{2+}	Mg^{2+}	K^+	P	S value	T value	V value
	H_2O	cmol$_c$ dm^{-3}				mg kg^{-1}		cmol$_c$ dm^{-3}		%
0 – 10 cm										
Tomato	6.01 a	0.00 a	4.94 a	6.7 a	3.27 b	12.98 a	502.03 a	9.52 a	14.46 a	65 a
Corn	5.91 a	0.00 a	2.87 a	4.65 a	5.84 a	13.15 a	253.14 a	8.95 a	11.83 a	75 a
Forest	3.97	1.58	10.38	0.10	3.25	4.53	6.14	3.30	13.68	26
CV (%)	2.24	0.00	19.43	17.67	10.48	17.27	49.65	22.78	14.22	11.34
10 – 20 cm										
Tomato	6.36 a	0.00 a	3.41 a	5.90 a	3.58 a	6.75 a	215.72 a	9.51 a	14.49 a	67 a
Corn	5.87 b	0.00 a	3.55 a	3.68 b	4.75 a	6.28 a	127.80 a	8.46 a	12.04 a	70 a
Forest	4.16	1.07	8.14	0.07	5.50	3.57	6.02	5.60	13.74	41
CV (%)	1.34	0.00	12.82	10.33	25.72	14.26	51.84	15.64	17.99	14.43
20 – 40 cm										
Tomato	6.43 a	0.00 a	4.19 a	4.78 a	3.90 a	3.90 b	125.78 a	8.70 a	12.90 a	68a
Corn	5.75 b	0.00 a	3.78 a	3.55 b	4.75 a	5.35 a	142.68 a	8.33 a	12.12 a	69 a
Forest	4.21	1.08	7.08	0.03	4.60	3.38	5.66	4.63	11.71	40
CV (%)	1.20	0.00	22.79	6.78	14.03	12.82	31.87	7.70	9.52	6.82

Averages followed by letters separated by the F t-test ($p<0.05$). Ca: Exchangeable calcium; Mg: Exchangeable magnesium; Al: Exchangeable aluminum; H+Al: Acid potential; K: Exchangeable potassium; P: Available phosphorus; S value: Sum of exchangeable bases; T value: cation exchange capacity; V value: Base saturation.

The Ca^{+2} contents in the tomato and maize areas did not differ at 0-10 cm depth, but higher in the tomato area at deeper layers (6.7 to 5.9 cmol$_c$ dm^{-3}). Forest Ca^{2+} levels were low. Mg^{2+} Mg^{2+} was highest in the maize area at 0–10 cm, with no significant differences at other depths. In the forest area, values were close to those observed in the cultivated areas. Potassium (K^+) differed only in the 20–40 cm depth, with higher levels in maize cultivation area (5.35 mg kg^{-1}). Forest K^+ ranged from 3.38 (20–40 cm) to 4.53 (0–10 cm) mg kg^{-1}.

Phosphorus (P) levels were uniformly high in cultivated areas, especially at 0–10 cm, decreasing with depth; forest values were low and stable. No differences in sum of exchangeable bases (S value), cation exchange capacity (T value) and base saturation (V value) were observed between cultivated areas, while forest values were consistently low and variable.

3.2. Physical analysis

No significant differences ($p<0.05$) were observed in sand, silt, or clay contents between the tomato and maize cultivation areas, with both soil texture classified as sandy clay loam (Figure 2). In the forest area, slight increases in silt and decreases in clay content were noted, resulting in a sandy loam texture.

