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Soil properties characterization and constraints for rice cultivation in Vinh Long Province, Vietnam

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ABSTRACT

The study aimed to determine and characterize the physicochemical properties of rice soil in the triple, double, and single rice-upland crops in Vinh Long province, Vietnam. The results showed that rice cultivation soil in Vinh Long province had a relatively low pH (4.3–5.4). Most of the physical parameters in the soil were within limits suitable for plant growth. Electrical conductivity (EC), total dissolved salts, and exchanged aluminum (Al^{3+}) in the soil were in normal ranges. The total cation exchange and zinc were not in the practical ranges for plant growth. Total nitrogen (TN), total phosphorus (TP), total potassium (TK), and total organic matter (OM) content ranged from moderate to good, rich, medium to poor, and rich, respectively. Potassium (K^+), sodium (Na^+), calcium (Ca^{2+}), and magnesium (Mg^{2+}) were the exchange base cations in the soil that were present in low, medium, and high concentrations, respectively. Manganese (Mn) content was suitable for plant growth. Interestingly, the highest concentrations of OM, TP, exchangeable base cations, and Mn were found in the soil of triple rice, while the highest TN and TK content was found in a single rice-upland crop. As a result of the cluster analysis, it was possible to reduce the number of soil sample monitoring sites from 13 to 5 to guarantee the representativeness of the physiochemical characteristics of the soil in the study area. The results also showed that the soil quality of different rice-based soils was disparity mainly due to exchanged Al^{3+}, EC, soil structure, and density. The present findings provide useful scientific information for sustainable soil management in agricultural production in the study area.

1. INTRODUCTION

According to Mulat *et al*., agricultural soil is one of the critical elements of the ecosystem and the location where human food is produced. The quality of the soil environment significantly impacts production productivity [1]. Soil quality evaluation has traditionally been crucial for monitoring and evaluating how soil properties vary over time and space [2]. In addition, while deciding how to utilize land and executing sustainable land environmental management in regions with a tropical monsoon climate, evaluating soil environmental quality according to various land use purposes is particularly helpful [3]. To ensure optimal plant growth, the soil must achieve certain conditions of stability, structure, aeration, and a suitable amount of nutrients [4].

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There are many different total concentrations of the chemical element sulfur in soils. The mechanical makeup of the soil, its organic content, its level of contamination, and sulfur content all affect how much sulfur forms there [4]. The amount of salt in the soil is the total amount of dissolved minerals, including cations of Ca^{2+}, Mg^{2+}, K^+, Na^+, NH_4^+, and anions of Cl^-, NO_3^-, SO_4^{2-}, and CO_3^{2-} and the substances that make up the salinity in the soil comes typically from five sources (1) salinity due to the reactions of weathering, dissolving minerals in the soil, this type of soil occurs in areas with less rainfall than evapotranspiration; (2) due to the intrusion of salt into the soil by seawater containing a lot of salt, this type of soil occurs in most of the areas where sea water intrudes; (3) brought about by irrigation water, the water is evaporated, and salt is left behind; (4) rainwater; and (5) artificial [5,6].

Electrical conductivity (EC) measures a solution's ion concentration; as ion concentration increases, EC also increases. At the same time, EC is a correlative measure of soil properties that affect soil texture, cation exchange (CEC) capacity, drainage conditions, organic matter (OM) levels, salinity, and subsoil properties [7]. According to Wagh *et al*., electric conductivity is frequently used to measure salinity and estimate the dissolved salt concentration in the soil [8]. Nitrogen is an essential nutrient for plants' growth and development, especially for the green color of leaves [2,9]. In soil, nitrogen exists in two forms: Inorganic and organic. The inorganic form is mainly NO_3^- and NH_4^+, which are active products of microorganisms readily soluble in water so that plants can use them. Phosphorus is one of the most important nutrients, essential for plant growth, and acts as a reserve energy source [10]. According to Agrawal *et al*., potassium is involved in various metabolic processes in plants, from producing plant sugars for different metabolic purposes and regulating photosynthesis to forming lignin and cellulose, which are used to form cellular structural components [11]. Bulk density is an important physical property for evaluating soil compaction and plant root growth [12]. In general, the higher the density of the soil, the lower the porosity. Dense soil has more compaction, interfering with root growth and nutrient absorption [13].

