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Soil quality assessment on different land use types in the coastal saline acid sulfate soils of Can Gio District, Vietnam

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ABSTRACT

This study aims to use SQI to evaluate the quality of the saline acid sulfate soil in Can Gio district, Ho Chi Minh City, Vietnam, on different land use types, including annual crops (AC), perennial crops (PC), rice land (RL), aquaculture land (AL), and natural land (NL). The study employs the SQI formula to assess the soil quality index of 136 samples from two distinct soil layers (0–30 cm and 30–60 cm). The 17 soil properties relate to acidity, salinity, toxicity, and nutrition. In the surface layer (0–30 cm), the land use type of AL has the highest SQI (0.57), followed by NL, AC, and PC (0.53–0.55). The land use type of RL exhibits the lowest SQI of 0.50. In the deeper layer (30–60 cm), the difference in SQI among the land use types becomes less pronounced. The land use type of AL has high toxicity (0.15) and a high nutrient accumulation (0.21) in the surface layer. The land use type of RL indicates that the soil exhibits signs of recession, with the lowest SQI values in toxicity (0.12) and nutrition (0.18). For land close to the coast, certain soils can become more acidic and salty due to processes like pyrite oxidation and saline intrusion, which can lower soil pH and raise salt and toxic levels, especially in the top layer. The effectiveness of using SQI to evaluate soil quality was demonstrated, thereby supporting the management of soil quality, particularly in cases such as coastal saline areas. However, it is necessary to evaluate the effectiveness of the index in proposing recommendations for soil improvement.

Keywords: soil quality index, SQI, saline acid sulfate soil, Can Gio.

INTRODUCTION

Saline acid sulfate soils (SASS) are a significant challenge in coastal areas due to their combined acidity, salinity, and toxicity, which significantly limit agricultural productivity (Lindgren et al., 2022; Minh et al., 2024; Morton et al., 2023; Nguyen and Nguyen, 2023; Shamshuddin et al., 2014). These soils are characterized by high sulfide content that, upon oxidation, produces sulfuric acid, increasing acidity and releasing toxic elements such as aluminum (Al) and iron (Fe) (Minh et al., 2024; Shamshuddin et al., 2014). Globally, SASS covers approximately 12 million hectares of acid sulfate soils (Minh, 2015), with Vietnam accounting for 1.8 million hectares, representing 5.5% of the country's total land area. The Mekong Delta provinces have 1.6 million hectares of acid sulfate soils (Minh, 2015), of which 0.74 million are saline-acid sulfate soils, accounting for approximately 19% of the total. Sea-level rise is intensifying the spread and degradation of these soils (IPCC, 2021; Wassmann, 2024). Despite this, current soil management and reclamation efforts remain insufficient, mainly due to knowledge gaps and economic constraints faced by local farmers (Bui, 2020; Nguyen, 2018). This soil group poses significant challenges to crop growth and development (Toan et al., 2021). Different land use types (e.g., rice cultivation, fruit trees, vegetables, and aquaculture) also significantly impact soil properties, requiring an integrated evaluation approach to guide effective land use and reclamation strategies. Andrews et al. (2004) have documented the physical and chemical constraints of SASS; however, an integrated, quantitative evaluation of soil quality across different land use types and salinity gradients remains lacking.

Soil fertility is regarded as a critical soil function for long-term agricultural productivity and ecosystem health. Soil fertility loss is a concern in many parts of the world, and it continues to limit agricultural productivity. Soil fertility is primarily determined by soil nutrient availability, pH, and organic matter (Nguemezi et al., 2020). The soil quality index (SQI) is a statistic that evaluates the overall health and quality of soil. It is calculated by adding scores from various soil indicators, each indicating a distinct aspect of soil health. Physical, chemical, and biological characteristics can all be used as markers. The SQI facilitates an understanding of the impact of soil management methods and can be utilized to track changes in soil quality over time.

The Can Gio district in Ho Chi Minh City, Vietnam, has 43,945 hectares of saline-acid sulfate soils, which are impacted by increasing seawater intrusion (Can Gio DONRE, 2023). Therefore, this study aims to utilize SQI to assess the quality of different soil layers in saline acid sulfate soils of the study area across various land-use types, while also considering the influence of distance from the coastline, thereby contributing to enhanced recommendations for agricultural productivity.

MATERIALS AND METHODS

The study area and soil sampling sites

Can Gio is a coastal suburban area in Ho Chi Minh City, in Vietnam's Southeast region. The district is 50 kilometers from the center of Ho Chi Minh City. In 2019, the district covered an area of 704,45 km² and had a population of 71,526.

The study was conducted from 2022 to 2023. Soil samples were taken from July to August 2022. A map of the study area and soil sampling sites is shown in Figure 1.

The method of soil sampling used in the study followed the procedure outlined in TCVN 7538-1:2006/BKHCN on Soil Quality – Sampling Procedure (MONRE, 2006), which includes five steps: soil data sampling, soil analysis, statistical analysis, and SQI calculation (Figure 2).

Sampling locations were identified and GPS-located, and their coordinates were compared with those on the map. Soil samples were taken at two depths (0–30 cm and 30–60 cm), and visible litter, roots, branches, woody debris, and soil-dwelling animals were removed to minimize the addition of organic carbon to the soil. Soil samples were preserved in loosely tied polyethylene bags to avoid environmental conditions affecting changes in soil properties (Figure 3).

A total of 68 locations with 136 samples at two layers were taken on four soil groups as follows:

- Potentially shallow acid sulfate soils of mangroves (Sp1Mm) (No 1–23)

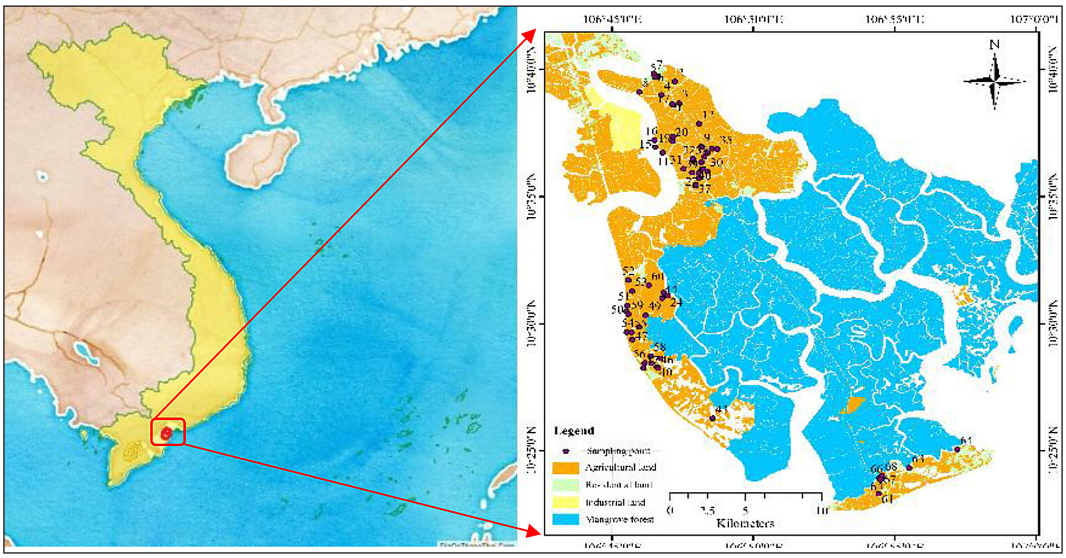


Figure 1. Study area and soil sampling sites are located in the Can Gio district, Ho Chi Minh City, Vietnam

