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Absorção foliar de nutrientes pela videira em Argissolos do submédio do Vale São Francisco, semiárido do nordeste do Brasil

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R E S U M O

O crescimento da videira em clima tropical semiárido é fortemente influenciado pelo tipo de solo e seus atributos químicos e físicos. Este trabalho investigou a relação entre propriedades do solo e a absorção de nutrientes pelas folhas em vinhedos no Vale do São Francisco, nordeste do Brasil, para contribuir com a produção de vinho. Foram selecionados cinco tipos de solos, sob cultivos de uvas das variedades Tempranillo e Syrah conduzidos em sistema de espaldeira. Os solos foram classificados como Argissolos Vermelho-Amarelo (Argissolo) (PVA) com textura argilosa e quatro Argissolos Amarelos (Argissolo), (PA1, PA2, PA3 e PA4) com média/argilosa, média/argilosa, arenosa/média, respectivamente. As características morfológicas foram determinadas no vinhedo, enquanto os atributos físicos e químicos do solo e o conteúdo nutricional da folha foram analisados em laboratório. Não foram encontradas diferenças nos teores de nutrientes nas folhas da uva durante a maturação. A subsuperfície do PVA apresentou distribuição adequada de nutrientes, pH, soma de base e teor de argila, o que é favorável ao desenvolvimento das videiras. Embora o PA2 tenha apresentado elevados teores de fósforo (436 mg kg^{-1}) e carbono orgânico total (25 g kg^{-1}) em seus horizontes superficiais (0-10 cm), uma maior densidade aparente (~2,0 kg dm^{-3}) e menores porosidades totais (~30%) foram encontradas nos horizontes diagnósticos como ocorreu em Argissolo PA3, comprometendo a infiltração de água no solo e consequentemente a qualidade das uvas. De forma geral, o Argissolo Vermelho-Amarelo foi o mais promissor na obtenção de uvas de boa qualidade para produção de vinho.

Palavras-chave: vitivinicultura, solos tropicais, caracterização química do solo, diagnose foliar.

Leaf nutrient absorption by grapevines in Argisols of the sub-middle São Francisco Valley, semiarid region of northeastern Brazil

A B S T R A C T

The growth of vines in a semi-arid tropical environment climate is heavily influenced by soil type and its chemical and physical attributes. This work investigated the relationship between soil properties and leaf nutrient absorption in the São Francisco Valley vineyards, northeastern Brazil, to contribute to wine production. Five types of soils were selected, under crops of Tempranillo and Syrah grape varieties conducted in an espalier system. The soils were classified as Argissolo Vermelho-Amarelo (Ultisol) (PVA) with clay texture and four Argissolos Amarelos (Ultisols), (PA1, PA2, PA3, and PA4) with medium/clayey, medium/clayey, sandy/medium, respectively. Morphological characteristics were determined in the grapevine field, while physical and chemical attributes of the soil and nutritional contents of the leaf were analyzed in the laboratory. No differences were found in nutrient contents in the grape leaves during maturation. The subsurface of PVA had a suitable distribution of nutrients, pH, base sum, and clay content, which is favorable for the development of vines. Although PA2 has had high contents of phosphorus (436 mg kg^{-1}) and total organic carbon (25 g kg^{-1}) in its shallow horizons (0-10 cm), a higher bulk density (~2.0 kg dm^{-3}) and a lower total porosity (~30%) were found in the diagnostic horizons, as occurred in Argissolo PA3, thereby jeopardizing the infiltration of water into the soil and the quality of the grapes, consequently. In general, Red-Yellow Argisol was the most promising for obtaining fine-quality grapes for wine production.

Keywords: vitiviniculture, tropical soils, chemical characterization of soils, foliar diagnosis.

Introduction

Climate plays a crucial role in determining the potential for viticulture, as it directly affects grapevine growth and grape characteristics. However, soil quality, its chemical and physical properties, as well as management practices are imperative for the healthy development of vineyards (Luo et al., 2024). For instance, stony soils in non-tropical regions are beneficial for both table grape and wine production due to their heat retention, which aids grape ripening. On the other hand, clayey soils, with their ability to retain nutrients and water, are suited for areas that require long-term fertility management (Mpanga et al., 2023). Conversely, sandy soils, commonly found in semi-arid climates like northeastern Brazil, drain well but have low nutrient retention, requiring high levels of fertilizers, such as phosphates, to maintain productivity (Fracetto et al., 2023). This raises concerns about the sustainability of such practices, as excessive reliance on external inputs may lead to soil degradation and increased costs, making it critical to evaluate the long-term ecological and economic impacts of current viticultural practices.

In the geological context, the sub-middle São Francisco Valley in northeastern Brazil exhibits significant pedological variability, as the region's soils are derived from rocks and sediments associated with formations of different geological periods (Fonsêca et al., 2020; Schaefer et al., 2023a). Moreover, the parent material of many soils in this area can originate from diverse sources, while human activity, particularly agriculture, further accentuates the contrasts in this unique biome known as the Caatinga (De Souza et al., 2023). Despite this complexity, grapevines are capable of growing in various soil types, typically in depths of approximately 1.50 meters. However, Oxisols and Ultisols are particularly prominent for viticulture in this region, owing to their favorable properties for supporting grapevine growth (Schaefer et al., 2023b).

The soils in the Caatinga biome have undergone significant degradation due to land-use changes and the exploitation of native forests for commercial timber (Neves et al., 2021; Santos et al., 2022). Certain soil classes, such as Ultisols, Luvisols, and Planosols, exhibit high salinity and increased apparent density, which can hinder root development and water infiltration. Other soils, like Neossolos, are characterized by excessive stoniness, which, combined with their susceptibility to nutrient leaching, further diminishes soil fertility (Moro et al., 2024). These soil characteristics present challenges for viticulture in the region, as they may affect both soil structure and nutrient availability. Understanding these pedological limitations is critical for the successful implementation of viticultural practices, requiring a comprehensive assessment of soil properties to ensure sustainable agricultural development.