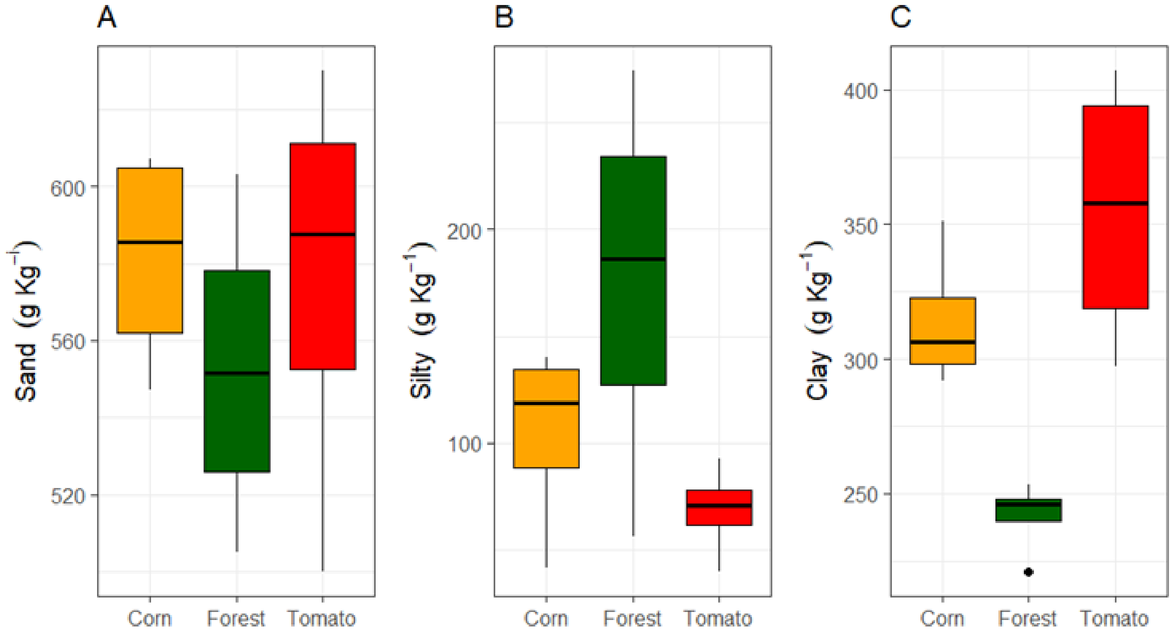

Figure 2. Characterization of soil granulometry at a depth of 0-10 cm, in tomato and corn areas, Sumidouro, RJ. Values followed by an asterisk (*) differ from the others according to the F test ($p<0.05$).

No significant difference ($p<0.05$) was observed in the mean weight diameter (MWD) of aggregates between the cultivation areas, with values of 3.48 mm in the tomato and 3.60 mm and maize area (Figure 3). Bulk density (BD) differed significantly ($p<0.05$), with higher values in the maize area (1.60 Mg m^{-3}), compared to the tomato area (1.25 Mg m^{-3}). Particle density (PD) did not differ ($p<0.05$) between the cultivation areas. In the forest area, MWD showed little variation, while both BD and PD were lower.