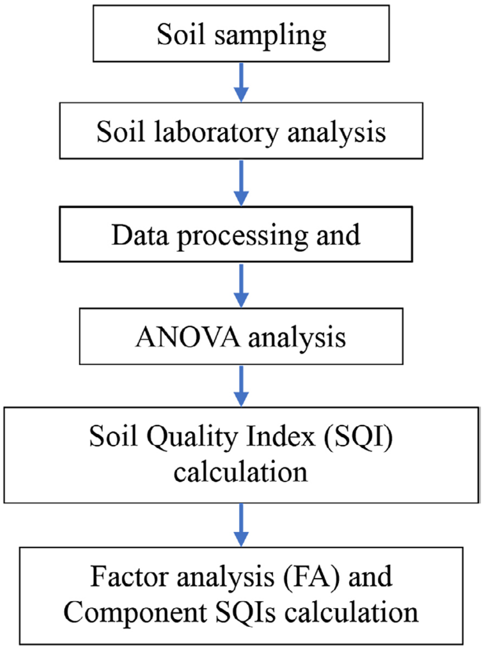


Figure 2. Steps for SQI calculation in the study area

- Potentially shallow acid sulfate soils, moderately saline (Sp1M) (No 24–37)
- Potentially deep acid sulfate soils, moderately saline (Sp2M) (No 38–60)
- Raised bed (lip) saline acid sulfate soils (SMv) (No 61–68)

Soil analysis

After being air-dried, ground up, and sieved through a 2 mm mesh, the soil samples were analyzed for various parameters, including pH, electrical conductivity (EC), organic carbon (OC), ammonium (NH_4^+), Mehlich-1 phosphorus (P), exchangeable acidity, exchangeable H^+, exchangeable aluminum (Al), iron (Fe), potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), and manganese (Mn), cation exchange capacity (CEC), chloride (Cl^-), and sulfate (SO_4^{2-}). Figure 4 shows the laboratory activity for soil treatments and soil analysis of this study.

These soil parameters were selected for analysis and combined into four groups, as they effectively represent the key limiting factors of saline acid sulfate soils (Morton et al., 2023; Nguyen et al., 2022; Nguyen and Nguyen, 2023), including:

- acidity (pH, SO_4^{2-}, exchangeable acidity, and exchangeable H^+)
- salinity (EC, Cl^-, Na^+)
- toxicity (Al, Fe, Mn), and
- nutrition (Mehlich-1 P, OC, NH_4^+, CEC, Ca, K, Mg)

The methods of soil analysis for parameters are shown in Table 1.

ANOVA analysis

All data were analyzed using a two-way ANOVA, and the model used was:

$$\gamma_{ije} = \mu + \beta_i + \alpha_j + \alpha\beta_{ij} + \varepsilon_{ije} \tag{1}$$

where: γ_{ije} represents the response variable; μ is the overall mean; βi and αj denote the land use types and soil layers, respectively; $\alpha\beta_{ij}$ represents their interaction; and ε_{ije} is the random error (Akhtar and Dr. Memon, 2009).

ANOVA evaluates the individual effects of different land use types on the soil quality index.

Figure 3. Field soil sampling

When ANOVA indicated significance ($p \leq 0.05$), Tukey's honest significant difference test was applied for mean separation.

Soil quality index (SQI) calculation

The SQI was calculated using the method of Andrews et al. (2002), as outlined in Equation 2.

$$SQI = \sum_{i=1}^{n} w_i s_i \quad (2)$$

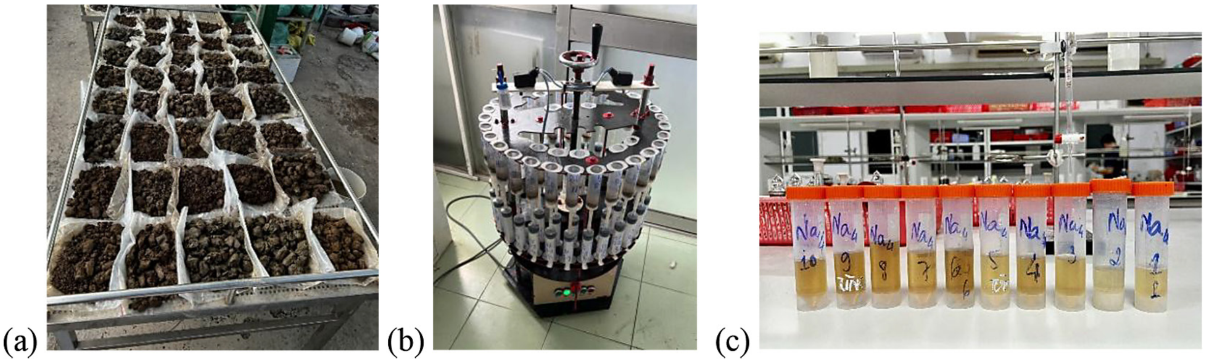
where: n was the number of soil parameters (17 parameters), w_i was the weightage of the i[th] parameter, and s_i was the score of the i[th] parameter. w_i was determined using FA (Table 4), and s_i is the standardized value calculated through Equations 3 and 4.

The 17 analyzed soil parameters were divided into three groups: „higher is better," „optimal is better," and „lower is better." The parameters in the „higher is better" group included Ca, K, Mg, Mehlich-1 P, CEC, and NH_4^+, and parameters in the „optimal is better" group included pH. In comparison, the parameters in the „lower is better" group included the rest. For the first two groups, s_i was calculated using Equation 3.

$$s_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (3)$$

For the parameters in the „lower is better" group, s_i was calculated using Equation 4.

$$s_i = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (4)$$



(a) (b) (c)

Figure 4. Soil treatment and laboratory analysis: (a) air-dry soil, (b) soil sample filtration for CEC estimation, (c) prepared samples for cation measurement

Table 1. Methods of soil analysis

Parameters	Unit	Soil analysis methods	References
pH	-	Measured by a pH meter	(Carter and Gregorich, 2008)
EC	$dS\ m^{-1}$	Measured by the EC meter	
CEC	$cmol(+)\ kg^{-1}$	Ammonium acetate pH = 7	
Exchangeable acidity	$cmol(+)\ kg^{-1}$	Titration method	
P	$mg\ kg^{-1}$	Mehlich-1	
NH_4^+	$g\ kg^{-1}$	Extraction method with $CaCl_2$	
Exchangeable H^+	$cmol(+)\ kg^{-1}$	Titration method	
Organic Carbon	%	Walkley Black	
Cl^-	$g\ kg^{-1}$	Titration method	(Hajrasuliha et al., 1991)
SO_4^{2-}	$g\ kg^{-1}$	Turbidimetric method	(Rice et al., 2017)
Exchangeable Fe	$mg\ kg^{-1}$	Measured by ICP-OES (Inductively Coupled Plasma Optical Emission Spectrometer)	(Carter and Gregorich, 2008)
Exchangeable Al			
Exchangeable Mn			
Exchangeable Ca			
Exchangeable Mg			
Exchangeable K			
Exchangeable Na			

where: x_i, x_{min}, and x_{max} were the analyzed value, the minimum value, and the maximum value of the i[th] parameter, respectively.

