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Evaluation of soil chemical, physical and biological quality in an Amazonian agroforestry system as a basis for 'IrrigaPote' social technology

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A B S T R A C T

This study used an integrated approach to evaluate the soil chemical, physical, and biological quality within an agroforestry system located in the Cristo Rei community, municipality of Capitão Poço, Pará State, to provide a technical basis for implementing the social irrigation technology IrrigaPote. The results indicated acidic soil reaction (pH 5.26–5.30), low cation exchange capacity (< 4.0 cmolc dm^{-3}), and low levels of available phosphorus—attributes typical of Amazonian soils dominated by kaolinite and iron and aluminum oxides. Overall, the findings demonstrate that the agroforestry system evaluated promotes gradual improvement of soil quality.

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INTRODUCTION

Family farming plays a strategic role in food supply, income generation, and the promotion of socio-environmental sustainability in Brazil. This sector is responsible for a significant share of staple food production and performs a central function in ensuring food and nutritional security, while also contributing substantially to rural development. In the Amazonian context, its relevance becomes even more evident due to the edaphoclimatic particularities of the region, characterized by highly weathered soils, high rainfall, and pronounced environmental fragility—conditions that demand well adapted and ecologically balanced production systems.

Within this scenario, agroforestry systems (AFSs) emerge as productive arrangements capable of integrating agricultural production, environmental conservation, and the socio-economic strengthening of rural families. These systems represent a technically viable and environmentally sustainable alternative for family farming, particularly in tropical regions. The structural and functional diversity inherent to AFSs enhances nutrient cycling, ensures the continuous input of organic matter into the soil, and contributes to the progressive improvement of edaphic quality, as widely discussed in agroecological literature and sustainability-oriented studies on agroecosystems.

Soil degradation constitutes one of the main challenges to agricultural sustainability worldwide, undermining essential ecosystem functions, such as nutrient cycling, water retention, and carbon sequestration. In tropical regions, AFSs have been widely recognized as effective strategies for improving soil quality and increasing organic carbon stocks, thereby contributing simultaneously to environmental restoration and climate change mitigation.

Recent evidence further indicates that the adoption of AFSs can promote significant improvements in soil physical, chemical, and biological attributes, particularly when employed as a strategy for rehabilitating degraded areas. Studies demonstrate that the conversion of degraded pastures into AFSs results in substantial enhancements in soil properties, thereby contributing to the sustainability and resilience of Amazonian agroecosystems.

As a central component of agricultural ecosystems, soil performs fundamental functions related to water supply, nutrient availability, and physical support for plant development. Moreover, it acts as a biogeochemical regulator, a carbon reservoir, and a key element for maintaining the sustainability of productive systems. In Amazonian environments, characterized by naturally low fertility, high acidity, and reduced cation exchange capacity (CEC), soil conservation management becomes essential for sustaining agricultural productivity and the stability of agroecosystems.

THEORETICAL REVIEW

Several studies conducted in the Amazon indicate that agroforestry systems exhibit superior bioeconomic performance compared with conventional land-use systems, particularly when considering ecosystem services associated with nutrient cycling, productive stability, and greater resilience to climate change. However, the success of these systems is directly contingent on soil quality. Highly weathered tropical soils, often dominated by minerals like kaolinite and iron and aluminum oxides, present low cation exchange capacity and high acidity, factors that limit the retention and availability of essential nutrients for plant development.

In this context, the literature emphasizes that the adoption of AFSs contributes to the gradual improvement of soil chemical attributes, primarily through the increase in organic matter and organic carbon content. These components play a fundamental role in raising effective CEC, improving soil structure, and mitigating aluminum toxicity, thereby enhancing nutrient availability for plants.

Among essential nutrients, phosphorus stands out as one of the main limiting factors for productivity in tropical soils, due to its strong adsorption to iron and aluminum oxides. Even in conservation-oriented systems like AFSs, available phosphorus levels tend to remain low, requiring the adoption of specific management strategies, including localized fertilization and the strengthening of biological nutrient cycling.

In parallel with chemical and physical attributes, biological indicators of soil quality have gained prominence in sustainability assessments of agroecosystems. Enzymatic activity and soil quality indices (SQI) are considered sensitive tools for detecting changes resulting from management practices, as they reflect processes related to nutrient cycling, storage, and availability. Positive outcomes for these indicators have frequently been associated with well-managed AFSs, characterized by high organic residue input and elevated plant diversity.