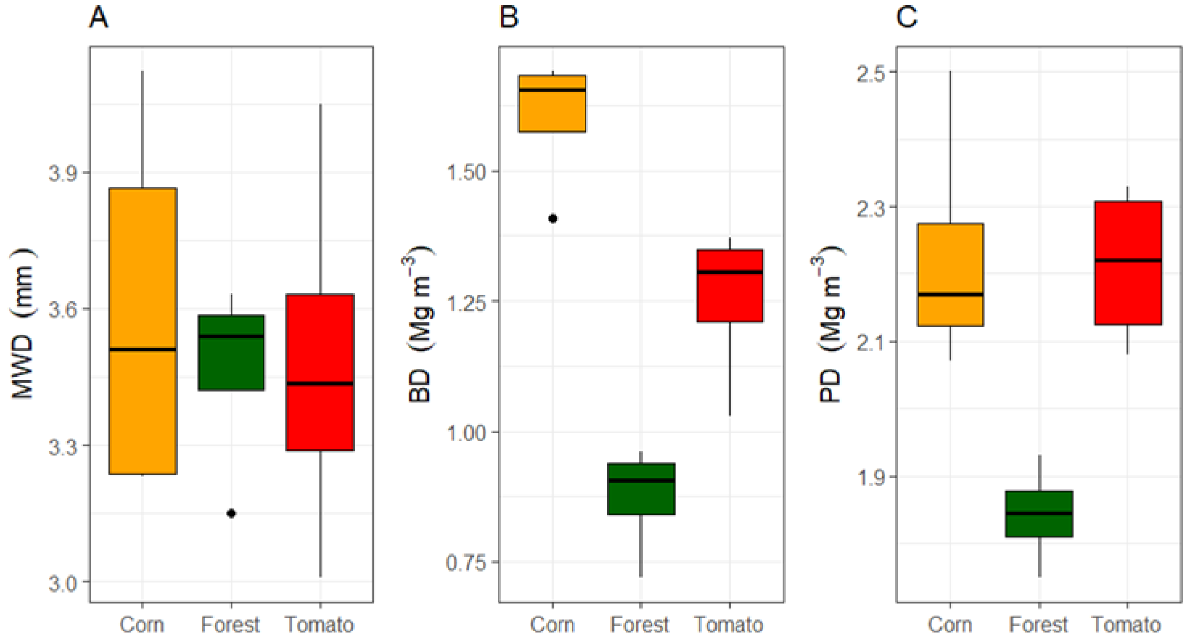

Figure 3. Mean weighted diameter (MWD) of aggregates obtained in water, bulk density (BD) and particle density (PD), at a depth of 0-10 cm, from tomato and corn areas, Sumidouro, RJ. Values followed by an asterisk (*) varied from the others according to the F test ($p<0.05$).

3.3. Carbon, nitrogen and soil carbon stock contents

Regarding the organic matter fractions, POC and MAOC contents did not differ between the cultivation areas (Table 2). Concerning the forest area, there were higher values of POC (4.46 g kg^{-1}) and MAOC (26.42 g kg^{-1}).

Table 2. Fractions of soil organic matter and nitrogen, at a depth of 0-10 cm, in tomato and corn areas, Sumidouro, RJ.

Areas	POC	AMOC	FLF	ILF	C	N	C/N	SCS
	g kg^{-1}					g kg^{-1}		MgC ha^{-1}
Tomato	3.08 a	15.74 a	0.61 a	0.06 b	18.1 a	1.40 a	13 a	23.25 a
Corn	1.98 a	14.58 a	0.20 b	0.09 a	13.6 b	1.10 b	12 b	22.32 a
Forest	4.46	26.42	4.30	0.12	30.5	2.30	13	28.92
CV (%)	25.71	16.95	37.88	21.97	8.17	11.05	4.17	7.8

Means followed by distinct letters differ from each other by the F t-test ($p<0.05$). POC: Particulate organic carbon; TOC: Total organic carbon; AMOC: Organic carbon associated with minerals; FLF: Organic carbon contents of the free light fractions; ILF: Organic carbon contents of the intra-aggregate light fractions; C: Total carbon; N: Total nitrogen; SCS: Carbon stock.

For the free light fraction carbon (FLFC), difference was observed between the cultivation areas, with the highest value in the tomato area (0.61 g kg^{-1}). Regarding the intra-aggregate light fraction carbon (ILFC), difference was observed between the cultivation areas, with the highest value in the maize area (0.09 g kg^{-1}). For the forest area, the ILFC value was high (0.12 g kg^{-1}).

Regarding C contents, there was a difference between the tomato and maize areas, with the highest value in the tomato area (18.1 g kg^{-1}). In the forest area, the C content was considered high (30.5 g kg^{-1}). Analysis of the N contents showed that they differed between the cultivation areas, with the highest values in the tomato area (1.4 g kg^{-1}). With respect to the reference area, N contents were higher (2.3 g kg^{-1}). C/N ratio differed among the areas, with higher values in the tomato area (13 g kg^{-1}) and lower values in the maize area (12 g kg^{-1}). The forest area showed little variation in C/N ratio. In relation to SCS values, there was no difference between the cultivated areas. In the forest area, SCS value was higher (28.92 MgC ha^{-1}).

3.4. Principal Component Analysis

Principal component analysis (PCA) referring to the chemical and physical attributes in the 0-10 cm layer, the sum of the F1 and F2 axes explained 74.5% of the total variability, with PC1 explaining 59.9% and PC2 14.6% (Figure 4). The separation of the cultivation areas from the forest area was observed in axis 1. The variables of organic matter fractions, SCS, Al^{+3}, silt and N are more related to the forest area, while BD, PD, P, K, S value, T value and clay are connected to the cultivated areas.

4. DISCUSSION

4.1. Chemical analysis

The lowest pH values were observed in the reference area, indicating that the studied soils are naturally acidic. These findings align with those of Lima *et al.* (2020), who reported similar pH levels in forest fragments in Nova Friburgo, RJ. The acidic character of these soils is primarily attributed to the nature of the parent material, typically acidic rocks or their weathered sediments (Pereira *et al.*, 2022), as well as the influence of the climate, which intensifies weathering processes due to the region's climate regime, characterized by high water input from rainfall.