Factor analysis (FA) and component SQI calculation

Besides, the soil properties were categorized into four distinct groups using the factor analysis (FA) method (Nguyen et al., 2021), which reflects the four primary constraints of saline acid-sulfate soil, including those reflecting soil acidity (pH, SO_4^{2-} content, exchangeable acidity, and exchangeable H^+), salinity (EC, Na, and Cl^-), toxicity (Al, Fe, Mn), and nutrition (CEC, OC, NH_4^+, P, K, Ca, and Mg).

Consequently, the overall SQI was further fractionated into four component SQIs corresponding to these four constraints, including acidity SQI, salinity SQI, toxicity SQI, and nutritional SQI. The componential SQIs were calculated based on Equation 5.

$$Componential\ SQI = \sum_{j,i=1}^{z} w_i\, s_i \qquad (5)$$

where: z was the total number of soil parameters belonging to constraint j[th] (j varying from 1 to 4, corresponding to four constraints of saline acid sulfate soil); i, w_i, and s_i were the same as those in Equation 2.

Univariate correlation analysis between distance (km) from the coastline and individual Componential SQIs to determine which distance influences the component soil quality index in two soil layers across five land use types in the study area.

RESULTS AND DISCUSSIONS

Soil properties of the study area

Table 2 presents the mean, minimum, and maximum values for soil parameters across soil layers at 68 sampling points, supporting the normalization of data in SQI calculations. Parameters such as pH (3.24–7.65), EC (2.13–12.79 dS m^{-1}), CEC (4.26–18.68 cmol(+) kg^{-1}), and OC (3.93–6.38 %) reflect the diversity of soil quality, ranging from acidic to saline soils with varying cation exchange capacities. Certain factors, such as exchangeable Al (860.73 mg kg^{-1}) and exchangeable Na (593.46 mg kg^{-1}), are at levels potentially harmful to crops. Normalizing these parameters using methods such as min-max normalization ensures effective data integration, enabling SQI values to reflect soil quality accurately.

Soil properties on different land use types

Table 3 summarizes the acidity, salinity, toxicity, and nutrition components of saline acid sulfate soils across two layers (0–30 cm and 30–60 cm) in five land use types.

Table 2. Average, minimum, and maximum values of soil parameters

Soil parameters	Unit	Mean	Min	Max
pH	-	4.70	3.24	7.65
EC	dS m^{-1}	6.37	2.13	12.79
CEC	cmol(+) kg^{-1}	13.42	4.26	18.68
NH_4^+	mg kg^{-1}	125.55	77.05	196.52
P	mg kg^{-1}	9.00	3.26	16.82
OC	%	5.26	3.93	6.38
Cl^-	g kg^{-1}	1.87	0.89	3.47
SO_4^{2-}	g kg^{-1}	1.17	0.48	2.35
Exchangeable acidity	cmol(+) kg^{-1}	3.63	1.73	7.26
Exchangeable H^+	cmol(+) kg^{-1}	2.31	1.12	8.11
Exchangeable K	mg kg^{-1}	593.46	12.83	1082.26
Exchangeable Na	mg kg^{-1}	4291.11	87.91	12000.00
Exchangeable Ca	mg kg^{-1}	494.72	156.72	1333.53
Exchangeable Mg	mg kg^{-1}	860.73	197.07	1590.83
Exchangeable Al	mg kg^{-1}	176.60	7.92	905.19
Exchangeable Fe	mg kg^{-1}	336.29	10.00	1533.08

The analysis results showed the acidity in natural land (NL) with the lowest pH (4.05) and highest exchangeable acidity (4.33 cmol (+) kg^{-1}) and H^+ (2.99 cmol (+) kg^{-1}) in the 0–30 cm layer. In contrast, aquaculture land (AL) had the highest pH (4.95) and lowest exchangeable acidity (3.37 cmol (+) kg^{-1}). Sulfate concentrations were highest in NL and AL land use types (1.27 g kg^{-1}) and lowest in rice land (RL) at 0.94 g kg^{-1}. In the 30–60 cm layer, NL showed the highest acidity with exchangeable acidity of 4.21 cmol (+) kg^{-1} and H^+ of 2.72 cmol (+) kg^{-1}, while perennial crops (PC) showed the lowest acidity (pH 4.96). These findings underline the need for remediation in RL land use type to mitigate acidity and highlight the impact of land management practices on soil quality in Can Gio.

An analysis of soil salinity (EC, Cl^-, and exchangeable Na) and toxicity (exchangeable Al,