Soil is a precious and essential resource for agricultural production in the Mekong Delta. However, soil resources are being degraded and facing problems such as salinization, acidity contamination, pollution, and severe depletion of nutrients and fertility. It has been determined that the area of land with reduced fertility is 857,150 ha (21% of the total natural land area), saline soil with an area of 688,423 ha (16.87% of the total natural land area), and acidified soil with an area of 436,001 ha (accounting for 10.68% of the total natural land area) [14]. According to the DONRE (Department of Natural Resources and Environment) Vinh Long province, the soils of Vinh Long province have 38 soil units based on the WRB classification system. These units belong to four major soil groups: Anthrosols (AT), Arenosols (AR), Fluvisols (FL), and Gleysols (GL). The Gleysols and Anthrosols soil groups occupy the most significant area (70,487 ha and 63,024 ha), while Fluvisols and Arenosols occupy a negligible area (2961 ha and 145.81 ha). There are three diagnostic horizons, including Mollic, Plinthic (Epi and Endo), and Thionic (Proto, Ortho, and Bathy), and three diagnostic properties, including Gleyic, Eutric, and Haplic [15].

Over the years, the intensification of land use for crop cultivation and the massive use of chemical fertilizers and pesticides caused drastic changes in soil properties [16]. Soil quality and fertility loss and soil acidification increase the risk of soil surface hardening and degradation [17]. In addition, the soil is also affected by climate change with drought, waterlogging, and saltwater intrusion deep into the province [18]. In time, FS in the Vinh Long Province decreased by 2,705.45 ha, mainly being transformed into AT soil group. It can result from migrating to the Gleysols soil group because of agricultural activity and increasing the demand for non-agricultural land from horticulture activities. GL soil group decreased by 2,041.98 ha, primarily transitioning to AT due to horticultural operations and the requirement to expand the non-agricultural area. An additional 9,688.34 ha of AT soil groupings were produced, which can be the changes of soil groups of FL (2,705.45 ha), GL (2,041.98 ha), and AR (1.37 ha) for fruit gardens, canals, construction, etc. According to the scenario on climate change in Vinh Long province to 2020, and 2030, the even more abnormal influence of water level from upstream in the dry season [18]. Some sub-regions along the riverside of the province suffer from partial drought, requiring dynamic irrigation or additional pumping in the dry season, especially in the sandy area of the province. Tra On and Vung Liem districts suffer from mild partial drought. The detrimental effects reduce crop yields and the sustainable growth of the agricultural industry while hastening some processes of soil quality degradation, pollution, and deterioration [17,19,20].

This study aims to evaluate and characterize the physicochemical properties of rice-cultivated soils in Vinh Long province under different intensive rice cropping models. The present findings could help local authorities to identify constraints affecting the agricultural farming process and assist in planning appropriate use of rice-land.

2. MATERIALS AND METHODS

2.1. Description of the Study Area

The study area is between the Tien and Hau Rivers in the Mekong Delta in Viet Nam. Compared to other regions of the Mekong Delta, it was exploited and farmed earlier. Consequently, the province's agriculture has become fairly diverse, and most of the land has been fully utilized. In the province's agricultural vegetation, annual cropland has the most significant area, with 73,123.6 ha, accounting for 51.01% of agricultural production land, where rice and upland crops are the most cultivated. According to the land statistics results in 2022, the total natural land area of Vinh Long province is 152,573.3 ha, of which the agricultural land group occupies a large area of 120,490.1 ha (accounting for 78.97%) [15]. Besides, the whole province is in plain terrain, relatively flat, with a slope <5°, and located in the tropical monsoon region, hot and humid all year round, relatively high-temperature regime, located in an area with high rainfall. The average rainfall (1.742 mm) from April to November is comparable to that of the Mekong Delta region (1.350–2.400 mm). The climate is divided into two seasons: The rainy season goes from May to December, accounting for 95% of the annual rainfall. The region is influenced by the irregular semi-diurnal tide regime of the East Sea, surrounded and affected by four major river systems, namely, the Tien River, the Co Chien River (a branch of the Mekong River Delta), Hau River, and Mang Thit River [15].