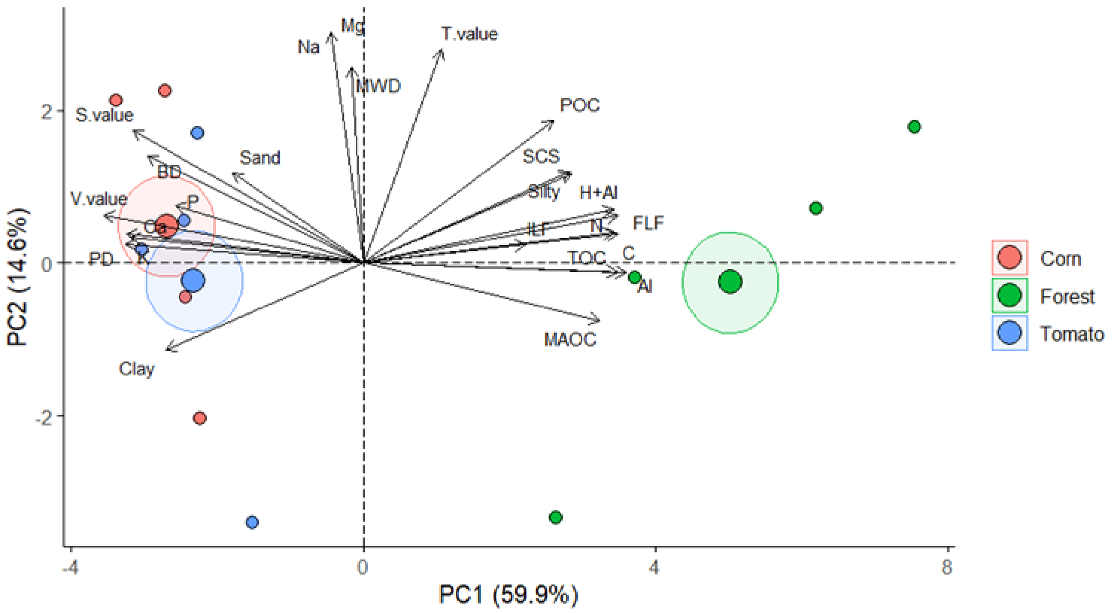

Figure 4. Principal component analysis of soil chemical and physical properties at 0-10 cm depth in tomato, corn and forest areas.

Al^{+3} values were null in both cultivation areas but high in the forest area, indicating elevated levels in environments without soil correction. As high Al^{+3} concentrations are detrimental to root development in crops (Oliveira-Silva *et al.*, 2020), proper liming is essential for sustainable production in this region.

The high Ca^{2+} and Mg^{2+} contents observed in the cultivation areas are likely associated with frequent liming practices for soil correction. In contrast, K^{+} levels were low (< 45 mg kg^{-1}) in both areas (Freire *et al.*, 2013). Similar chemical characteristics were observed by Salles *et al.* (2022), in an organic production unit in the Cardinot neighborhood, Nova Friburgo, RJ. However, this study showed significantly higher P contents under conventional cultivation compared to organic systems evaluated by Salles *et al.* (2022), indicating the intense use of phosphate fertilizers. This finding supports Gonçalves *et al.* (2022), who highlighted the excessive P fertilizer application in Rio de Janeiro. Therefore, monitoring and regulating P input are critical, as the lack of recycling practices poses risk to food and global security, as well as pollution (Bai *et al.*, 2024). Optimizing P use in the evaluated tomato and maize systems is thus essential, given the high P concentrations detected. Regarding base saturation (V%), values exceeded 50% across all zones, classifying the soil as eutrophic, consistent with studies carried out by Rossi *et al.* (2015) in the same region.

4.2. Physical analysis

The areas are positioned at different points in the landscape; however, it was observed that there was no variation in the textural class, which is an essential factor to consider when comparing areas, given that soil texture influences various attributes.

In the tomato area, the combination of textural class, mid-slope position, undulating relief, and conventional management practices, characterized by high soil disturbance and removal of vegetation cover, may intensify erosion and nutrient leaching (Pinheiro Junior *et al.*, 2019). Vegetative cover plays a crucial role in protecting soil from the direct impact of raindrops (Santos and Guerra, 2021). The study area's topography, ranging from undulating to strongly undulating, can lead to substantial material removal and accelerated rejuvenation process, as observed by Dortzbach *et al.* (2016) in a high mountainous environment in Santa Catarina. Thus, the scarcity of vegetation cover in the evaluated area poses ecological risks and may promote movement of mass and soil degradation.