The characteristics of grapes, including acidity, sugar content, and color, are significantly influenced by soil properties such as pH and nutrient availability. Consequently, the application of a balanced nutrient regime is critical for producing high-quality wine; inadequate or excessive nutrient supply can lead to poor vine health, faster leaf senescence, and diminished competitiveness in the global market (Silva et al., 2023; Souza Leão et al., 2024). Furthermore, some vineyards aim to adopt organic farming practices, avoiding synthetic fertilizers. However, to maintain grape productivity and optimize yield under organic management, farmers must possess a comprehensive understanding of their soil's physical and chemical properties. This knowledge enables them to effectively manage soil fertility and ensure sustainable production without compromising the quality of the grapes (Binfare et al., 2024; Silva et al., 2024). Thus, a well-informed approach to soil management is paramount for both organic and conventional viticulture to thrive in a competitive market.

There is a lack of comprehensive studies in semi-arid northeastern Brazil that integrate regional factors, grape varieties, and wineries as critical elements for defining Geographical Indications (GIs) and characterizing terroir. Particularly, it was postulated that Red-Yellow Argisol could be more suitable for obtaining high-quality grapes for wine production. Thus, this study aimed to investigate soil attributes in vineyards of the São Francisco Valley, focusing on the physical and chemical properties of the soil and their influence on the oenological potential of wine grapes. Additionally, the study assessed the relationship between soil characteristics and leaf nutrient content, which are key factors in vine development and may contribute to the typicity of the wine produced in the region. This research seeks to enhance the understanding of terroir in the São Francisco Valley and inform vineyard management practices for improved wine quality.

Material and methods

Study areas and soil characterization

An exploratory survey was conducted to select appropriate study areas, utilizing soil borings to obtain samples from different soil types under the cultivation of the same grape variety, with uniform cultural practices and plant, soil, and irrigation management. The survey involved visiting the largest wineries in the region to identify suitable areas for the study. As a result, three soil profiles were selected from a commercial winery in Lagoa Grande, Pernambuco, Brazil, where *cv. Tempranillo* is cultivated on the IAC 572 rootstock. Additionally, two profiles were chosen from another commercial winery in Casa Nova, Bahia, where *cv. Syrah* is grown on the IAC 766 rootstock. The vineyards at both the Lagoa Grande and Casa Nova wineries were established in an ascending trellis system, with planting dates dating from eight and seven years ago, respectively.

The trenches were excavated parallel to the plant rows to facilitate a detailed study of the soil profiles. Morphological descriptions of the soil profiles were conducted, following the guidelines provided in the Field Soil Description and Collection Manual (Santos et al., 2015), to ensure consistent and standardized data collection. Soil sampling was carried out at various depths using both deformed and undisturbed soil samples, allowing for a comprehensive analysis of the soil's physical and chemical properties.

The taxonomic classification of soils was performed according to the Brazilian Soil Classification System - SiBCS (Santos et al., 2018): Plintosolic Abrupt Eutrophic Argissolo Vermelho-Amarelo (Ultisol) (hereafter mentioned as PVA), Abrupt Eutrophic Argissolo Amarelo (Ultisol) (hereafter mentioned as PA1), Abrupt eutrophic Argissolo Amarelo (Ultisol) (hereafter mentioned as PA2), Plintosolic abrupt eutrophic Argissolo Amarelo (Ultisol) (hereafter mentioned as PA3), Plintosolic abrupt eutrophic Argissolo Amarelo (Ultisol) (hereafter mentioned as PA4) (Figure 1).

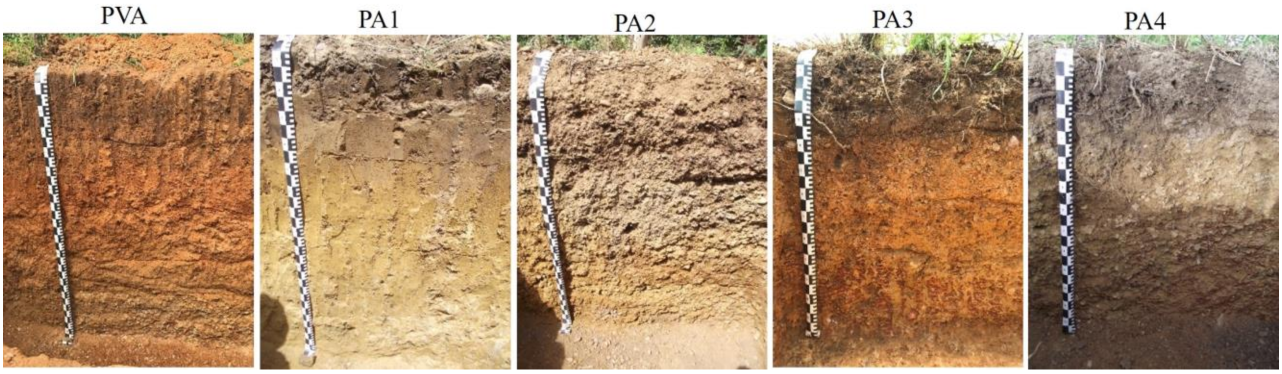

Figure 1. Profile of soils under Tempranillo and Syrah vineyards in the Sub-Middle São Francisco Valley. PVA - Argissolo Vermelho-Amarelo, PA1- Argissolo Amarelo, PA2 – Argissolo Amarelo, medium gravelly texture / gravelly clayey; PA3 – Argissolo Amarelo, medium texture gravel; PA4 – Argissolo Amarelo, sandy/medium texture.

Soil physical and chemical analyses

The physical characterization of the soil included the determination of particle size distribution and water-dispersible clay content using the densimeter method (Almeida et al., 2012). These values were subsequently used to calculate the degree of soil flocculation. Bulk soil density was measured using the volumetric ring method, as described by Grossman and Reinsch (2002), and also using the paraffin clod method.

Particle density was determined using the volumetric balloon method with ethyl alcohol, following the procedure outlined by Flint and Flint (2002). Total porosity was calculated based on the difference between the soil mass at saturation and the dry soil mass, the latter being determined by drying the samples in a greenhouse at 105 °C for 24 hours. This set of measurements provides a comprehensive understanding of the soil's physical properties, essential for evaluating its suitability for viticulture.