The rice land group has an area of 71,665.0 ha, accounting for 46.97% of the natural land area. Depending on the type of soil, hydrology, and water regime condition, rice cultivation includes five types of specialized cultivation models. 3L (three rice cropping seasons within a year, each rice cropping season is about 3 months), 2L (two rice cropping seasons within a year, each rice cropping season is about 3 months), 2L-1M (two rice cropping seasons continuously and one upland crop after second rice crop harvested, all cropping season within a year), 1L-1M (one rice crop and one upland crop after rice harvested, all cropping season within a year), and 1L-2M (one rice crop and two upland crop after rice harvested, all within a year) are distributed across districts, towns, and cities, including Vung Liem, Tam Binh, Mang Thich, Binh Tan, Tra On, Long Ho, Vinh Long, and Binh Minh. Triple rice, double rice-upland crop, and single rice-upland crop occupy a large area of 62,967.5 ha, accounting for 87.86%; 6.558.0 ha accounted for 9.15%, and 446.5 ha accounted for 0.62%, respectively [15]. Therefore, the three main cultivating models were selected for studying the physicochemical properties of soil [Figure 1].

2.2. Soil Sampling and Analysis

The soil sampling concentrated in the agricultural production areas within the province, including the Vinh Long, Binh Minh, Long Ho, Mang Thit, Vung Liem, Tam Binh, and Tra On districts. According to the procedure for soil sampling to evaluate the soil for the project, depending on the scale of the current land use area in the area [15], the larger area will take higher samples and vice versa, the surface soil samples were collected from L3 (n = 8), 2L-1M (n = 4), and 1L-1M (n = 1<). Details of the soil sample collection are shown in Table 1. About 1.5 kg of soil was collected for each sample. According to FAO [21], when taking soil samples in the profile for soil profile description, they are taken first at the bottom, then up to the top; the soil's depth is not more than 30 cm. Then, it was put in a separate bag and labeled with the number, soil layer depth, and sampling layer.

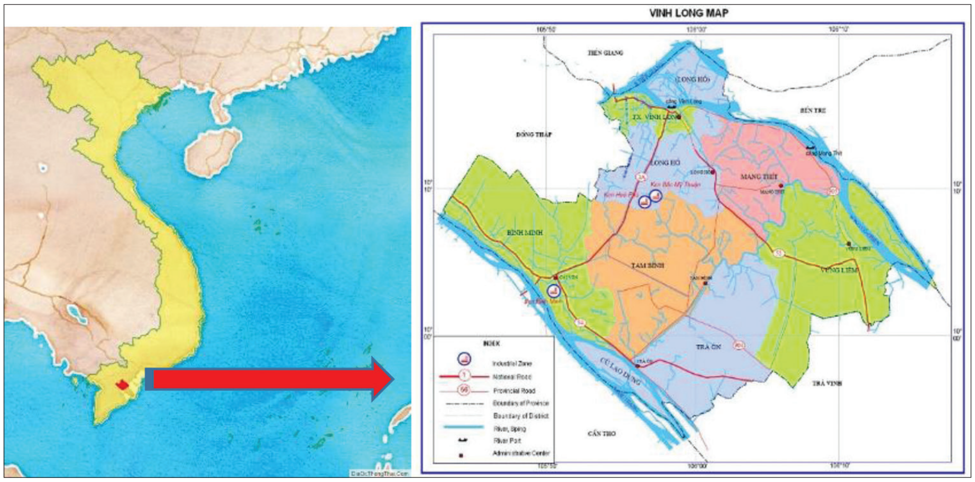

Figure 1: Map of the study area in Vinh Long province, Viet Nam.

Table 1: Locations of soil sampling.

No.	Code	Land use type	District
1	D1	Triple rice (3L)	Vinh Long city
2	D2		Binh Minh town
3	D3		Long Ho district
4	D4		Mang Thit district
5	D5		Vung Liem district
6	D6		Tam Binh district
7	D7		Binh Tan district
8	D8		Tra On district
9	D9	Double rice-upland crop (2L-1M)	Vinh Long city
10	D10		Long Ho district
11	D11		Mang Thit district
12	D12		Binh Tan district
13	D13	Single rice-Upland crop (1L-1M)	Binh Minh town