Regarding water management, social irrigation technologies have been identified as promising alternatives to strengthen family farming in the Amazon. Recent evidence indicates that the efficiency of these technologies is directly associated with soil physical and biological conditions, in which systems with good water infiltration, high biological activity, and permanent vegetative cover are favored. In this regard, the integrated characterization of soil chemical, physical, and biological attributes is thus fundamental to support the adoption of social water management technologies, such as the IrrigaPote system.

Thus, the literature converges on the understanding that integrated soil quality assessment constitutes an essential approach for strengthening AFSs and for the efficient implementation of social irrigation technologies, particularly in Amazonian contexts. Accordingly, the present study aimed to characterize the main soil chemical, physical, and biological attributes in an AFS located in the Cristo Rei community, municipality of Capitão Poço, state of Pará, to provide technical support for implementing the social technology IrrigaPote, in line with recent scientific evidence on soil quality, agroecology, and sustainability in Amazonian environments.

METHODOLOGY

This study employed a mixed-methods approach (qualitative and quantitative) with an observational-descriptive design to characterize soil conditions prior to the implementation of the IrrigaPote social irrigation technology in the rural community of Cristo Rei, Vila Rural Barro Vermelho, Capitão Poço Municipality (figure 1a), Pará, Brazil, conducted from August 2023 to August 2024. The study site was purposively selected based on the representativeness of an agroforestry system (AFS) consisting of lemon cultivation associated with native tree species. Soil sampling was carried out using a non-probabilistic purposive technique at three depths (10 cm, 20 cm, and 40 cm) in areas with homogeneous topography, vegetation cover, and management practices to reduce spatial variability. Samples were collected using standardized procedures, properly labeled, and analyzed at the Embrapa Amazônia Oriental Soil Laboratory and the Soil & Plant Laboratory (Paragominas) for chemical (pH, organic matter, CEC, base saturation, macro- and micronutrients), physical (soil texture), and biological (microbial and enzymatic activity using BioAS) parameters. Data were analyzed descriptively using basic statistical comparisons across soil depths to support the evaluation of soil suitability for the adoption of the IrrigaPote irrigation technology (figure 1b) in sustainable agroforestry systems (figure 2).

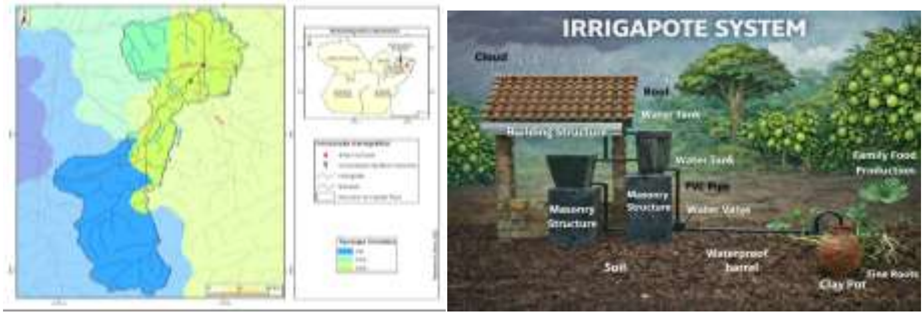

Figure 1 (a). Climatic typology map of the municipality of Capitão Poço, indicating the location of the Cristo Rei rural community, Vila Barro Vermelho. 2 (b) Simulation of the IrrigaPote system in the production area.

Figure 2. Map of the study area showing the location of the soil sampling points.

RESULTS AND DISCUSSION

The results of the chemical analysis of the soil from the AFS under study are presented in Table 1. Overall, a vertical distribution pattern typical of soils under systems with high organic residue deposition was observed, characterized by elevated levels of soil organic carbon and organic matter in the surface layer (0–20 cm). The soil organic carbon content was 20.02 g kg^{-1} in the surface layer, decreasing to 8.60 g kg^{-1} in the 20–40 cm layer. A similar trend was noted for soil organic matter, which measured 34.5 g kg^{-1} in the surface layer and decreased to 14.8 g kg^{-1} in the subsurface layer.