The chemical characterization of the soil involved several analytical procedures to assess key soil properties. pH was determined in both water and 1 mol L^{-1} KCl (1:2.5 ratio). Exchangeable sodium and potassium were quantified by flame photometry following extraction with Mehlich-1 solution, while exchangeable aluminum, calcium, and magnesium were measured using atomic absorption spectrophotometry, also after extraction with 1 mol L^{-1} KCl. Potential acidity was determined by titration with NaOH in the presence of phenolphthalein as an indicator, following extraction with 0.5 mol L^{-1} calcium acetate at pH 7. Available phosphorus was measured by colorimetry, using ascorbic acid as a reducing agent, after extraction with Mehlich-1 solution.

The concentrations of iron, manganese, copper, and zinc were analyzed using atomic absorption spectrophotometry, after extraction with the same Mehlich-1 solution (Teixeira et al., 2017). Total organic carbon was determined using the Walkley and Black method (Yeomans & Bremner, 1988). Additionally, the sum of bases (SB), cation exchange capacity (CEC), base saturation (V), and percentage of sodium saturation (PSS) were calculated to provide a comprehensive assessment of the soil's chemical fertility and nutrient availability.

Sampling and characteristics of grape leaves

Leaf samples for analysis were collected at the onset of berry ripening, specifically during the painter's stage. For each soil type, 30 plants were sampled, with 10 plants per replication. From each plant, three fully mature and healthy leaves, positioned opposite to the grape bunch, were collected, following the methodology outlined by Terra (2003). After collection, the leaves were placed in paper bags and transported to the laboratory. In the lab, the concentrations of phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), sodium (Na), copper (Cu), iron (Fe), manganese (Mn), and zinc (Zn) were determined using the procedures described by Malavolta et al. (1997).

Data analysis

The morphological, physical, and chemical attributes of the soils were organized in tables for detailed characterization. Leaf analysis data were subjected to descriptive statistics to summarize the variables studied. Subsequently, the results were analyzed using analysis of variance (ANOVA), and mean comparisons were performed using the Tukey test at a 5% significance level. The statistical analysis was carried out using the Sisvar software program.

Results and discussion

Morphological and physical attributes of soils

The *Plintosolic Abrupt Eutrophic Argissolo Vermelho-Amarelo* (Ultisol) (PVA) profile exhibits a depth exceeding 160 cm and is characterized by a sequence of Apf, Btf1, Btf2, Btf3, and Cr horizons, indicative of significant clay accumulation and plinthic material. According to the Brazilian Soil Classification System (Santos et al., 2018), plintite soils are typically formed under conditions of alternating wetting and drying cycles over extended periods. The presence of a high-water table in these soils promotes the chemical reduction of iron compounds, facilitating the transport, mobilization, and concentration of iron-rich materials (Zhao et al., 2023). The soil color varied along the profile, with a 10YR hue observed in the Apf horizon, a 5YR hue in the Btf1 and Btf2 horizons, and a 2.5Y hue in the Btf3 horizon. These reddish tones are primarily influenced by the convexity of the pedoform profile and the resulting drainage conditions. In the Btf1 horizon, mottling with 10YR and plinthite formations was noted, reflecting moderate drainage and the subsequent formation of plinthic features.

The root distribution along the soil profile varied in density and size. In the Apf horizon, roots were abundant and thick, whereas in the Btf1, Btf2, and Btf3 horizons, roots were more commonly of medium to thin caliber. In the Cr horizon, roots were sparse and thin, which was associated with the plastic and sticky consistency of the soil (Table 1) and the increased clay content in the subsurface horizons (Table 2). Bulk soil density showed minimal variation across the profile. However, total porosity increased in the subsurface horizons, rising from 34% in the Ap horizon to 42-44% in the Btf horizons, suggesting a more favorable particle arrangement in these deeper layers (Table 2). This increase in porosity is indicative of improved soil structure in the subsurface, which may contribute to enhanced root development and water retention.

The *Abrupt Eutrophic Argissolo Amarelo* (Ultisol) (PA1) exhibits a horizon sequence of Ap, E, Bt, Btg1, and Btg2. The concave pedoform, in which the profile is situated, promotes imperfect drainage conditions, leading to the occurrence of reduction reactions and the development of gleization (g). The color profile shows a 10YR hue in the Ap, E, and Bt horizons, while the Btg1 and Btg2 horizons present a variegated coloration, consisting of red (2.5YR 4/8), gray (10YR 6/1), and brownish yellow (10YR 6/6) tones. These color variations are attributed to fluctuations in the water table, which influence the soil's redox conditions and contribute to the distinct hues observed in the deeper horizons.

The root distribution varies across the soil profile, with many thick roots present in the Ap horizon, medium and thin roots common in the E and Bt horizons, fewer medium and thin roots in the Btg1 horizon, and rare thin roots in the Btg2 horizon. A noticeable increase in clay content is observed from the Bt horizon onwards (Table 2), resulting in a textural gradient of 1.88. The Btg1 horizon exhibits a very hard consistency when dry, firm when wet, and plastic and sticky when saturated, which presents a significant barrier to root growth (Kahsay et al., 2023). This physical property must be considered when selecting sites for fruit crop cultivation in the São Francisco Valley, as it could restrict root development and overall plant growth (Gomes et al., 2024; Queiroz et al., 2018).

The water-dispersed clay content was notably high in the deeper horizons of the PA1 profile, distinguishing it from the other soils studied and resulting in a lower degree of flocculation (Table 2). This high dispersion is likely associated with deep gleyization processes, where Fe^{3+} is reduced to Fe^{2+}, a more soluble form that is easily leached from the system. This reduction process may lead to the predominance of negative charges in the soil, which contributes to the greater dispersion of soil particles. Additionally, the higher magnesium content (7 $cmol_c\ kg^{-1}$) compared to calcium (5.3 $cmol_c\ kg^{-1}$) in the Btg2 horizon may further promote the dispersion of soil particles, as Mg tends to weaken soil structure by displacing calcium from the exchange sites. In contrast, surface horizons typically exhibit high WDC values in cultivated soils, primarily due to the effects of surface tillage, fertilizer application, and organic matter amendments, which can disrupt soil aggregation and increase particle dispersion (Macedo et al., 2024).