According to the TCVN [9], the method of soil chemical analysis of specific criteria is as follows: pH_{H2O} and pH_{KCl} were extracted from the ratio of soil: water (1:5) and soil: KCl solution (1:5), measured by pH meter; the Walkley determined Total OM-Black method; Unbuffered CEC, pH7 buffered CEC, and pH 8.1 buffered CEC were determined by $BaCl_2$ measured at actual soil pH, pH7 buffer and pH 8.1, respectively; total protein was determined by the Kjeldahl method; total phosphorus (TP) was determined by colorimetric method; total potassium was determined by flame photometric method; total sulfur is determined by dry burning method, total dissolved salts are determined by gravimetric method; exchange base cations (K^+, Na+, Ca^{2+}, and Mg^{2+}) were extracted with NH_4AC (pH_7) measured by an atomic absorber, aluminum (Al^{3+}) exchanged extracted with KCl 1N, titrated with NaOH 0,01N complexed with NaF, titrated with 0.01N H_2SO_4, and zinc (Zn) was extracted by Mehlich 1, measured by atomic absorption machine.

2.3. Data Analysis

Using Microsoft Excel, descriptive statistics were used to compute the mean and standard errors and plot the data using a box plot. Cluster analysis (CA) was performed using Primer software to group soil samples with similar physiochemical characteristics, reducing the sample size to a smaller number of groups [17]. The numerical discriminant analysis (DA) method was performed using SPSS Statistical software to determine the best parameters of the two soil quality groups [22]. The larger the absolute values of the normalization coefficients, the more significantly they would contribute to the difference in soil quality groups.

3. RESULTS AND DISCUSSION

3.1. Soil Physiochemical Properties in the Study Area

3.1.1. Soil texture

Soil texture is a summation of sand, silt, and clay content proportions. Soil texture influences soil biophysical properties [23]. The soil texture of the studied samples is presented in Table 2. The average sand, silt, and clay percentage in rice cultivation soil range from 0.83–1.84%, 48.54–51.20%, to 47.03–50.63%, respectively. Clay and silt content dominates the soil composition. The soil composition of the Vinh Long Province area is classified as clay soil by the USDA Soil Taxonomy [24]. Furthermore, the predominant alluvial content in the soil texture was also reported in studies in U Minh Thuong District-Kien Giang province, Mekong Delta (Viet Nam) [12,17]. Thus, with the rate of the soil texture in the study area, it is considered good soil and suitable for plant growth and development [25].

The size of the soil's component particles will typically determine the soil textures in different geographical areas. Kekane *et al*. assert that soil texture affects root penetration and aeration [10]. It also affects the soil's nutrient content. According to Bon [7], the soil texture also determines the soil density, porosity, cohesion, and stickiness; it affects the accumulation and decomposition of humus, the adsorption capacity, the ability to supply nutrients to plants, and the activity of soil microorganisms.

3.1.2. Soil bulk density, density, and porosity

The analysis results show that the average bulk density soil in 3L, 2L-1M, and 1L-1M was relatively similar, reaching 0.91 ± 0.15 g/cm^3; 1.1 ± 0.14 g/cm^3; and 1.1 ± 0 g/cm^3, respectively [Figure 2a]. According to Dang and Hung [25], it is reported that in Vietnamese soil, bulk density usually ranges from 0.7 to 1.7 g/cm^3. Therefore, a soil density between 1.0 and 1.1 g/cm^3 would be ideal for healthy plant growth. On the other hand, farming is difficult when the soil bulk density is >1.2 g/cm^3. Moreover, crop yields are frequently low due to the high amount of clay, a lack of OM, and restrictions on root growth. Soil

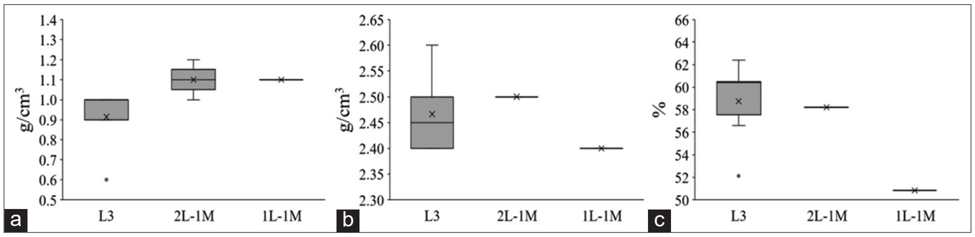

Figure 2: (a) Bulk density; (b) Density; and (c) porosity in the rice cultivating areas.

bulk density resulted within the appropriate threshold for developing rice and vegetable roots.