Table 1. Results of soil chemical analysis in the agroforestry system

Depth (cm)	C g kg^{-1}	OM g kg^{-1}	N %	N g kg^{-1}	C/N	P mg dm^{-3}	K mg dm^{-3}	Na cmolc dm^{-3}	Al cmolc dm^{-3}	Ca cmolc dm^{-3}	Ca+Mg cmolc dm^{-3}	pH H_2O	H+Al cmolc dm^{-3}	CEC cmolc dm^{-3}	Base saturation %	Al saturation %
0–20	20.02	34.5	0.04	0.40	49.67	1.43	12.68	3.75	0.15	1.20	1.65	5.30	2.18	3.87	43.85	8.11
20–40	8.60	14.8	0.04	0.38	22.92	0.72	14.13	1.88	0.23	0.84	1.29	5.26	1.99	3.32	40.17	14.70

This vertical distribution pattern is associated with the continuous input of litter, plant residues, and root exudates, which are characteristic of AFSs and promote greater incorporation of carbon into the soil surface. In highly weathered tropical soils, such vertical gradients are common and play a fundamental role in maintaining soil quality, contributing to improvements in structure, water retention, and nutrient cycling. The higher concentration of organic matter in the surface layer also directly influences the CEC, since a substantial portion of the negative charges in these soils is linked to the organic fraction.

The C/N ratio exhibited values of 49.67 in the 0–20 cm layer and 22.92 in the 20–40 cm layer. Higher values of this ratio indicate greater presence of organic residues still undergoing decomposition, characterizing an environment with recent inputs of plant material. This behavior is typical of tropical AFSs, in which species diversity and continuous biomass production favor nutrient cycling and the maintenance of soil fertility.

Regarding soil reaction, pH values in water were relatively similar between the layers evaluated, ranging from 5.30 in the surface layer to 5.26 in the subsurface layer. These values characterize a moderately acidic soil, a typical condition of highly weathered tropical soils in the Amazon region. According to, soils with pH in this range may present nutritional limitations, mainly related to low phosphorus availability and the presence of exchangeable aluminum.

Available phosphorus contents were low in both layers evaluated: surface layer, 1.43 mg dm^{-3}; and subsurface layer, 0.72 mg dm^{-3}. Low phosphorus availability is a common feature of highly weathered tropical soils, where this nutrient is often immobilized by adsorption processes in iron and aluminum oxides present in the soil mineral fraction. In AFS, however, part of this limitation may be mitigated by biological nutrient cycling, promoted by litter decomposition and the root activity of tree species.

Potassium contents were relatively similar between the two depths: surface layer, 12.68 mg dm^{-3} and subsurface layer, 14.13 mg dm^{-3}. This distribution may be related to the greater mobility of this nutrient in the soil profile, since potassium exhibits lower electrostatic retention compared with bivalent cations like calcium and magnesium.

With respect to basic cations, calcium and magnesium levels were slightly higher in the surface layer. The sum of Ca+Mg was 1.65 cmolc dm^{-3} in the 0–20 cm layer and 1.29 cmolc dm^{-3} in the 20–40 cm layer. This behavior may be associated with nutrient cycling processes promoted by organic residue deposition and soil biological activity.

Base saturation (V%) presented values of 43.85% in the surface layer and 40.17% in the subsurface layer, indicating intermediate levels of chemical fertility. According to fertility interpretation criteria for tropical soils, values within this range may be considered adequate for various agricultural systems, particularly when associated with conservation-oriented management practices.

In contrast, aluminum saturation (m%) was higher in the subsurface layer (14.70%) than in the surface layer (8.11%), indicating greater presence of exchangeable aluminum in the subsoil. Elevated aluminum concentrations in acidic soils may represent a limitation to root growth in certain crops, affecting nutrient and water uptake.

The CEC exhibited values of 3.87 cmolc dm^{-3} in the surface layer and 3.32 cmolc dm^{-3} in the subsurface layer. In highly weathered tropical soils, CEC tends to be relatively low due to the predominance of low-activity clays, such as kaolinite, and iron and aluminum oxides. In this context, organic matter plays a fundamental role in generating negative charges responsible for nutrient retention.

Overall, the results indicate that the AFS favors the accumulation of organic matter and contributes to the improvement of soil chemical quality, particularly in the surface layer. This behavior highlights the potential of AFS as a sustainable management strategy in tropical regions, promoting greater ecological stability and conservation of soil resources.