Bulk soil density was notably higher in the gleyed horizons (Btg1 and Btg2), which can be attributed to compaction induced by the overlying layers' mass and the elevated moisture content in these horizons. High moisture levels generally reduce the soil's load-carrying capacity, as the soil reaches a plastic state, making it more prone to non-recoverable deformations. This condition significantly increases the risk of compaction, particularly when the soil is subjected to mechanical traffic (Braga et al., 2015; Long et al., 2023). Given that viticulture in this region relies heavily on irrigation, it is crucial to monitor soil moisture levels closely and assess the water retention capacity of these soils. This will help mitigate the potential for soil degradation and improve the sustainability of vineyard operations.

The *Abrupt Eutrophic Argissolo Amarelo* (Ultisol) (PA2) profile extends to depths greater than 150 cm and consists of a sequence of Ap, A, E, Bt, and Btc horizons. The transitions between the Ap, A, and E horizons are clear and flat, while the transition between the E and Bt horizons is abrupt and flat, and the boundary between the Bt and Btc horizons is diffuse and flat. At depths greater than 120 cm (Btc), iron (c) concretions are present, where Fe minerals from plinthite have become more consolidated into petroplinthites (Scarciglia et al., 2023; Santos et al., 2018). This consolidation likely occurred due to the accumulation of water at this depth, followed by lateral drainage, which resulted in irreversible drying and subsequent hardening of the material into a more compacted and cemented form.

The soil color in the Abrupt Eutrophic Argissolo Amarelo (Ultisol) (PA2) profile is characterized by a 10YR hue in the Ap, A, and E horizons, extending to a depth of 70 cm. Below this, the Bt horizon exhibits a 7.5YR hue with red mottling (2.5YR 4/6), while the Btc horizon displays a variegated coloration, composed of dark red (2.5YR 3/6), yellowish-brown (10YR 5/6), and brownish-yellow (10YR 5/8) hues. The soil structure is generally weak and fine, with the Ap, A, and E horizons exhibiting a non-plastic, non-sticky consistency. The Bt horizon has a plastic and sticky consistency, and the Btc horizon is slightly plastic and sticky. These soil characteristics are attributed to the rocky nature of this profile, with only 30% of the material being fine earth (<2 mm), while the remaining 70% consists of gravel and pebbles (Mendoza et al., 2023; Santos et al., 2015) (Table 2). This rocky composition significantly influences soil consistency and structure, particularly in the deeper horizons.

Despite the increase in clay content with depth, the textural composition of the soil contributed to elevated bulk density values (Hailemariam et al., 2023; Maurya et al., 2020). In the deeper horizons, bulk soil density exceeded the critical threshold of 2.07 kg dm³ in the A horizon. High bulk density can restrict root growth and lead to significant root deformation, such as thickening and concentration in the surface layers. However, each soil type has a critical density beyond which resistance becomes so high that it impedes or even halts root growth (Topa et al., 2021). This soil profile is classified as moderately drained, with total porosity values of 52% in the Ap horizon and 33-31% in the clay-rich Bt and Btc horizons. These values suggest that while bulk density is elevated in the subsurface, it may not be detrimental to root growth, as a considerable number of roots were observed in the Ap and A horizons, fewer in the E horizon, and sparse in the deeper Btf1 and Btf2 horizons. This pattern of root distribution aligns with the changes in soil porosity and the physical conditions of each horizon.

Table 1. Morphological characteristics of wine soils of the Sub-middle São Francisco Valley.

Horizons		Color Munsell	Texture	Structure [1]	Consistency	
Symbol	Depth (cm)				Moist [2]	Wet[3]
PVA - plintosolic abrupt eutrophic Ultisol						
Apf	0-30	10YR 3/3	Sandy loam	W, P/M, G/BA	F	PL / St
Btf1	30-75	5YR 4/6 10YR 4/6	Clay	Mo, P, BA	F	PL / St
Btf2	75-100	5YR 5/6 10YR 6/1	Clay	Mo, P/M, BA	MF	PL / St
Btf3	100-123	2,5Y 6/3 10YR 4/6	Clay	W, P/M, BA	Fr	Sp / Ss
Cr	123-160⁺	-	Clay	-	-	-
PA1 – abrupt eutrophic Ultisol						
Ap	0-20	10YR 3/2	Sandy clay loam	W, S/M, G/BA	F	PL / St
E	20-37	10YR 5/4	Sandy loam	Massive	Fr	NPL / Ss
Bt	37-80	10YR 5/6 2,5YR 4/8	Clay	Mo, S/M, BA	F	PL / St
Btg1	80-120	2,5YR 4/8 10YR 6/1 10YR 6/6	Clay	Mo/ St, S/M, BA	Vh/F	PL / St
Btg2	120-150⁺	2,5YR 4/8 10YR 6/1 10YR 6/6	Clay	M, M, BA	Vh/ MF	PL / St
PA2 – abrupt eutrophic Ultisol						
Ap	0-20	10YR 3/2	Sandy loam	W, S, G	MFr	NPL / NS
A	20-40	10YR 4/3	Sandy loam	W, S, G/BA	L/Fr	NPL / NS
E	40-70	10YR 5/3	Sand loam	W, S, G/BS/BA	Sh/MFr	NPL / NS
Bt	70-120	7,5YR 4/4 2,5YR 4/6	Clay	W, S/M, BA	F	PL / St
Btc	120-150⁺	2,5YR 3/6 10YR 5/6 10YR 5/8	Clay	W, S, BA	Sh	Sp / St
PA3 – plintosolic abrupt eutrophic Ultisol						
Ap	0-25	10YR 3/2	Sandy loam	W, S, G/BS	MFr	Sp / Ss
Bt	25-57	10YR 5/6 10R 3/6	Clay	W, S/M, BA	Fr	Sp / Ss
Btf	57-86	10YR 5/4 10R 4/6	Clay	W, S, BA	Fr	Sp / Ss
Btfc	86-130⁺	2,5YR 3/6 2,5YR 4/8 10YR 5/4 10YR 6/1 10YR 6/6	Clay	Mo, S/M, BA	Vh/F	Sp / Ss
PA4 – plintosolic abrupt eutrophic Ultisol						
Ap	0-25	10YR 4/2	Sand loam	W, S/M, BS	L/F	NPL / NS
Bt	25-60	10YR 4/6	Sandy clay loam	W, S/M, BA	L/Fr	Sp / NS
Btf1	60-90	10YR 4/4 10R 6/1 2,5YR 4/8	Clay	Mo, S/M, BA	Fr	Sp / Ss
Btf2	90-130⁺	10YR 5/6 10YR 5/2 2,5YR 4/8	Clay	Mo, S/M, BA	L/F	Sp / Ss

Structure: W: weak; Mo: moderate; St: strong; S: small; M: medium; G: granular; BA: angular blocks; BS: subangular blocks; Consistency: F: firm; MF: Very firm; Fr: friable; Vh: Very hard; MFr: very friable; L: lasts;

Sh: Slightly hard; PL: plastic; St: sticky; Sp: slightly plastic; Ss: slightly sticky; NPL: non-plastic; NS: Not sticky.