Figure 2b reports that the average soil densities in the soil in the 3L, 2L-1M, and 1L-1M areas were 2.47 ± 0.08 g/cm³, 2.5 ± 0 g/cm³, and 2.40 ± 0 g/cm³, respectively. The results are consistent with the average topsoil values of the main soil types in Vietnam, ranging from 2.49 to 2.83 g/cm³ [4]. Soil densities <2.5 g/cm³ are associated with high humus content, which is suitable and favorable for rice cultivation [26]. However, particularly in the 3L soil, a 2.6 g/cm³ density was observed. All soil types had a porosity value above 50% [Figure 2c], considered ideal for plant growth [27]. According to Khoa and Ti [26], high soil porosity is for plants to grow and vice versa. On the other hand, poorly aerated soil can limit roots' growth, mainly affecting nutrient absorption. The results show that density and porosity values in the study area are within the appropriate thresholds for good plant growth.

3.1.3. Soil structure stability

In farming, soil structure stability is considered an essential indicator in the physical assessment of soil quality. Itreflects the degree of association of soil particles to form chloroplasts with diameter. The more extensive and stable with texture effects and the higher the durability index, the more stable the soil structure [28]. The soil structure stability in3L, 2L-1M, and 1L-1M crops in the study area had a relatively low average value [Figure 3]. When the soil has low structural strength, it will easily be leached, and the ability to hold nutrients and water is poor and not favorable for the growth of plant roots. Studies have demonstrated a strong correlation between soil OM (SOM) content and soil structure stability [26,29,30]. Therefore, mulching the soil surface with organic materials such as rice straw, applying organic fertilizers, specially with high humic content, or combining inorganic and organic fertilizers will have a better soil structure effect [26].

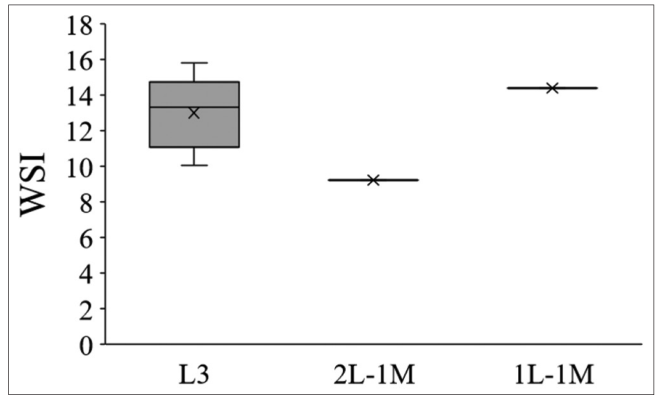

Figure 3: Soil structure stability.

Table 2: Soil texture in rice cultivating areas.

Soil texture (according to USDA's soil taxonomy	Unit	Triple rice (3L)	Double rice-upland crop (2L-1M)	Single rice-upland crop (1L-1M)
Sand	%	1.84±0.70	1.5±0.53	0.83±0
Silt	%	51.13±4.49	51.20±4.77	48.54±0
Clay	%	47.03±4.50	47.31±4.24	50.63±0

3.2. Soil Chemical Properties in the Study Area

3.2.1. Soil pH and OM

pH is an important soil property that significantly influences solute concentration and absorption in the soil [31]. In addition, soil pH affects the availability of nutrients for plants, and acidic soils typically contain higher concentrations of Fe, Mn, Zn, and Cu than alkaline soils [32]. According toKekane *et al.*, if a pH <6 is said to be acidic, pH ranges from 6 to 8.5 in average arable soil, and a pH >8.5 would be alkaline soil [10]. The average values of pH_{KCl} in 3L, 2L-1M, and 1L-1M crops were 4.26 ± 0.12, 3.93 ± 0.34, and 4.30 ± 0, respectively [Figure 4a]. The values of pH_{H2O} in triple rice, double rice-upland crop, and single rice-upland crop were 5.18 ± 0.26, 4.3 ± 0, and 5.40 ± 0, respectively [Figure 4b]. According to DONRE of Vinh Long province [15], Vinh Long province has 59,860 ha acid sulfate soil (39.23% total area), with the sulfuric horizon and sulfidic material occurring at the deep layer, which can release Al and Fe, causing plant toxicity, lowering the pH, and increasing micronutrients leaching from the soil [32]. According to Du *et al.*, soil tends to be acidic due to root activity and chemical and biological reactions occurring herein [33].