The results of the physical analysis of the AFS soil are presented in Table 2. The particle-size characterization of the surface layer (0–10 cm) indicated a predominance of the sand fraction (782.5 g kg^{-1}), followed by clay (175 g kg^{-1}) and silt (42.5 g kg^{-1}). According to textural classification, the soil was classified as medium-textured.

Table 2. Data from the physical analysis of soil in the Agroforestry System (AFS).

Sample description	**Depth (cm)**	**Clay (g kg^{-1})**	**Silt (g kg^{-1})**	**Total sand (g kg^{-1})**	**Soil type**	**Textural classification**
Soil	0–10	175	42.5	782.5	AD 3	Medium

Source: Laboratório de Solo & Plantas (2023)

The predominance of the sand fraction is a relatively common characteristic of many soils in the Amazon region, particularly in areas associated with sedimentary parent materials. According to, soils with a higher proportion of sand exhibit a lower specific surface area, which reduces their capacity for water retention and nutrient adsorption, thereby increasing susceptibility to leaching, especially under conditions of high rainfall.

Despite these inherent physical limitations associated with texture, AFS can significantly contribute to the improvement of soil physical properties over time. The continuous deposition of organic residues from litterfall, combined with the development of the root systems of both tree and crop species, promotes the formation of stable aggregates, enhances soil structure, and increases water-holding capacity. In this context, organic matter becomes a fundamental component in mitigating the limitations associated with sandy or medium-textured soils.

The clay content (175 g kg^{-1}) observed also plays an important role in water and nutrient retention dynamics. Although relatively low compared with more clay-rich soils, this fraction can contribute to the formation of organo-mineral complexes when associated with SOM, thereby enhancing CEC and structural stability. In highly weathered tropical soils, the interaction between organic matter and fine mineral fractions represents one of the primary mechanisms for maintaining fertility and soil quality.

Another relevant aspect concerns the role of permanent vegetation cover, which is a defining feature of AFSs. Maintaining soil cover reduces the direct impact of rainfall on the surface, thereby minimizing erosive processes and favoring water infiltration into the soil profile. Furthermore, the diversified root systems of agroforestry species contribute to the formation of biopores, which increase porosity and facilitate the movement of water and air within the soil.
Thus, although medium-textured soils with a predominance of sand represent a natural limitation in terms of water and nutrient retention, the adoption of AFS can play a crucial role in the gradual improvement of soil physical properties, contributing to greater structural stability, enhanced water infiltration, and improved ecological functioning of the edaphic system.

The integration of chemical, physical, and mineralogical analyses provides a deeper understanding of the mechanisms responsible for maintaining fertility in the AFS evaluated. The results indicate that, although the soil exhibits a texture dominated by sand and a low-activity mineralogy, chemical fertility is strongly influenced by the presence of organic matter and the nutrient cycling dynamics promoted by the AFS.

Even with a relatively low clay content, the CEC presented moderate values, associated with intermediate levels of base saturation and low concentrations of exchangeable aluminum. This behavior indicates that soil chemical fertility is not primarily sustained by the mineral fraction, but rather by the organic fraction. In highly weathered tropical soils, where low-activity minerals predominate, organic matter often constitutes the main source of negative charges responsible for nutrient retention in the exchange complex.
To better understand the mineralogical factors associated with this chemical behavior, X-ray diffraction (XRD) analysis was performed. The obtained diffractograms revealed the predominance of quartz, kaolinite, and anatase, as illustrated in Figures 3 and 4.

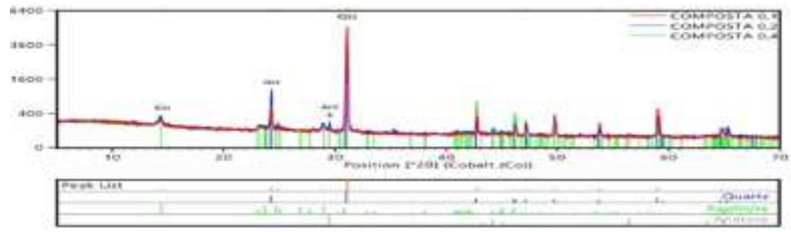

Figure 3. Superimposed X-ray diffraction patterns of soil samples from the agroforestry system