Table 3. The soil properties of different land use types in the study area

Soil properties	Soil layer	Land use types				
		AC	PC	RL	AL	NL
pH	0–30 cm	4.50^{a}	4.69^{a}	4.05^{b}	4.95^{a}	4.68^{a}
	0–60 cm	4.79^{ab}	4.96^{a}	4.63^{ab}	4.81^{ab}	4.77^{b}
SO_4^{2-} (g kg^{-1})	0–30 cm	0.98^{b}	0.96^{b}	0.94^{b}	1.25^{a}	1.27^{a}
	0–60 cm	1.25^{a}	1.27^{a}	1.11^{a}	1.26^{a}	1.30^{a}
Exchangeable acidity (cmol(+) kg^{-1})	0–30 cm	3.73^{ab}	3.75^{ab}	3.60^{ab}	3.37^{b}	4.33^{a}
	0–60 cm	3.14^{b}	3.23^{b}	3.26^{b}	3.45^{b}	4.21^{a}
Exchangeable H^+ (cmol(+) kg^{-1})	0–30 cm	2.29^{b}	1.91^{b}	2.25^{b}	2.26^{b}	2.99^{a}
	0–60 cm	2.11^{ab}	1.64^{b}	1.84^{ab}	2.65^{a}	2.72^{a}
EC (dS m^{-1})	0–30 cm	5.10^{b}	5.27^{b}	6.35^{a}	7.12^{a}	7.02^{a}
	0–60 cm	5.82^{b}	6.12^{b}	5.56^{b}	7.12^{a}	7.26^{a}
Cl^- (g kg^{-1})	0–30 cm	1.83^{ab}	1.84^{ab}	1.96^{a}	1.87^{ab}	1.68^{b}
	0–60 cm	2.20^{a}	2.17^{a}	1.64^{b}	1.78^{b}	1.82^{b}
Na (mg kg^{-1})	0–30 cm	2649.27^{c}	3669.97^{bc}	3807.74^{bc}	4059.62^{b}	5368.15^{a}
	0–60 cm	3116.25^{b}	2794.28^{b}	4519.36^{ab}	5226.41^{a}	6402.61^{a}
Exchangeable Al (mg kg^{-1})	0–30 cm	228.24	143.81^{b}	341.82^{a}	164.32^{b}	181.93^{b}
	0–60 cm	157.57^{a}	86.16^{a}	142.54^{a}	153.81^{a}	175.98^{a}
Exchangeable Fe (mg kg^{-1})	0–30 cm	304.69^{b}	366.60^{b}	578.48^{a}	265.56^{b}	377.78^{ab}
	0–60 cm	304.19^{ab}	189.31^{b}	349.81^{a}	326.13^{a}	319.23^{a}
Exchangeable Mn (mg kg^{-1})	0–30 cm	32.19^{ab}	41.60^{a}	32.02^{ab}	27.38^{b}	29.77^{b}
	0–60 cm	27.77^{b}	38.51^{a}	30.67^{b}	28.72^{ab}	28.42^{b}
CEC (cmol(+) kg^{-1})	0–30 cm	12.42^{b}	13.43^{b}	13.00^{b}	12.97^{a}	12.80^{a}
	0–60 cm	13.82^{b}	15.50^{a}	14.54^{ab}	12.68^{b}	13.56^{ab}
NH_4^+ (mg kg^{-1})	0–30 cm	103.34^{c}	114.18^{bc}	123.63^{b}	140.71^{a}	124.87^{b}
	0–60 cm	139.14^{a}	137.78^{a}	105.75^{b}	134.19^{a}	124.52^{a}
P (mg kg^{-1})	0–30 cm	8.28^{b}	9.16^{ab}	8.35^{b}	10.17^{a}	10.20^{a}
	0–60 cm	7.22^{c}	7.53^{c}	6.96^{c}	9.53^{b}	10.95^{a}
OC (%)	0–30 cm	5.07^{bc}	4.87^{cd}	4.62^{d}	5.85^{a}	5.27^{b}
	0–60 cm	5.43^{a}	5.33^{a}	5.21^{a}	5.34^{a}	5.35^{a}
Exchangeable K (mg kg^{-1})	0–30 cm	613.62^{a}	588.85^{a}	625.37^{a}	616.24^{a}	579.49^{a}
	0–60 cm	597.93^{a}	563.90^{a}	676.65^{a}	581.95^{a}	516.96^{a}
Exchangeable Ca (mg kg^{-1})	0–30 cm	522.27^{a}	570.37^{a}	458.02^{a}	484.81^{a}	489.56^{a}
	0–60 cm	545.93^{a}	486.50^{a}	489.04^{a}	457.36^{a}	469.27^{a}
Exchangeable Mg (mg kg^{-1})	0–30 cm	891.32^{a}	930.72^{a}	859.49^{a}	790.59^{a}	858.13^{a}
	0–60 cm	932.15^{a}	796.61^{a}	915.65^{a}	783.73^{a}	889.30^{a}

Note: Data with the same letters are not statistically significantly different from each other at $p \leq 0.05$; Annual crops = AC; Perennial crops = PC; Rice land = RL; Aquaculture land = AL; and natural land = NL.

Fe, and Mn) in saline acid sulfate soils under five land uses types revealed variations across soil layers and land uses showing that the highest EC in the 0–30 cm layer was recorded in land use types of AL (7.12 dS m^{-1}) and NL (7.02 dS m^{-1}), further increasing in the 30–60 cm layer (NL: 7.26 dS m^{-1}). Exchangeable Na was also highest in NL and AL, indicating significant salt accumulation. Chloride concentrations were highest in RL (1.9 g kg^{-1}) in the 0–30 cm layer but shifted to AC and PC land use types in the 30–60 cm layer. Regarding toxicity, RL exhibited the highest Al^{3+} (341.82 mg kg^{-1}) and Fe^{2+} (578.48 mg kg^{-1}) levels in the 0–30 cm layer, negatively impacting crops, while exchangeable Mn^{2+} was highest in PC. AL and NL soils were characterized by prominent salinity, whereas heavy metals significantly affected RL. These findings highlight the importance of effective soil remediation strategies in enhancing agricultural productivity.

According to Table 3, seven soil nutrient properties (CEC, NH_4^+, P, OC, exchangeable K, Ca, and Mg) across two soil layers (0–30 cm and 30–60 cm) in five land use types are compared. In the 0–30 cm layer, PC had the highest CEC (13.43 cmol(+) kg^{-1}), maintaining its lead in the 30–60 cm layer (15.50 cmol(+) kg^{-1}). NH_4^+ in the 0–30 cm layer was highest in AL land use type (140.71 mg kg^{-1}), and lowest in AC (103.34 mg kg^{-1}); in the deeper layer, PC and AC had the highest values. P content was highest in NL and AL across both layers, while RL and PC had lower values. OC in the 0–30 cm layer was highest in AL (5.85%) and lowest in RL (4.62%), with a more uniform distribution in the deeper layer (5.21–5.40%). Exchangeable K was relatively uniform in the 0–30 cm layer, but RL led in the deeper layer (676.65 mg kg^{-1}). Ca was highest in AC and PC, while Mg showed no significant differences across land types. In summary, PC soil demonstrated the best nutrient exchange capacity (highest CEC), AL was rich in NH_4^+, P, and OC, but had lower CEC. Especially RL for its highly exchangeable K, while NL was abundant in the contents of P and OC. These findings reflect the varying nutrient potentials of soils in Can Gio, which are suitable for specific land-use purposes.

Additionally, the comparison of soil properties between the 0–30 cm and 30–60 cm layers across land-use types revealed significant differences in acidity, salinity, toxicity, and nutrient properties. The pH values were generally higher in the upper layer (e.g., 5.03 in AC) compared to the lower layer (4.79), reflecting increased acidity at depth. Salinity-related parameters, such as EC and exchangeable Na, show a pronounced increase with depth, particularly in NL, where EC rises from 6.41 dS m^{-1} in the upper layer to 7.26 dS m^{-1} in the lower layer, and exchangeable Na increases from 5123.73 mg kg^{-1} to 6402.61 mg kg^{-1}. Toxicity indicators like exchangeable Fe are higher at 30–60 cm, with RL showing an increase from 305.41 mg kg^{-1} in the upper layer to 349.81 mg kg^{-1} at depth. Conversely, nutrient availability (e.g., NH_4^+ and P) is reduced in the lower layer; NH_4^+ in RL drops from 118.64 mg kg^{-1} to 105.75 mg kg^{-1}, while P in AC decreases from 8.36 mg kg^{-1} to 7.22 mg kg^{-1}. These findings highlight the stratified distribution of soil properties, characterized by increasing salinity and toxicity, as well as declining nutrient availability in deeper soil layers, which is shaped by both land-use practices and inherent soil characteristics.