The SOM comprises plant and animal remains in various stages of decomposition, microbial cells, tissues, and substances that soil microbes produce [34]. According to Ha, if the soil is poor in OM, it accelerates leaching and soil erosion [4]. Applying composted materials to soils is expected to increase the quantity and quality of soil organic matter. The OM content in Vietnamese soil ranges from 0.5% to 7.5% and is mainly concentrated in the topsoil [4]. [Figure 4c] reports the OM content in the soil of 3L, 2L-1M, and 1L-1M, which resulted in 5.30 ± 0.81%, 4.95 ± 1.62%, and 4.00 ± 0%, respectively. A 5.1–8% OM content is relatively good for crop production [35]. According to Horneck *et al.*, the CEC, total soil N content, and other soil properties, including water-holding capacity and microbial activity, are all increased with an increase in SOM [36].

3.2.2. CEC capacity and EC

An essential characteristic of clay minerals is their ability to exchange cations and the CEC results frequently characterize and quantify sorbents in clays and soils [29,37]. In the case of unbuffered CEC [Figure 5a], the CEC values in the soil samples for 3L, 2L-1M, and 1L-1M crops were lower than those where pH 7 buffered CEC [Figure 5b] and pH 8.1 buffered CEC was applied

[Figure 5c]. According to Bon, when soil pH increases, CEC usually also increases [7]. The average values of CEC without buffer in 3L, 2L-1M, and 1L-1M crops were 12.83 ± 1.65 meq/100 g; 12.01 ± 0 meq/100 g; and 12.26 ± 0 meq/100 g, respectively [Figure 5b]. The average CEC buffered pH_7 in the soil in three rice cultivation areas corresponded to 15 ± 2 meq/100 g, 15 ± 2.45 meq/100 g, and 19 ± 0 meq/100 g. Finally, CEC buffered $pH_{8.1}$ in the soil in three rice cultivation areas had average values of 16.29 ± 1.43 meq/100 g, 15.94 ± 0 meq/100 g, and 16.86 ± 0 meq/100 g, respectively [Figure 5c]. The 1L-1M soils had the highest CEC content. According to Bon, soil with heavy texture composition is rich in clay and often has high CEC [7]. It is consistent with the results in the study, which have low to medium clay composition and then low to medium CEC content. According to the rating scale of Landon (2023), the value of unbuffered CEC in rice cultivation soil is assessed at a low level, especially for the case of pH_7 buffer CEC and pH 8.1 buffered CEC, which are in the medium range [38]. It shows that the ability to retain and exchange nutrients in rice cultivation soil in the study area is not high.

Figure 5d reports EC values which were the highest in the 2L-1M crop with 0.52 ± 0 mS/cm; for the 3L and 1l-1M crops, EC values were 0.26 ± 0.07 mS/cm and 0.23 ± 0 mS/cm, respectively. According to the rating scale of Western Agricultural Laboratories, the EC value in the soil is considered not to affect the crop [39]. However, according to Eswaran (1985), rice plants are susceptible to salinity and cannot grow if the rice soil has EC >6 mS/cm [40].

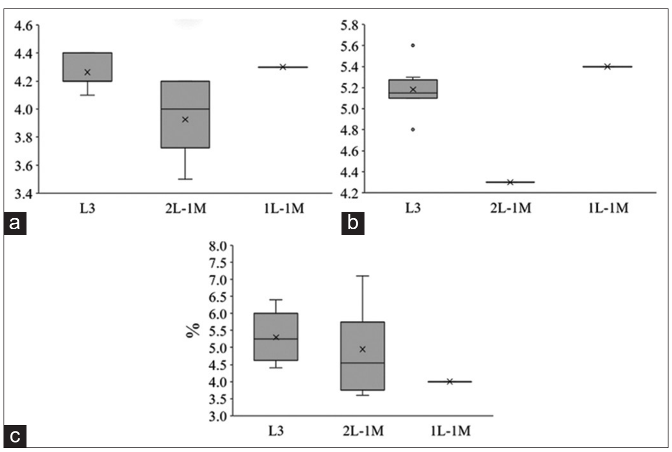

Figure 4: (a) pH_{KCl}, (b) pH_{H2O}, and (c) soil organic matter in the rice cultivating area.