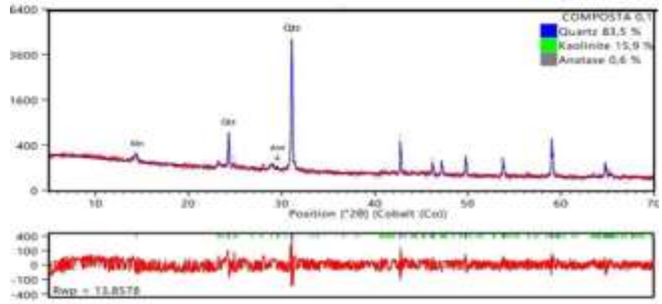

Figure 4. X-ray diffraction pattern of the composite soil sample, highlighting the dominance of quartz (Qtz)

Qualitative interpretation of the diffraction peaks revealed a dominant quartz peak near 26° (2θ), characteristic of this mineral, with high relative intensity compared with the other peaks observed. Kaolinite was identified by peaks around 12–13° and 24–25° (2θ), while less intense signals attributed to anatase were observed near 25° and 48° (2θ). Based on the relative intensity of the peaks, it can be qualitatively inferred that quartz represents the predominant mineral fraction, followed by kaolinite as the principal clay mineral, with anatase occurring as an accessory phase.

The predominance of quartz indicates a high degree of weathering and strong leaching throughout the pedogenetic process, as this mineral exhibits high resistance to chemical alteration and tends to remain as a residual component in highly weathered soils. The presence of kaolinite confirms the dominance of 1:1 clay minerals in the soil fraction, typical of tropical environments subject to intense chemical weathering. Minerals of this type exhibit low CEC compared with 2:1 minerals, such as smectites or vermiculites, thereby contributing to the low chemical activity of the soil mineral fraction.

The occurrence of anatase, a polymorph of titanium dioxide (TiO_2), is also frequently reported in highly weathered tropical soils and is associated with advanced stages of pedogenetic evolution. This mineral generally occurs as an accessory phase resistant to weathering and can serve as an indicator of the degree of mineralogical development of the soil.

The mineralogical association observed—dominant quartz, kaolinite as the principal clay mineral, and accessory resistant minerals—is typical of highly weathered soils in the Amazon region, such as Oxisols and Ultisols. Studies conducted in the Brazilian Amazon have demonstrated that these soils exhibit mineralogy dominated by kaolinite, iron oxides, and quartz, reflecting pedogenetic processes characterized by intense leaching and base removal over geological time.

In this context, the relationship between mineralogy, CEC, and soil carbon becomes fundamental to understanding fertility in these environments. In soils with mineralogy dominated by quartz and kaolinite, the contribution of the mineral fraction to CEC is relatively limited. Thus, organic matter assumes a central role in nutrient retention and the maintenance of chemical fertility. Functional organic compounds, present in humic substances, provide a high density of pH-dependent negative charges, functioning as important cation adsorption sites in the soil.

Accordingly, the accumulation of organic carbon observed in the surface layer of the AFS studied represents a key component in the functioning of the edaphic system. The interaction between organic matter, fine mineral fractions, and biological activity contributes to increased CEC, improved soil structure, and intensified nutrient cycling. This process reinforces the importance of AFS as sustainable management strategies in highly weathered tropical soils, since the continuous input of organic residues helps compensate for the limitations imposed by low-activity mineralogy.

The integrated interpretation of soil mineralogy and biological fertility indicators provides a broader understanding of the mechanisms responsible for maintaining soil quality in the AFS under study. The results indicate that, although the soil exhibits mineralogy typical of highly weathered environments, biological dynamics and organic matter accumulation play a central role in sustaining fertility and nutrient cycling.

Mineralogical analysis revealed the predominance of quartz in the sand fraction, a mineral characterized by high crystalline stability and the absence of permanent charges in its structure. Due to these properties, quartz does not directly contribute to the soil's CEC, thereby limiting the role of the mineral fraction in nutrient retention. Consequently, in soils with a high proportion of quartz, fertility maintenance depends strongly on the presence of organic matter and associated biological activity.

The presence of kaolinite as the principal clay mineral reinforces this interpretation. Kaolinite is a 1:1 mineral characterized by low intrinsic CEC and predominance of pH-dependent charges. Although its direct contribution to nutrient retention is relatively limited compared to 2:1 clay minerals, such as smectites or vermiculites, kaolinite plays an important role in soil structural stability and the formation of organo-mineral complexes. The interaction between kaolinite and organic matter contributes to the formation of stable aggregates and the physical protection of organic matter, aspects that are fundamental to maintaining soil quality in tropical environments.