Table 2. Physical characteristics of wine soils of the Sub-middle São Francisco Valley.

Horizons		**Total sample fractions**			**TFSA particle size composition**				**WCD**	**FD**	**Bd**	**Pd**	**Tp**
Symbol	Depth	PE	GR	TADE	Coarse sand	Fine sand	Silt	Clay					
	cm	%			g kg^{-1}				g kg^{-1}	%	kg dm^{-3}		%
PVA – plintosolic abrupt eutrophic Ultisol													
Apf	0-30	0	4	96	242	411	159	188	146	22	1.63	2.74	34
Btf1	30-75	0	15	85	130	224	168	479	24	95	1.56	2.71	42
Btf2	75-100	0	10	90	102	217	197	483	0	100	1.63	2.79	42
Btf3	100-123	0	8	92	112	265	214	410	0	100	1.53	2.74	44
Cr	123-160$^+$	5	53	42	83	220	238	459	0	100	-	2.76	-
PA1 – abrupt eutrophic Ultisol													
Ap	0-20	0	4	96	239	372	139	250	147	41	1.68	2.71	37
E	20-37	0	2	98	270	426	132	172	124	28	1.73	2.75	32
Bt	37-80	0	4	96	129	240	158	472	0	100	1.69	2.77	36
Btg1	80-120	0	12	88	119	241	157	483	12	98	1.88	2.75	32
Btg2	120-150$^+$	0	15	85	97	222	218	463	232	50	1.91	2.78	31
Ap	0-20	25	46	29	200	387	238	175	73	58	1.27	2.67	52
A	20-40	22	48	30	204	494	170	132	74	44	2.07	2.78	26
E	40-70	18	45	37	245	513	123	119	66	45	2.04	2.80	27
Bt	70-120	28	42	30	116	227	190	468	0	100	1.88	2.79	33
Btc	120-150$^+$	9	48	43	72	167	277	483	0	100	1.96	2.83	31
PA3 – plintosolic abrupt eutrophic Ultisol													
Ap	0-25	3	25	72	267	472	112	150	74	51	1.59	2.71	40
Bt	25-57	4	53	43	165	264	107	464	231	50	1.79	2.70	34
Btf	57-86	3	54	43	116	227	179	478	0	100	1.87	2.71	31
Btfc	86-130$^+$	4	63	33	114	227	201	458	0	100	1.82	2.79	35
PA4 – plintosolic abrupt eutrophic Ultisol													
Ap	0-25	0	4	96	322	468	80	130	72	45	1.27	2.76	51
Bt	25-60	0	6	94	288	399	73	240	194	19	1.58	2.75	34
Btf1	60-90	0	9	91	154	233	135	478	0	100	1.74	2.74	36
Btf2	90-130$^+$	0	10	90	137	228	135	500	0	100	1.72	2.76	38

PE: pebbles; GR: gravels; TADE: thin air-dried earth; WDC water-dispersed clay; FD: flocculation degree; Bd: bulk density; Pd: particle density; Tp: total porosity.

The Plintosolic Abrupt Eutrophic Argissolo Amarelo (Ultisol) PA3 profile extends beyond 130 cm in depth and consists of the following horizons: Ap, Bt, Btf, and Btfc. The transition between the Ap and Btf horizons is clear and flat, while the Bt horizon shows a diffuse and flat transition. The Ap, Bt, and Btf horizons are characterized by a 10YR hue, with the Bt horizon exhibiting dark red mottling (10R 3/6) and the Btf horizon displaying red (10R 4/6) interspersed with plinthite (f). The Btfc horizon is variegated, with a complex color composition including dark red (2.5YR 3/6), red (2.5YR 4/8), yellowish brown (10YR 5/4), gray (10YR 6/1), and brownish yellow (10YR 6/6), along with a significant presence of gravel-sized ferruginous concretions (c) (Table 2).

The soil structure is generally weak, with small to medium angular blocks, except for the Ap horizon, which exhibits a granular structure with subangular blocks. The flocculation degree of the plinthite-rich horizons (Btf and Btfc) is 100%, indicating a high level of soil aggregation in these layers. Additionally, the particle density in these horizons is 2.71 and 2.79 kg dm³, respectively, suggesting that the presence of iron oxides, particularly in the plinthite content, plays a significant role in particle aggregation and the overall soil structure (Dong et al., 2023). These characteristics highlight the influence of iron-rich minerals on soil physical properties, contributing to the formation of dense, compact horizons with distinct redox features.

The soil consistency throughout the profile is slightly plastic and slightly sticky, which facilitates mechanization despite the presence of stony fragments, including pebbles and gravel. Root distribution shows a predominance of very thick and medium-sized roots in the Ap horizon, with progressively thinner roots in the deeper horizons. A noticeable horizontal orientation of roots is observed at the top of the Btf horizon, likely due to the high bulk soil density (1.87 kg dm³) in this clay-textured horizon, a value that falls outside the range typically considered optimal for this soil texture (Koudahe et al., 2022). This increased density may impede root penetration and growth, particularly in the subsurface layers, highlighting the importance of managing soil compaction and ensuring adequate aeration in viticultural practices.