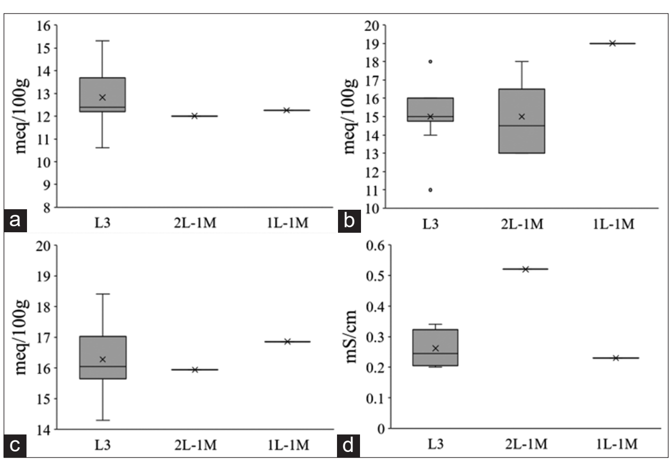

Figure 5: (a) Unbuffered cation exchange (CEC), (b) pH 7 buffered CEC, (c) pH 8.1 buffered CEC, and (d) electrical conductivity.

3.2.3. Total soil nitrogen, phosphorus, and potassium

The total nitrogen (TN) content in Vietnam ranges from 0.05 to 0.62% [4]. In the study area, the TN content in 3L, 2L-1M, and 1L-1M crops had an average value of 0.25 ± 0.06%, 0.21 ± 0.08%, and 0.26 ± 0%, respectively [Figure 6a]. According to the rating scale of Kyuma [41], the TN in the studied soil was assessed as rich, thereby contributing to an increase in the nitrogen content of the harvested products [32]. TP content in the soil in Vietnam is recorded in the range of 0.03–0.3% and usually depends on the parent rock composition, mechanical composition, and OM [4]. The results show that the TP content in soil samples in 3L, 2L-1M, and 1L-1M crops has an average value of 0.11 ± 0.04%; 0.07 ± 0.03%; and 0.08 ± 0%, respectively [Figure 6b]. Compared with the rating scale of Can [42], the soil in the 3L cultivation area in the study area is evaluated as having a moderate phosphorus level (0.081–9.13%). Especially for the soil sample cultivating 2L-1M and 1L-1M upland crops, the TP content in the soil is at the medium level (0.061–0.080%). The analysis results showed that the total potassium content in the soil in the rice cultivation areas was assessed as rich (>1.45%) according to the evaluation scale of Kyuma [41], and the soil in the area cultivating 1L-1M crop had the highest $\%K_2O$ content in the soil. Specifically, the land cultivated with 3L, 2l-1M crops, and 1L-1M crops had total potassium content of 1.71 ± 0.24%, 1.85 ± 0.10%, and 2.10 ± 0%, respectively [Figure 6c]. The research results are consistent with the potassium level threshold in Vietnam soil ranging from 0.5% to 3% [4].

3.2.4. Total soil sulfur and dissolved salts

In this study, the total soil sulfur content in the 3L, 2L-1M, and 1L-1M crops had an average value of 0.36 ± 0.01%, 0.43 ± 0.24%, and 0.05 ± 0%, respectively [Figure 7a]. It can be seen that the total sulfur concentration is high in the soil in the double rice-upland crop (2L-1M) [Figure 7a]. It indicated that the soil under rice cultivation of triple or double rice–upland crops (2L-1M) on acid sulfate soil is evaluated as low according to the rating scale of Hung [5]. Therefore, extremely acid-sulfate soil would affect the growth and development of plants.

The study showed that the total soil soluble salt content of 3L or 2L-1M and 1L-1M had the average value of 0.038 ± 0.01%, 0.035 ± 0.01%, and 0.01 ± 0%, respectively. It was highly concentrated in the 3L and 2L cultivation areas [Figure 7b]. Therefore, the total dissolved salt content has not significantly affected the crop.