Another mineral identified in the analysis was anatase (TiO_2), which occurs as an accessory phase in highly weathered soils. The presence of this mineral is associated with environments subjected to intense leaching of bases during pedogenesis, a condition typical of many tropical soils in the Amazon region. Although anatase does not directly participate in cation exchange processes, its surfaces may interact with organic compounds, favoring the physicochemical stabilization of SOM. This stabilization process is particularly important in tropical soils, where organic matter plays an essential role in nutrient retention and in regulating soil biological activity.

In this context, the interaction between low-activity mineralogy and organic matter emerges as one of the main factors responsible for maintaining soil fertility in AFS. The continuous deposition of litter and plant residues in these systems contributes to the increase of soil organic carbon, favoring the formation of organo-mineral complexes and enhancing nutrient retention capacity.

Biological indicators obtained through the analysis of soil biological fertility (FertBio) reinforce this interpretation. The results presented in Table 3 indicated high microbial activity in the evaluated soil.

Table 3. Soil fertility analysis (FertBio) in the agroforestry system using BioAS technology.

Sample	**System**	**Clay content (%)**	**Depth (cm)**	**Analysis**	**Arilsulfatase**	**β-glycosidase**	**SOM**
Soil	AFS	18	10	FetBio	97	63	23

Legend	very high	high	medium	low	very low

SOM, soil organic matter

Source: Laboratório de Solo & Plantas (2003)

The activity of the enzyme arylsulfatase exhibited values (97) classified as very high, which indicates intense mineralization and cycling of organic sulfur within the system. Arylsulfatase is considered an important indicator of microbial activity related to the sulfur cycle, reflecting the capacity of the soil microbiota to transform organic compounds containing this nutrient into plant-available forms.

Similarly, β-glucosidase activity also presented values (63) classified as high, indicating intense microbial activity associated with the carbon cycle. This enzyme is involved in the degradation of cellulose-derived compounds and other polysaccharides present in litterfall, and is regarded as one of the main indicators of organic matter decomposition dynamics in soil. Elevated β-glucosidase values generally reflect greater availability of organic substrates and enhanced microbial activity, characteristics frequently observed in AFS with high biomass productin.

FertBio analysis also revealed a SOM content of 23 g kg^{-1}, classified as medium to high, reinforcing the importance of continuous organic residue inputs in the functioning of the edaphic system. In AFS, species diversity and permanent soil cover favor litter deposition and stimulate soil microbiota activity, thereby promoting greater efficiency in nutrient cycling.

Although the soil exhibits mineralogy dominated by quartz and kaolinite—typical of highly weathered environments with low mineral activity—taken together, the mineralogical and biological results indicate that the high biological activity and accumulation of organic matter play a fundamental role in maintaining soil fertility in the AFS studied. The interaction between organic matter, microbial activity, and fine mineral fractions contributes to strengthening biogeochemical nutrient cycling and improving soil quality, highlighting the potential of AFSs as sustainable management strategies in tropical environments.

The integrated assessment of soil quality through biological, chemical, and functional indicators has been widely used to understand the capacity of agroecosystems to sustain essential ecological processes, such as nutrient cycling and storage. In this context, the synthetic SQIs obtained through FertBio analysis reinforce the interpretation that the AFS evaluated exhibits a high level of edaphic functionality (Table 4).

Table 4. Soil fertility analysis (FertBio) in the agroforestry system using BioAS technology.

Sample description	**SQI FertBio**	**SQI Biological**	**SQI Chemical**	**CYCLING nutrient**	**STORAGE nutrient**	**β-glycosidase**	**Methodology reference**
Soil	0.8	0.91	0.75	0.91	0.96	0.53	BioAS [51]

Legend	very high	high	medium	low	very low
	0.81 to 1	0.61 to 0.80	0.41 to 0.6	0.21 to 0.40	0 to 0.20

SQI, soil quality index

Source: Laboratório de Solo & Plantas (2023)

The FertBio SQI presented a value of 0.80, classified as high according to the interpretation criteria established for this methodology. This result indicates that the soil exhibits favorable conditions for the development of ecological functions associated with biological fertility. The high soil quality observed may be attributed to the presence of permanent vegetation cover and the continuous input of organic residues characteristic of AFSs, factors that stimulate microbial activity and intensify biogeochemical nutrient cycling.