Factors analysis

Factor analysis was a statistical method for describing variability among observed, correlated variables in terms of fewer unseen variables known as factors (Jöreskog, 1983).

The results from Table 4 reveal that the four factors identified through FA offer distinct insights into soil properties, each highlighting a unique set of relationships among the measured parameters Factor 1, accounting for the highest variance (26.51%), reflects the fundamental soil fertility and exchange capacity, emphasizing parameters such as exchangeable Mg, Fe, Ca, cation exchange capacity (CEC), and pH. These variables are critical for nutrient availability and soil structure stability, suggesting that:

Factor 1 represents the soil's inherent fertility and its capacity to buffer against environmental stresses. Soils with high values in this factor are likely more fertile and capable of supporting diverse crop growth with minimal acidity issues.

Factor 2 explains 11.85% of the total variance and is associated with parameters related to salinity (EC, Cl^-, SO_4^{2-}) and organic content (OC, NH_4^+). This factor captures the impact of salinity and organic matter on soil quality. High scores in Factor 2 indicate soils with a significant influence of salinity, which can adversely affect plant growth if not properly managed. However, the presence of organic matter might buffer some of the adverse effects, as organic compounds can

Table 4. The loading value and weightage of measured parameters are estimated using FA

Soil parameters	Factor 1	Factor 2	Factor 3	Factor 4	Weightage of parameters
Exchangeable Mg	**0.8**	0.3	0.2	0.1	0.100
Exchangeable Fe	**0.7**	0.1	0.2	-0.4	0.100
Exchangeable Ca	**0.7**	0.1	0.3	0.4	0.100
CEC	**0.5**	0.1	-0.5	0.1	0.100
pH	**-0.7**	0.3	0.0	0.5	0.100
Exchangeable Mn	0.2	**-0.5**	-0.3	0.0	0.044
OC	0.0	**0.7**	0.1	0.1	0.044
EC	0.4	**0.6**	0.5	-0.2	0.044
NH_4^+	0.1	**0.6**	-0.2	0.1	0.044
SO_4^{2-}	0.3	**0.5**	0.3	-0.3	0.044
Cl^-	0.2	**0.5**	0.1	-0.1	0.044
Exchangeable acidity	0.1	0.1	**0.8**	-0.1	0.043
P	0.3	0.3	**0.7**	-0.1	0.043
Exchangeable H^+	0,1	0.0	**0.7**	0.0	0.043
Exchangeable Al	0.0	-0.3	0.2	**-0.7**	0.035
Exchangeable K	0.0	-0.4	-0.2	**0.6**	0.035
Exchangeable Na	0.0	-0.4	0.3	**0.5**	0.035
Eigenvalue	4.51	2.01	1.96	1.59	
Percent (%)	26.51	11.85	11.54	9.38	
Cumulative percent (%)	26.51	38.36	49.90	59.28	
Factor weightage	0.45	0.20	0.19	0.16	

Note: Bold numbers are those having absolute values greater than 0.5; CEC = cation exchange capacity; and EC = electrical conductivity.

improve soil structure and water retention. While Factor 1 emphasizes inherent soil fertility, Factor 2 focuses on salinity and organic matter. High scores in both factors indicate fertile soils with moderate salinity and high organic matter content, which can support a diverse range of crops if managed effectively.

Factor 3, contributing 11.54% of the variance, highlights the soil acidity parameters (exchangeable acidity, exchangeable H^+) and phosphorus (P). This factor signifies the acidification processes, particularly in soils with sulfur compounds or low buffering capacity. High values in this factor indicate soils that are prone to acidification, which may require liming or other interventions to enhance phosphorus availability for plant uptake. Factor 4, explaining 9.38% of the variance, emphasizes the dynamics of exchangeable cations such as Al, K, and Na. This factor represents the interaction between salinity and acidity, particularly in soils influenced by sodium and potassium levels. High scores here indicate soils that are susceptible to sodicity or alkali soil conditions, which can impair soil structure and reduce permeability, negatively affecting plant growth. Factor 3 deals with acidity-related limitations, whereas

Factor 4 addresses acidic conditions. Soils scoring high in Factor 3 require interventions to manage acidity, while those high in Factor 4 might need amendments to mitigate sodicity. Factor 1 has the most significant influence on the dataset, reflecting core soil properties, while Factors 2–4 capture specific issues such as salinity, organic matter, acidity, and sodicity. Together, they account for 59.28% of the total variance, indicating a comprehensive representation of the soil's physical and chemical properties.

Soil quality index on different land use types

At the 0–30 cm soil layer (Figure 5a), AL exhibited the highest SQI value (0.57), which can be attributed to organic deposition from aquaculture activities and effective water management, helping to maintain better soil quality, consistent with the findings of Li (2018b). Following this, the average SQI values ranged from 0.53 to 0.55 for NL, AC, and PC, respectively. NL reflects a

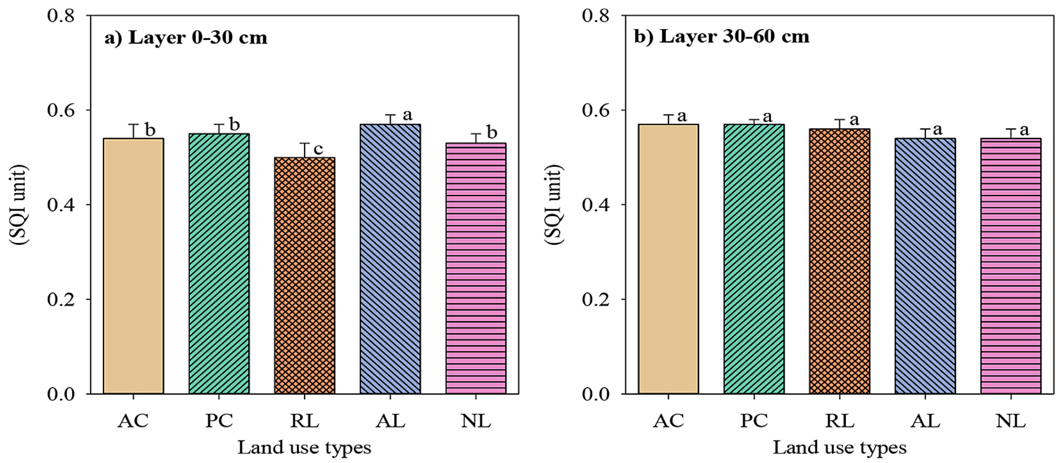


Figure 5. Overall SQI of land with five land use types

soil ecosystem that is minimally impacted by human activity, aligning with the research of Doran (2000), which emphasized the role of natural ecosystems in maintaining soil quality. RL had the lowest SQI value (0.50), possibly due to continuous paddy rice cultivation, which causes nutrient depletion and adversely affects soil structure, as documented in the study by Zhang (2020) on soil quality degradation under rice cultivation. At the 30–60 cm soil layer (Figure 5b), all land-use types exhibited statistically indistinguishable SQI values, indicating greater homogeneity in deeper soil layers.