The *Plintosolic Abrupt Eutrophic Argissolo Amarelo (Ultisol)* (PA4) profile extends beyond 130 cm in depth and contains a small amount of gravel (Table 2). The horizon sequence includes Ap, Bt, Btf1, and Btf2, with clear and flat transitions between the Ap and Bt horizons, and a diffuse, flat transition between the Bt and Btf1 horizons. The color of the soil is characterized by a 10YR hue in the Ap and Bt horizons, with variegated colors in the Btf1 horizon, including dark yellowish-brown (10YR 4/4), gray (10YR 6/1), and red (2.5YR 4/8). The Btf2 horizon shows a further variegation, with yellowish-brown (10YR 5/6), grayish-brown (10YR 5/2), and red (2.5YR 4/8) hues. This soil profile is well-drained, with a noticeable presence of thick roots in larger amounts in the Ap horizon, and progressively fewer roots in the subsequent horizons.

Medium and thin roots are common in the Bt and Btf1 horizons, while thin roots are rare in the Btf2 horizon. The distribution of roots appears to be related to the textural composition, with higher sand content in the Ap (790 g kg^{-1}) and Bt (687 g kg^{-1}) horizons, creating a textural gradient of 1.84. The soil structure is weak, consisting of small to medium subangular blocks in the Ap and Bt horizons, while the Btf1 and Btf2 horizons exhibit a more moderate structure, with small to medium angular blocks. This variability in structure and texture may influence root penetration and soil aeration, with implications for the cultivation of crops such as vines (Hunter et al., 2024).

The consistency of the *Plintosolic Abrupt Eutrophic Argissolo Amarelo (Ultisol)* (PA4) profile exhibits notable variation across different horizons. When dry, the consistency is hard throughout all horizons. Upon wetting, the consistency is firm in the Ap and Btf2 horizons, friable in the Bt and Btf1 horizons, and non-plastic and non-sticky in the Ap horizon, slightly plastic and non-sticky in the Bt horizon, and slightly plastic and slightly sticky in the Btf1 and Btf2 horizons. Consistency, which reflects the physical cohesion between soil particles and adhesion to other materials, varies with moisture content (Cheng et al., 2021). Therefore, optimal soil management should be guided by maintaining appropriate moisture levels to minimize compaction and improve workability, reducing traction effort during mechanization and preventing excessive compaction.

Bulk soil density increases with depth (Table 2), which can be attributed to several factors, including lower organic matter content, reduced aggregation, fewer roots, and compaction from the overlying layers. Additionally, the gradual increase in gravel content further contributes to the increase in soil density at greater depths (Blanco-Canqui & Ruis, 2020). These factors highlight the importance of considering soil consistency and bulk density when managing vineyard soils, as they influence root growth, water retention, and overall soil health.

Chemical attributes

The chemical attributes of the soil, including both macro and micronutrients, are presented in Tables 3 and 4, respectively. The *Plintosolic Abrupt Eutrophic Argissolo Vermelho-Amarelo (Ultisol)* (PVA) exhibited a pH value in the surface horizon that is considered optimal for grapevine growth, falling within the range where nutrients are generally available to plants (van Leeuwen, 2022). The concentrations of calcium, magnesium, and potassium were also within favorable levels for plant nutrition, except for Mg, which was slightly elevated concerning the Ca ratio. This imbalance, however, did not appear to significantly affect the overall nutrient availability in the soil.

The observed nutrient levels are reflected in a favorable sum of bases, which can be attributed to the soil's organic matter content and clay fraction. These factors contribute to a good cation exchange capacity, enhancing the soil's ability to retain and supply essential nutrients for vine growth. The high CEC also suggests that this soil is capable of supporting healthy vine development, provided that proper management practices are applied to maintain nutrient balance and prevent potential imbalances that could hinder plant growth.

In the subsurface horizons, a decrease in pH values is observed, which are considered low according to Gomes et al. (2021), potentially leading to increased leaching of macronutrients. However, in the subsurface horizon Btf1, there is an increase in the values of Ca, Mg, and Na, while the subsequent horizons remain within the same range as the surface horizon. These values may be associated with organic matter and clay content, as, despite the depth, the organic carbon content remains adequate, according to Chen et al. (2023). Additionally, being classified as an Argissolo, the clay content tends to increase with depth, contributing to a higher proportion of micropores. The available phosphorus decreases significantly in the subsurface horizons due to its low mobility in the soil. Regarding micronutrients, all values in the surface horizon are considered adequate, as reported by Fracetto et al. (2023).

Abrupt eutrophic Argissolos Amarelos (Ultisols) (PA1 and PA2) exhibit similar chemical profiles. The pH is not suitable for agricultural use, being high in the surface horizons and low in the subsurface horizons (Nguyen, 2023). The contents of Ca, Mg, and K range from high to moderate along the profiles, resulting in high base saturation values. An increase in Na is observed at the Bt horizon of PA1, which may be related to the reduced free drainage at the E horizon, due to the massive structure and high bulk density of the soil (1.73 kg dm^{-3}). Available phosphorus is very high throughout most of the profile, likely due to the residual effects of fertilizers, as well as the high organic matter content, with carbon levels also remaining elevated along the profile (Francaviglia et al., 2023).

Table 2 shows that the bulk soil density in these profiles is high, which impedes soil drainage. Iron (Fe) content is low in the PA3 Ap horizon, while it ranges from moderate to very high in the other horizons of these soils. Manganese, copper, and zinc contents are high in the surface horizons and decrease to medium to low levels in the subsurface horizons. However, in PA2, these values remain high throughout most of the profile.

The *Plintosolic Abrupt Eutrophic Argissolos Amarelos* (Ultisol) (PA3 and PA4) exhibit similarities in their chemical composition, with both profiles showing a consistently high pH across the horizon sequence. For optimal nutrient absorption, the pH is typically recommended to fall between 6.0 and 6.5 (Morais et al., 2022). In both profiles, the calcium and magnesium concentrations in the surface horizons are within suitable ranges for vine growth, though in PA3, the Ca content increases with depth. Conversely, potassium levels decrease substantially in the subsurface horizons, while sodium content rises, resulting in an elevated Na ratio that could potentially favor Na uptake by the plants.

Phosphorus availability is limited in both profiles, with PA3 showing consistently low P levels throughout the profile. In PA4, the P content is adequate only in the Ap horizon. The elevated sand and gravel content in PA3, coupled with low organic carbon levels in the subsurface horizons, likely facilitates the leaching of essential nutrients like phosphorus (Queiroz et al., 2018). While manganese levels are slightly below optimal in the surface horizons of both soils, the concentrations of other nutrients remain adequate for grapevine cultivation (Souza Leão et al., 2024). These findings underscore the importance of monitoring nutrient dynamics, especially P and K, to ensure balanced nutrition for grapevines in these soils.