The biological SQI presented a value of 0.91, classified as very high, evidencing elevated biological activity in the soil. This result indicates that the microbiological processes responsible for organic matter decomposition and nutrient mineralization are occurring intensively in the system studied. The high biological activity observed is consistent with the elevated values of soil enzymes previously discussed, particularly β-glucosidase and arylsulfatase, which act directly in the carbon and sulfur cycles.

Indices related to soil ecosystem functions also exhibited high values. The nutrient cycling index presented a value of 0.91, classified as very high, while the nutrient storage index attained 0.96, also classified as very high. These results indicate that the soil possesses a strong capacity to recycle nutrients derived from organic matter decomposition and to store them within the edaphic system, thereby ensuring greater nutritional stability for plants.

The high efficiency of these processes can be attributed to the dynamics of organic matter in AFSs. Continuous litter deposition, combined with species diversity and the development of deep and diversified root systems, promotes constant carbon inputs into the soil and stimulates microbial activity. This process results in greater efficiency in plant biomass decomposition and the gradual release of nutrients into the system.

The chemical SQI presented a value of 0.75, classified as high. This result indicates that, despite the low-activity mineralogy characteristic of highly weathered tropical soils, the soil's chemical attributes exhibit satisfactory fertility levels. This condition can largely be explained by the influence of organic matter and biological activity in nutrient retention and cycling, partially compensating for the limitations imposed by the mineral fraction.

Overall, the results corroborate the premise that biological soil indicators are highly sensitive to management practices and capable of reflecting soil system functionality in an integrated manner. Unlike isolated chemical indicators, biological indicators capture rapid responses to changes in the soil environment, making them particularly useful for assessing the sustainability of agricultural production systems.

In this regard, the high values of synthetic SQIs observed in the AFS studied demonstrate that agroforestry practices can significantly enhance soil biological and functional quality. The interaction between organic matter, microbial activity, and nutrient cycling contributes to the maintenance of fertility and the stability of ecological processes in the soil, reinforcing the role of AFSs as sustainable management strategies in tropical environments.

The stabilization of SOM constitutes one of the main processes responsible for maintaining fertility in highly weathered tropical soils. According to, SOM stabilization results from the interaction between microbial activity, soil aggregation, and physicochemical protection mechanisms, processes that are intensified in systems with high plant diversity and continuous organic residue inputs. In AFSs, the presence of multiple plant species and constant litter deposition favor the formation of stable aggregates and promote greater protection of organic matter against rapid decomposition, thereby contributing to soil carbon maintenance.

Although the soil mineralogy is dominated by low-activity minerals such as quartz and kaolinite, the integration of the results obtained in this study (Table 5) highlights that the system exhibits good edaphic functionality. In highly weathered tropical soils, chemical fertility is often not determined by the mineral fraction but by the interaction between organic matter, biological activity, and conservation-oriented management practices. This condition was observed in the AFS studied, where the presence of organic matter and high microbial activity compensate for the limitations imposed by low-activity mineralogy.

Table 5. Integration of mineralogy, chemical attributes, and biological indicators of soil in the agroforestry system

Component	**Characteristic**	**Implication for fertility**	**Relationship with FertBio**
Quartz	Dominant mineral, low reactivity	Does not contribute to CEC	Increases dependence on SOM
Kaolinite	1:1, clay mineral, low CEC	Limited cation retention	Fertility regulated by SOM and soil biota
Anatase	Accessory, highly weathered mineral	Indicator of leaching processes	Favors stabilization of SOM
Organic matter	Highly reactive	Main source of CEC	Stimulates β-glycosidase activity

Soil biota	High enzymatic activity	Enhances nutrient cycling	Elevates biological SQI

CEC, cation exchange capacity; SOM, soil organic matter; SQI, soil quality index.
Source: Produced by the authors

Taken together, the results demonstrate that the high biological indices observed in the AFS compensate for the limitations imposed by medium texture and the low mineral activity of the clay fraction. The interaction between organic matter, microbial activity, and soil structure promotes greater nutrient retention, improved structural stability, and increased resilience of the edaphic system to environmental disturbances. This behavior confirms the potential of AFSs as sustainable management strategies for improving soil quality in highly weathered tropical environments.