Component of the soil quality index

According to Sharma et al. (2014), the SQI is divided into various components, known as the CSQI, which enables the independent assessment of different aspects of soil quality. For example, some studies identify physical (PSQI – Physical SQI), chemical (CSQI – Chemical SQI), biological (BSQI – Biological SQI), or physicochemical (PCSQI – Physico-chemical SQI) component indices, which are then combined into an overall Additive Soil Quality Index (ASQI). Specifically, each component index was calculated from a corresponding group of indicators (e.g., PSQI from physical and mechanical properties such as soil aggregation and bulk density; CSQI from pH, cation exchange capacity (CEC), and nutrients; BSQI from microbial biomass, enzyme activity, etc.) and can be computed using various methods (e.g., summation, arithmetic mean, or geometric mean). Standard methods include simply summing the standardized values of the indicators (Aravindh et al., 2020) or using a scoring function for each indicator and then aggregating them. The selected indicators must be relevant to the soil function of interest and the local context.

The evaluation results of the Component Soil Quality Index (CSQI) in the study reveal significant differences among land-use types and soil layers surveyed. At the 0–30 cm layer (Figure 6a), the CSQI acidity was highest in PC and AL (both at 0.13), which may be related to the use of chemical fertilizers and crop rotation, as noted in the study by Rengel (2011). It was followed by land uses of AC and RL (0.12), which were slightly lower than those of PC and AL land use types. This finding aligns with the results of Fageria (2011), who observed that paddy rice cultivation can reduce acidity due to the reduction of iron and manganese under anaerobic conditions. Meanwhile, the lowest value was recorded in the natural land (NL) (0.11), indicating the effectiveness of soil improvement measures and cultivation management in mitigating acidification. At the 30–60 cm layer (Figure 6b), differences between land-use systems were less pronounced, except for NL (0.12), which maintained a low CSQI value, indicating the influence of leaching and dissolution processes in groundwater on the acidity of deeper soil layers. For the CSQI salinity, the surface layer (Figure 6c) shows that AC had the highest index (0.09).

In contrast, PC, RL, AL, and NL exhibited lower values, indicating better salinity control in smallholder farming systems. In the deeper layer (Figure 6d), NL and AL continued to record a low index (0.07). Notably, RL maintained its salinity CSQI value (0.08), reflecting

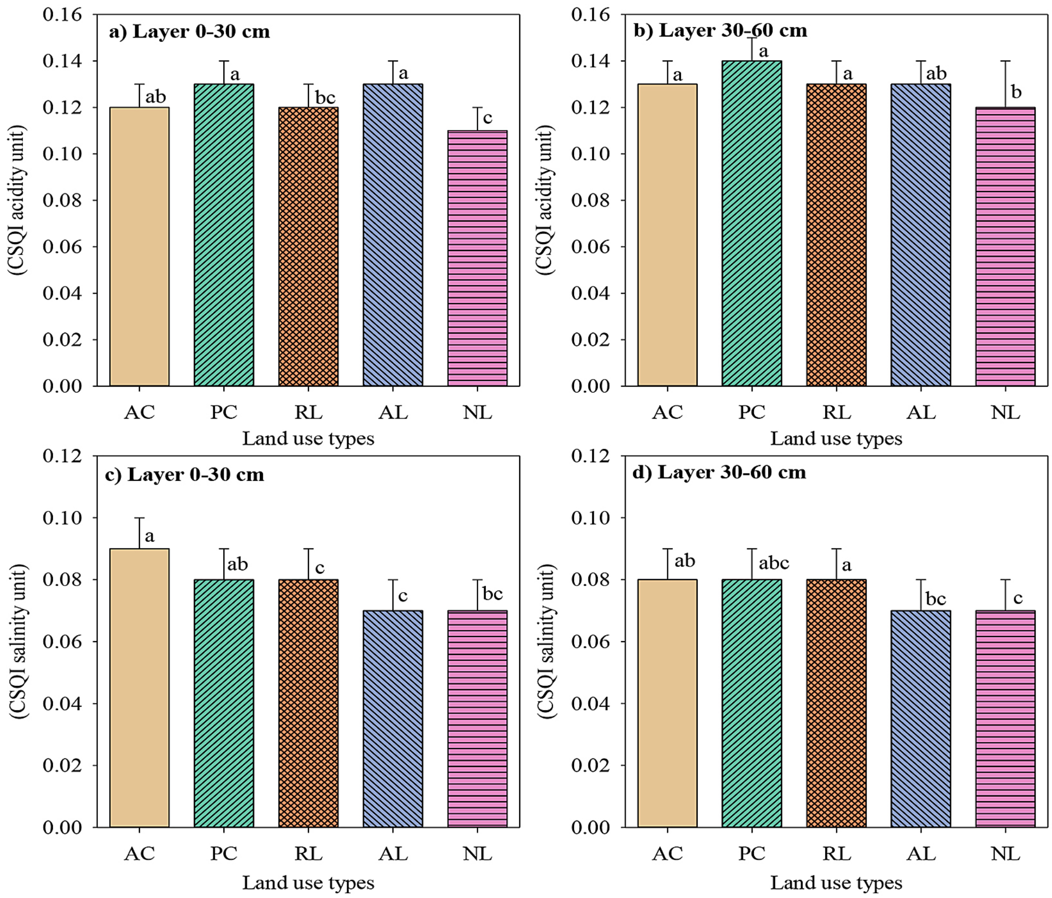


Figure 6. CSQI of soil acidity and salinity for five land use types

a trend of salt accumulation from the upper to the deeper layer. This observation aligns with Wong (2010), who noted that continuous paddy rice cultivation systems can lead to salt buildup in deeper soil layers due to prolonged waterlogging conditions that restrict salt leaching and ion diffusion.

Under the influence of land-use types, the CSQI toxicity and nutrition showed distinct variations across soil layers. In the 0–30 cm layer, AL demonstrated superior toxicity control (0.15) in Figure 7a and the highest nutrient accumulation (0.21) in Figure 7c, reflecting the benefits of reduced soil disturbance and surface organic material conservation. No-till farming helps reduce the rapid mineralization of organic carbon, maintaining stable soil structure and minimizing the accumulation of potential toxicants (Blanco-Canqui, 2008; Franzluebbers, 2002). Moreover, undisturbed plant residues provide favorable conditions for nutrient accumulation and recycling at the surface layer (Lal, 2015). In contrast, RL recorded the lowest CSQI values for both toxicity (0.12) in Figure 7a and nutrition (0.18) in Figure 7c, indicating signs of declining soil potential due to continuous cropping. Prolonged rice cultivation, particularly under continuous flooding conditions, may lead to nutrient leaching, the accumulation of harmful reductive compounds (Fe^{2+}, Mn^{2+}), and the degradation of organic carbon and soil structure over time (Sahrawat, 2004).