The maize cultivation area is located in the lower third position of the landscape, where it is influenced by sediment increments and subject to flooding. Under conventional management, combined with a clay content exceeding 300 g kg^{-1}, this setting may promote soil compaction (Yu *et al.,* 2024). Compaction reduces root development and crop yield by increasing bulk density and decreasing porosity, which limits the soil volume accessible to roots and impairs nutrient uptake (Medeiros *et al.*, 2005; Silva *et al.*, 2021).

In the forest area, soil texture was classified as sandy loam, with higher silt and lower clay contents. These variations are attributed to the landscape position, which influences sediment removal. Steeper slopes facilitate surface runoff (Horton flow) over infiltration, increasing susceptibility to erosion and mass movements (Dantas *et al.*, 2023) Understanding soil particle-size behavior is therefore essential for interpreting sediment distribution and soil dynamics (Campos *et al.*, 2007). Given the forest area’s position in the upper third of the landscape, greater transport and loss of the finer fraction (clay), resulting in the reduction of this fraction in the superficial layer of the soil.

Similar mean weight diameter (MWD) values of soil aggregates were observed in the tomato and maize areas, comparable to those in the forest area, suggesting that management practices did not significantly affect soil structure. These values align with those observed by Santos and Guerra (2021), in Paraty, RJ, indicating a predominance of macroaggregates, which enhance porosity and infiltration. Likewise, the MWD values correspond to those obtained by Lima *et al.* (2020) in unfertilized black oat cultivation at higher landscape positions in Nova Friburgo, RJ, reinforcing that cropping and soil management in the cultivated areas did not cause major impacts on soil aggregation.

Inadequate soil management practices tend to increase the degree of compaction and compromise structural stability, in addition to interfering with the absorption of nutrients by plants and consequently reducing crop yield (Silva, 2021). The higher BD values observed in the maize cultivation area (Figure 4) may pose limitations for certain commercial crops, as BD values above 1.45 Mg m^{-3} in clayey soils and 1.65 Mg m^{-3} in sandy soils are considered harmful to crop development (Reinert and Reichert, 2001). These elevated BD values may result from excessive soil disturbance and the area's lower landscape position, which promotes the accumulation of sediments, water, organic matter, and nutrients. Additionally, the deposition of fine clay particles into soil pores can increase cohesion and further elevate BD.

Particle density (PD) is influenced by mineralogical composition and organic matter content (Rossi *et al.*, 2015). In the tomato and maize cultivation areas, increased PD may be linked to reduced carbon input from crop residues due to management practices. In contrast, continuous organic matter input in the forest area contributed to lower PD values. Additionally, the higher PD in the cultivation areas may be attributed to greater clay contents. Lima *et al.* (2021) observed in their study medium values of PD and attributed the increase to soil texture, considering that clay soils have higher density and lower porosity due to the arrangement of particles.

4.3. Carbon, nitrogen and soil carbon stock contents

In the two cultivation areas, the similarity observed in POC and MAOC contents (Table 2) may be associated with the low accumulation of plant material in the soil resulting from the management adopted, as well as its constant turning, causing lower stability of organic matter (Nanzer *et al.*, 2019). The upkeep of the POC fraction in the soil is conditioned to the physical protection performed by the aggregates (Nanzer *et al.*, 2019), while MAOC is the fraction of soil organic matter (SOM) correlated with the silt and clay fractions of the soil, being the one which interacts with the surface of mineral particles, thus becoming more protected against decomposition (Loss *et al.*, 2009)

Thus, POC contents in cultivated areas are dependent on the capacity of each system to provide greater addition of residues on soil surface (Faccin *et al.*, 2016), associated with management practices that contribute to greater protection of this fraction. In this context, the greatest values of POC (4.46 g kg^{-1}) and MAOC (26.42 g kg^{-1}) were observed in the forest area, given the high accumulation of litter in these environments, in addition to the minimal soil disturbance, promoting better conditions for the preservation of these fractions.

The variation in the free light fraction carbon (FLFC) and intra-aggregate light fraction carbon (ILFC) contents may result from changes in the quantity and quality of plant residues that are added to the soil, as well as the relationship between the surface and subsurface input of these residues, and also from distinct forms of management adopted (Souza *et al.*, 2023). The evaluation of carbon in these light fractions is important because it indicates that alterations in land use can generate a reduction in soil carbon stocks, since they are sensitive to the agricultural management adopted (Chagas *et al.*, 2017; Marques *et al.*, 2017.).