Table 3. Chemical characteristics of wine soils of the Sub-middle São Francisco Valley.

Horizons		pH		Assortment complex								V	P	TOC
Symbol	Depht	H_2O	KCl	Ca	Mg	K	Na	SB	Al	H+Al	CEC			
	cm			cmol$_c$ kg^{-1}								%	mg kg^{-1}	g kg^{-1}
PVA – plintosolic abrupt eutrophic Ultisol														
Apf	0-30	6.0	5.3	3.5	2.8	0.20	0.02	6.5	0.0	2.6	9.1	71	125	8.97
Btf1	30-75	4.9	3.8	4.4	3.5	0.18	0.06	8.1	0.5	3.8	11.9	68	18	8.84
Btf2	75-100	4.9	3.9	3.4	2.1	0.14	0.08	6.2	0.4	4.3	10.0	57	2	7.70
Btf3	100-123	4.8	4.1	2.0	2.4	0.18	0.15	6.1	0.1	2.9	7.6	62	1	4.72
Cr	123-160$^+$	5.0	4.5	2.6	2.9	0.08	0.47	6.1	0.0	3.0	9.1	67	1	4.72
PA1 – abrupt eutrophic Ultisol														
Ap	0-20	6.8	5.9	4.6	3.9	0.21	0.06	8.8	0.0	1.7	10.5	84	104	19.08
E	20-37	6.4	5.3	2.2	0.8	0.15	0.10	3.3	0.0	1.9	5.2	63	118	6.05
Bt	37-80	4.6	3.8	3.9	4.2	0.10	0.66	8.9	0.4	3.0	11.9	75	28	5.48
Btg1	80-120	5.4	4.2	4.7	3.8	0.24	0.14	8.9	0.0	1.4	10.3	86	2	4.02
Btg2	120-150$^+$	6.4	5.1	5.3	7.0	0.08	0.54	12.9	0.0	1.3	14.2	91	2	3.07
PA2 – abrupt eutrophic Ultisol														
Ap	0-20	7.6	7.3	7.8	4.4	0.84	0.17	13.2	0.0	0.1	13.3	99	436	24.94
A	20-40	7.0	6.0	3.6	2.4	0.20	0.06	6.3	0.0	1.4	7.7	82	234	8.65
E	40-70	6.5	5.5	2.2	2.1	0.15	0.02	4.5	0.0	1.7	6.2	72	97	5.73
Bt	70-120	4.9	3.8	3.3	3.4	0.12	0.08	6.9	0.5	4.5	11.4	61	116	7.51
Btc	120-150$^+$	5.3	4.4	3.9	4.4	0.25	0.08	8.9	0.1	2.4	11.0	78	2	4.84
PA3 – plintosolic abrupt eutrophic Ultisol														
Ap	0-25	6.8	5.8	3.7	2.1	0.17	0.11	6.1	0.0	1.7	7.8	78	9	17.62
Bt	25-57	6.7	5.1	4.6	1.8	0.04	0.16	6.6	0.0	1.2	7.8	85	0	6.81
Btf	57-86	6.6	5.1	4.8	1.6	0.02	0.12	6.5	0.0	1.2	7.7	84	1	4.91
Btfc	86-130$^+$	6.4	5.2	4.3	2.0	0.02	0.11	6.4	0.0	1.4	7.8	82	0	5.16
PA4 – plintosolic abrupt eutrophic Ultisol														
Ap	0-25	7.2	6.2	3.4	0.8	0.32	0.08	6.8	0.0	1.0	5.6	82	24	9.10
Bt	25-60	7.0	5.3	1.8	2.1	0.05	0.10	4.1	0.0	1.2	5.3	77	14	3.13
Btf1	60-90	5.2	4.2	2.8	1.9	0.05	0.16	4.9	0.2	2.1	7.0	70	0	4.21
Btf2	90-130$^+$	4.8	4.0	2.8	1.9	0.08	0.09	4.9	0.5	3.0	7.9	62	0	3.00

Ca: exchangeable calcium; Mg: exchangeable magnesium; K: exchangeable potassium; Na: exchangeable sodium; SB: sum of bases; Al: exchangeable aluminum; H + Al: exchangeable hydrogen + aluminum; CEC: cation exchange capacity at pH 7; V: base saturation; P: phosphorus; TOC: total organic carbon.

Table 4. Descriptive analysis of leaves of vines grown in the Sub-middle São Francisco Valley.

Descriptive statistic	Nutrients in the leaves								
	P	K	Ca	Mg	Na	Cu	Fe	Mn	Zn
	g kg^{-1}				mg kg^{-1}				
cv. Tempranillo									
PVA – plintosolic abrupt eutrophic Ultisol									
Average	2.5 **a**	8.6 **a**	29.3 **a**	4.0 **a**	43.3 **a**	605.6 **a**	236.6 **a**	370.6 **a**	68.3 **a**
Median	2.5	8.5	30.0	4.1	40.0	599.0	235.0	365.0	65.0
SD	0.38	1.26	3.31	0.36	5.77	26.63	15.57	20.11	8.50
CV (%)	14.8	14.52	11.30	9.12	13.32	4.40	6.58	5.42	12.45
PA1 – abrupt eutrophic Ultisol									
Average	2.1 **a**	7.0 **a**	30.2 **a**	3.8 **a**	33.3 **a**	577.6 **a**	293.6 **a**	298.3 **a**	66.3 **a**
Median	2.2	7.0	32.1	3.8	30.0	547.0	306.0	324.0	68.0
SD	0.08	0.50	3.53	0.19	5.77	60.18	34.21	52.44	4.73
CV (%)	3.75	7.14	11.65	4.87	17.32	10.42	11.65	17.58	7.12
PA2 – abrupt eutrophic Ultisol									
Average	2.5 **a**	8.5 **a**	30.6 **a**	3.0 **a**	30.0 **a**	616.0 **a**	280.0 **a**	339.0 **a**	66.0 **a**
Median	2.6	9.0	29.6	3.1	30.0	629.0	285.0	331.0	66.0
SD	0.21	1.80	2.27	0.43	10.00	29.72	11.36	34.70	2.00
CV (%)	8.26	21.21	7.41	14.25	33.33	4.82	4.06	10.24	3.03
cv. Syrah									
PA3 – plintosolic abrupt eutrophic Ultisol									
Average	1.5 **a**	15.5 **a**	22.4 **a**	1.9 **a**	273 **a**	3.3 **a**	283.3 **a**	144.6 **a**	181 **a**
Median	1.5	15.5	23.5	1.9	270.0	1.0	324.0	144.0	182.0
SD	0.10	0.00	3.00	0.15	15.28	4.04	75.69	29.01	2.52
CV (%)	6.95	0.00	13.42	7.90	5.59	121.24	26.71	20.05	1.39
PA4 – plintosolic abrupt eutrophic Ultisol									
Average	1.4 **a**	18.1 **a**	20.8 **a**	1.5 **a**	276 **a**	1.6 **a**	286.6 **a**	165.3 **a**	147 **a**
Median	1.3	16.5	20.0	1.6	270.0	2.0	279.0	161.0	156.0
SD	0.21	3.33	1.93	0.25	20.82	0.58	14.15	10.21	22.87
CV (%)	14.27	18.33	9.27	16.06	7.52	34.64	4.94	6.18	15.56