The integrated analysis of soil physical, chemical, biological, and mineralogical attributes highlights that the IrrigaPote system exerts a positive influence on the functioning of the AFS studied, particularly regarding water-use efficiency and system resilience to climatic variability. These effects are especially relevant given the edaphic characteristics observed, marked by medium texture and predominance of low-activity minerals, such as quartz and kaolinite, which exhibit reduced water retention capacity and limited contribution to CEC.

By promoting slow and continuous water release into the soil, the IrrigaPote system contributes to improved water-use efficiency in the AFS. Unlike conventional surface irrigation methods, where significant water losses may occur through evaporation or deep percolation, IrrigaPote operates in a localized subsurface manner, allowing greater utilization of water stored in the soil. This mechanism favors the maintenance of more stable moisture levels in the root zone, reducing water losses and increasing plant water availability. The stability of soil moisture also directly influences biological activity. The elevated activity of these enzymes suggests that the soil microbiota finds favorable conditions for development, likely associated with the greater moisture stability provided by the irrigation system.

FertBio analysis corroborates this interpretation, evidencing high nutrient cycling and storage indices in the soil. In soils with low-activity mineralogy, such as those observed in this study, fertility maintenance depends strongly on organic matter and microbial activity. The moisture stability promoted by IrrigaPote helps preserve the CEC associated with the organic fraction, considered the main driver of nutrient retention in these environments. Moreover, maintaining more constant moisture reduces base leaching processes and enhances the efficiency of biogeochemical nutrient cycling.

From the perspective of climate change, characterized by increasing rainfall irregularity and intensification of extreme drought and precipitation events, efficient water management technologies are becoming increasingly relevant for agroecosystem sustainability. In this regard, IrrigaPote can be considered an adaptive technology capable of reducing water stress for plants and soil biota by providing water gradually and continuously. Subsurface irrigation also contributes to reducing thermal amplitude in the root zone, creating a more stable environment for root development and microbial activity.

Another important aspect concerns soil carbon dynamics. The maintenance of more stable moisture levels may contribute to the conservation of carbon stocks, since frequent drying and rewetting cycles tend to accelerate organic matter mineralization and increase soil CO_2 emissions. By reducing hydric variability in the edaphic environment, the IrrigaPote system may contribute to the maintenance of soil organic carbon and to strengthening the structural stability of the edaphic system. Overall, the results indicate that the interaction between the IrrigaPote irrigation system, agroforestry management, and high soil biological activity promotes a functional synergy capable of compensating for the limitations imposed by medium texture and low-reactivity mineralogy. This interaction favors water and nutrient retention, improves structural stability, and intensifies biogeochemical cycling processes. Therefore, the use of IrrigaPote demonstrates the potential to enhance water-use efficiency and strengthen the sustainability of the AFS, contributing to greater productive and environmental stability under scenarios of increasing climatic variability.

CONCLUSIONS AND RECOMMENDATIONS

The results obtained demonstrate that the IrrigaPote system exerts a significant positive influence on both edaphic and productive environments, establishing itself as a strategic technology for climate change adaptation. This is particularly relevant in tropical soils of medium texture and low-activity mineralogy, where water and nutrient retention are naturally limited.

The localized subsurface irrigation provided by IrrigaPote enhances the efficiency of rainwater use by reducing losses through evaporation and deep percolation. This hydric stability favors soil biological activity, strengthens nutrient cycling, and contributes to the maintenance of soil organic matter, which serves as the primary regulator of fertility and cation exchange capacity in environments dominated by kaolinite clay minerals.

In a climate change scenario marked by increasing rainfall irregularity, prolonged drought periods, and rising temperatures, IrrigaPote functions as a mitigating element against water stress for both plants and soil biota, thereby promoting greater resilience of agroforestry systems.

Thus, it seems reasonable to conclude that IrrigaPote not only improves water-use efficiency, but also reinforces environmental sustainability and the adaptive capacity of agroecosystems in the face of climate change. It represents a viable alternative aligned with conservation-oriented management strategies in tropical regions.

FURTHER STUDY

Future studies are recommended to evaluate the application of IrrigaPote technology across different soil types and agroecological conditions to better assess its effectiveness and sustainability.

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