In this context, the difference in the FLFC in the tomato area might be associated with the quality of the plant residue present in the soil. Although the values of this fraction in the tomato area were higher than those in the maize area, it is essential to consider that the values were low, which may be due to the low support of plant material, in addition to the influence of relief and soil turning. Souza *et al.* (2023) consider this fraction sensitive to degradation by cultivation, so it can be used as an indicator of the consequences of the management adopted with the decrease in the contents of these fractions. The higher C and N contents, as well as the C/N ratio in the tomato area, possibly derive from the physiology of the crop in the production area, since it is a factor dependent on the deposited material. The C/N ratio can be considered an important parameter in the study of soil organic matter dynamics and can be an indicator of stability of the fraction (Chagas *et al.*, 2017). Thus, materials with a high C/N ratio can generate N immobilization or cause a slower release of this element, reducing the entry of N into the soil (Moreira and Siqueira, 2006). Relative the forest area, cultivated areas have low plant diversity, in addition to the fact that intense turning activities are carried out in these areas, indicating that the studied systems do not favor the maintenance and/or accumulation of organic matter in the soil, resulting in C and N contents lower than those located in the natural system.

Soils in their natural condition have a balance between carbon input and output; however, in areas subjected to intensive activities for land management, this balance is affected, with significant reductions in soil carbon stocks, thus being considered a valuable tool in the context of climate change as they constitute important indicators of environmental services (Parron *et al.*, 2015; Baumgärtner *et al.*, 2021). In this context, the similarity of SCS between the cultivation areas could be connected to the same type of management to which these areas have been subjected. As for SCS, its values were similar to those observed by Mascarenhas *et al.* (2017) in the area of AFS (multi-stratified agroforestry system), in the most superficial layer of the soil. In turn, the SCS contents of the evaluated areas were higher than those observed by Hickmann and Costa (2012), who evaluated different conventional management systems and no-tillage systems. Thus, although the cultivation areas are intensively managed, they still have high carbon stocks, which can be little impacted as long as they are properly managed.

4.4. Principal component analysis

Principal component analysis shows the distribution of chemical and physical properties as a function of management in the distinct areas studied. Thus, it is possible to verify that the cultivated areas are similar, distinguishing themselves from the forest area. Thus, the different fractions of organic matter are related to the reference area in the first quadrant. This higher relationship between organic matter and forest area is due to the greater input of organic material (litter) associated with low anthropogenic interference, allowing the mineralization of organic matter to occur more slowly. Thus, the reduction of these fractions in the soil in the cultivation areas indicates that the removal of vegetation from the soil and the intense agricultural use reduce OM contents in the soil, as evidenced by Novak *et al.* (2021). Clay contents, BD and PD were grouped in the opposite position, indicating that in addition to the management adopted in the cultivation areas not favoring the maintenance of the organic fractions of the soil, it intensifies the rise in BD and PD values.

In the forest area, there is a greater relationship with the potential acidity of the soil (H+Al) than with the other soil properties associated with fertility. For natural soils, this acidity can be associated with leaching or adsorption of basic cations of the exchange complex, consequently with an accumulation of cations of acidic nature (Novak *et al.*, 2021). Another important factor is that potential acidity is directly related to soil organic matter, i.e., the higher the carbon contents, the greater the amount of free radicals and phenolics, resulting in the higher H+Al value, which is corroborated by Ebeling *et al.* (2008), who found a positive and significant correlation of the organic matter content with the extractable hydrogen content and with the potential acidity of the soil. Thus, similarity was observed with the study conducted by Oliveira *et al.* (2015), who found a strong association with potential soil acidity in areas of native vegetation.

5. CONCLUSION

Conventional management in tomato and maize areas has led to excessive phosphorus application in the soils.

The conventional management practices adopted in the cultivation areas have increased soil density and particle density.

The low levels of C, COp, COam, FLL, and FLI in the cultivation areas indicate that the management practices adopted are not promoting the accumulation and/or maintenance of organic matter in the soil.

Intensive management in mountainous areas results in chemical and physical soil degradation.

The findings emphasize the need for improved soil management strategies that prioritize organic matter conservation, controlled fertilizer application, and erosion mitigation to ensure the sustainability of agricultural systems in mountainous regions.

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