P: phosphorus; K: potassium; Ca: calcium; Mg: magnesium; Na: sodium; Cu: copper; Fe: iron; Mn: manganese; Zn: zinc; SD: standard deviation; CV: coefficient of variation. Means followed by the same letter in the column do not differ by Tukey's test at 5% probability.

Leaf analysis

Nutrient contents in the leaf samples of *Tempranillo* and *Syrah* grapevines were found to be similar across the different soil types, with no statistically significant differences observed between them (Table 4). This indicates that the higher nutrient concentrations observed in the chemical analysis of the soils (Table 3) did not result in corresponding changes in the nutrient content of the grapevine leaves. Specifically, the highest base saturation was observed in the Ap horizon (20–30 cm) of PA2 for the *Tempranillo* variety. Despite the greater availability of nutrients in the soil, their absorption by the vines remained unaffected. Similarly, Silva et al. (2024) found that in their study of fertigation applications to *Syrah* vines during the maturation phase, the nutrient content in the leaves did not significantly respond to varying fertigation doses. These findings suggest that factors beyond soil nutrient availability, such as plant-specific uptake mechanisms or environmental conditions, may play a more crucial role in determining nutrient status in grapevine leaves.

Leaf nutrient contents were compared with the reference values proposed by Silva et al. (2023). It was observed that the cv. Tempranillo meets the macronutrient requirements for phosphorus, calcium, and magnesium within the adequate sufficiency range for vines in the São Francisco Sub-Middle Valley (2.0-3.0; 20-35; 3.0-5.0 g kg^{-1} for P, Ca, and Mg, respectively), with potassium content being deficient (<12.0 g kg^{-1}). Since soil Ca levels are significantly higher than K levels (Table 3), there may be greater Ca uptake by plant roots due to the unbalanced Ca ratio, particularly in the subsurface horizons.

The micronutrient contents of copper, iron, manganese, and zinc were found to be excessive in *Tempranillo* grapevines, with concentrations surpassing the recommended ranges for optimal vine growth (>20 mg kg^{-1} for Cu, >180 mg kg^{-1} for Fe, >300 mg kg^{-1} for Mn, and >50 mg kg^{-1} for Zn). In contrast, *Syrah* grapevines exhibited an excessive range for Fe and Zn, a deficient range for Cu (<10 mg kg^{-1}), and appropriate levels for Mn (80-300 mg kg^{-1}). No toxic levels of sodium (Na) were detected in the leaf samples (Table 3). However, in the PA3 and PA4 profiles, significant decreases in potassium and increases in sodium were observed in the subsurface horizons, resulting in a very high Na ratio. This imbalance likely explains the elevated sodium concentrations in *Syrah* leaves. Root cells exhibit a high affinity for potassium and sodium transport, and according to Ramos and Romero (2017) and Payan et al. (2023), potassium is a critical cation for vine health, influencing wine quality by affecting its pH. Potassium contributes to the reduction of wine acidity through the salification of tartaric acid, thus impacting the typicality and overall quality of the wine produced.

Conclusions

The Argissolo Amarelo soils of the São Francisco Valley exhibit significant levels of carbon and phosphorus across their horizons, both of which are crucial for soil fertility and plant growth. However, the high bulk density and lower total porosity observed in the subsurface horizons hinder proper water infiltration, potentially limiting root access to water and nutrients. This physical characteristic may also restrict the overall health and development of grapevines, particularly during critical growth stages.

Interestingly, despite the higher nutrient reserves in these soils, the increased nutrient availability did not translate into greater nutrient absorption by the plants, particularly during the early phase of berry maturation. This suggests that factors such as soil compaction and water retention capacity may override the positive influence of nutrient-rich horizons, leading to suboptimal nutrient uptake. On the other hand, the Argissolo Vermelho-Amarelo (Ultisol) profile stands out as the most promising soil type for cultivating fine-quality grapes in the region. Its physical and chemical attributes such as better soil structure, lower compaction, and favorable nutrient balance make it more suitable for grapevine growth and productivity, particularly in the context of wine production.

Consequently, optimizing soil management practices in both Argissolos Amarelos and Argissolos Vermelhos-Amarelos, with an emphasis on improving water infiltration and nutrient availability, will be crucial for enhancing grape quality and ensuring the sustainability of viticulture in the São Francisco Valley.

Author Contributions

Conceptual idea: Santana, M.B.; Ribeiro Filho, M.R.; Pereira, G.L., Methodology design: Santana, M.B.; Ribeiro Filho, M.R.; Pereira, G.L., Almeida, B.G., Data collection: Santana, M.B.; Ribeiro Filho, M.R.; Pereira, G.L., Almeida, B.G., Data analysis and interpretation: Santana, M.B.; Ribeiro Filho, M.R.; Fracetto, F.J.C.; Fracetto, G.G.M. and Writing and editing: Santana, M.B.; Ribeiro Filho, M.R.; Fracetto, F.J.C.; Fracetto, G.G.M.

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