In the deeper layer (30–60 cm), differences in toxicity between land-use types were no longer evident (Figure 7b), implying a more uniform distribution of toxic elements with soil depth. It could reflect the leaching and redistribution of contaminants under waterlogged or regular irrigation conditions, as noted by Li (2018a). However, NL maintained a high nutrition CSQI value in the deeper layer (0.21) in Figure 7d, indicating the long-term accumulation of nutrients in undisturbed conditions. Natural ecosystems often have deep root structures and stable vegetation cover, which contributes to increased organic carbon and nutrient accumulation in subsoil layers, consistent with the findings of Jobbágy (2000).

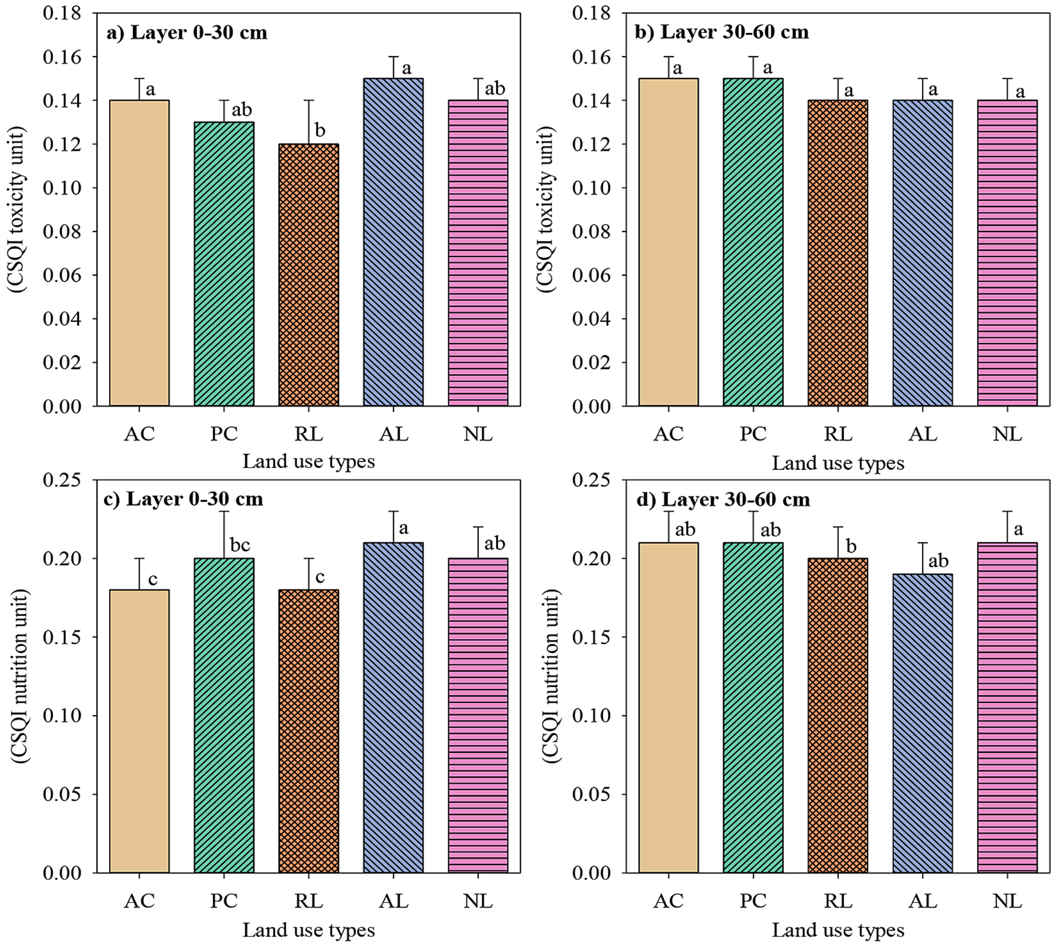


Figure 7. CSQI of soil toxicity and nutrition for five land use types

Salinity intrusion and components of soil quality

Examining the relationship between the components of the soil quality index and the distance from the coastline inland to assess the impact of salinity intrusion on soil quality in the study area. The correlation between the four CSQI indices and distance is shown in Figures 8 and 9.

In coastal areas, seawater carries high concentrations of salts, particularly Cl^- and Na^+ ions. These ions can replace weaker alkaline ions (Ca^{2+}, Mg^{2+}) in soil colloids, disrupting chemical balance and leading to the release of exchangeable H^+ ions, which causes soil acidification. It explains why areas near the coast (< 20 km) exhibit low and relatively stable Soil Quality Index values for acidity. However, as the distance from the coast increases (> 20 km), the degree of acidification rises rapidly in the 0–30 cm soil layer (Figure 8a). In the 30–60 cm layer, saline water penetrates deeper through capillary action and osmosis. The combination of high salt concentrations and the natural acidity of acid sulfate soils increases the adverse effects, as evidenced by the rapid increase in SQI for salinity in deeper layers. Within 20 km of the coast, the SQI for acidity remains low and changes slowly, reflecting the characteristics of areas heavily affected by saltwater intrusion and acid accumulation due to the soil's natural properties. Beyond the 20 km threshold, the SQI for acidity increases sharply in both the 0–30 cm (Figure 8a) and 30–60 cm (Figure 8b) layers. This increase indicates that acidification is not only confined to coastal areas but also progressively spreads inland as seawater infiltrates deeper soil layers. It is a clear sign of the long-term impact of saltwater intrusion. Similarly, the SQI for salinity within 20 km of the coast is low and changes slowly (Figure 8c,d). This area is directly influenced by seawater and evaporation, leading to salt accumulation. Beyond 20 km from the coast, the SQI for salinity increases significantly, particularly in the 30–60 cm layer (Figure 8d). It suggests that saltwater intrusion is not limited to

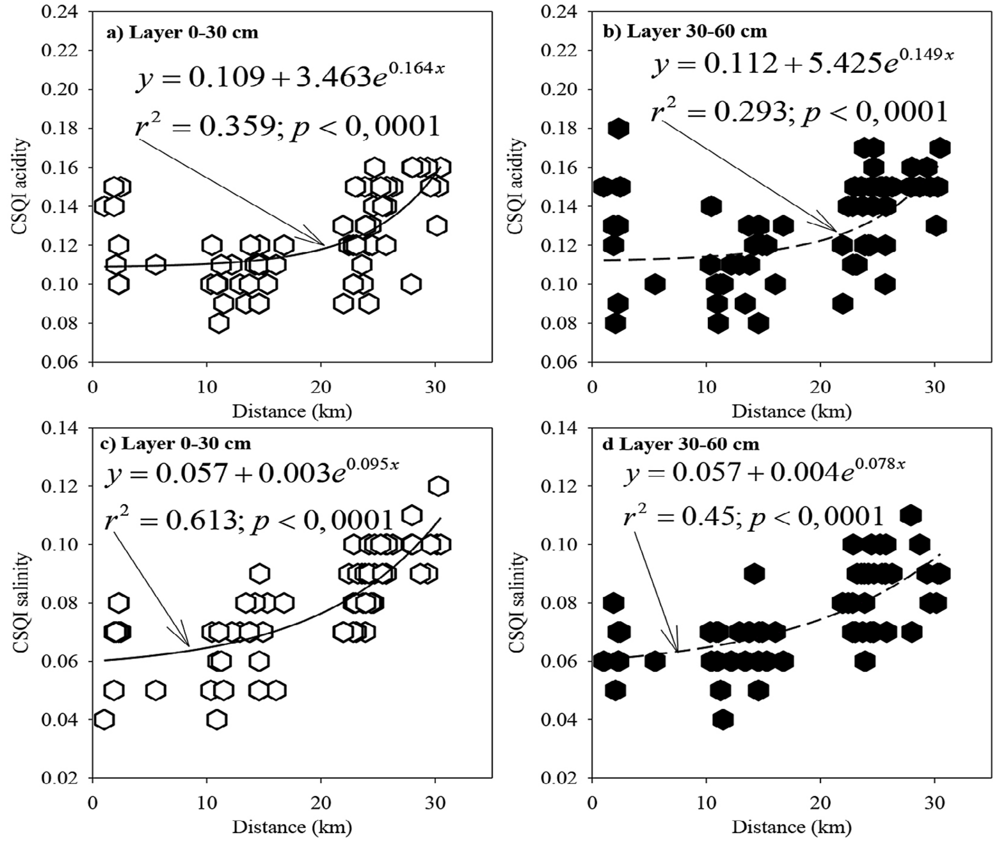


Figure 8. Correlation between the CSQI of acidity, the salinity of 0–30 cm and 30–60 cm layers, with distance from the coast to the mainland

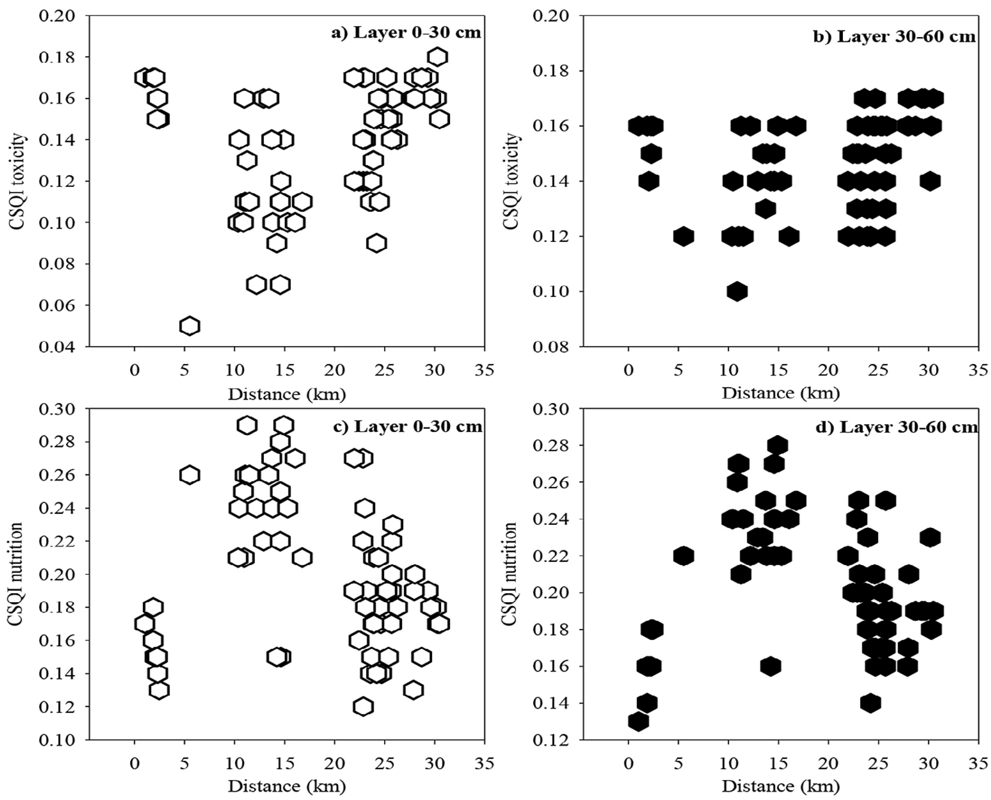


Figure 9. Correlation between the CSQI of toxicity, nutrition of 0–30 cm and 30–60 cm layers, with distance from coast to mainland

the surface layer but tends to spread and accumulate in deeper soil layers, reflecting the severity of the salinization process.

Figure 9 illustrates the variation of the soil quality index for toxicity and nutrient content across soil layers (0–30 cm and 30–60 cm) based on the distance from the coastline inland. In the 0–30 cm layer (Figure 9a), the SQI for toxicity ranges from 0.04 to 0.18, with values scattered and showing no clear trend related to the distance from the coast. In the 30–60 cm layer (Figure 9b), the SQI for toxicity ranges from 0.10 to 0.18, similar to the upper layer, and the data also shows no correlation with distance from the coast. Similarly, for nutrient content in the 0–30 cm layer (Figure 9c), the SQI for nutrients varies between 0.12 and 0.30, with an uneven distribution, particularly with higher values concentrated at distances of 15–25 km from the coast. In the 30–60 cm layer (Figure 9d), the SQI for nutrients ranges from 0.12 to 0.28, but the trend is also irregular and shows no significant dependence on distance.

From the results in Figure 9, a statistically significant relationship has been observed between soil quality indices (toxicity and nutrient content) and the distance from the coast. It may reflect the complex nature of saltwater intrusion and the region's environmental factors.

CONCLUSIONS

The results showed that land use type affected the variation of saline acid sulfate soil quality in the study area. In the surface layer, the land use type of AL had the highest pH value, abundant organic carbon (OC), NH4+, and relatively high salinity. In contrast, RL were heavily affected by acidic toxins, so they had the lowest pH and highest exchangeable Al. At the same time, EC and exchangeable Na increased while NH_4^+ and P decreased slightly. It showed that the chemical properties of the subsoil became uniform, and the salt concentration increased with depth. The Soil Quality Index of the land use types showed that AL had the highest SQI in the topsoil layer and lower in the NL, AC, PC, and RL land use types. It showed the uniformity of subsoil conditions. Analysis of the component SQI (CSQI) also showed that the AL land use type was the leading in toxicity and nutrient stabilization.

In contrast, the RL land use type, despite having the lowest score, maintained some functions. Spatially, the coastal sampling points – especially in the RL land use type – increased pyrite oxidation and saltwater intrusion, causing an evident decline in surface SQI and CSQI. In contrast, the AL and NL land use types upstream of the mangrove forest had higher SQI and CSQI.

These results demonstrate that the soil quality assessment provides a framework for optimizing fertility and minimizing toxicity in saline-acid sulfate soils.

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