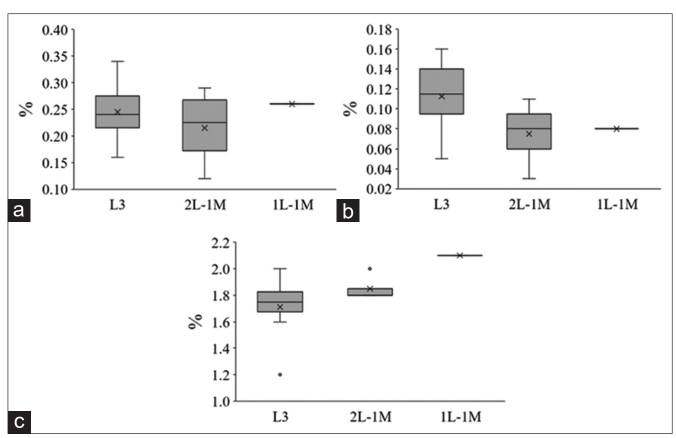

Figure 6: (a) Total nitrogen; (b) total phosphorus; and (c) total potassium.

3.2.5. Exchange base cations (K^+, Na^+, Ca^{2+}, Mg^{2+})

According to the rating scale of Horneck *et al*. [36], the exchangeable potassium content in rice soil in Vinh Long province was assessed to be low, with an average range of 0.31 ± 0.07 meq/100 g in 3L soil, 0.32 ± 0 meq/100 g in 2l-1M soil, and 0.21 ± 0 meq/100 g in 1L-1M soil [Figure 8a]. When the potassium concentration in the soil is too low, plant growth can be reduced; however, too high a potassium concentration can increase its concentration in the plant and be detrimental to the health of the consuming organism. The average exchangeable sodium content reached 0.8 ± 0.17 meq/100 g, 0.67 ± 0 meq/100 g, and 0.80 ± 0 meq/100 g, respectively, in the 3L, 2L-1M, and 1L-1M [Figure 8b]. In addition, the results showed that the Na^+ content in the study area's soil is in the average range according to the rating scale of the Euroconsult [43] cited by Hung *et al*. [44].

According to Horneck *et al*. [36], high sodium concentrations harm soil structure, permeability, and plant growth. In addition, too much Na^+ would cause saline, acidic soil and can create Na_2CO_3, affecting the growth and development of plants**.** According to Khuong, the exchangeable Ca^{2+} content in rice cultivation soil is low, ranging from 5.64 ± 0 to 7.67 ± 0 meq/100 g [Figure 8c] [45]. Calcium deficiency usually occurs only on very acidic soils, which is the reason for the low Ca content in the soil of the study area [36]. Particularly for $M^{g2}+$ content in the 3L 2L-1M and 1L-1M in the study area were evaluated at a high level according to the rating scale of Hornec*k et al*. [36], with average content ranging from 3.66 ± 0 to 4.65 ± 0.96 meq/100 g [Figure 8d].

3.2.6. Exchanged Al^{3+} and Zn

The concentration of Al^{3+} recorded in the cultivated land was low in the study area. Specifically, in 3L, 2L-1M, and 1L-1M crops, the mean exchanged Al^{3+} content was 0.51 ± 0.62 meq/100 g; 2.8 ± 0 meq/100 g and 0.52 ± 0 meq/100 g, respectively [Figure 9a]. Exchanged Al^{3+} is one of the causes of acidity. The more acidic the soil, the higher the mobile aluminum content and the more toxic it is to plants. Soils with pH_{KCl} >5 often do not have soluble aluminum [46]. On the other hand, when pH <4.5, Al^{3+} has high solubility and will replace the bases in the exchange complex [44]. In the soil, aluminum can combine with Cl^-, Br, I^-, and SO_4^{2-} to form easily hydrolyzed compounds and make the soil acidic. Besides, aluminum combines with phosphorus to create insoluble $AlPO_4$ or $Al_2(OH)_3PO_4$. That is one of the reasons for phosphorus being fixed in the soil [4].

Trace elements exist in the soil in very low proportions but are essential for plant life. Plants have six vital micronutrients: Cu, Zn, B, Mo, and Fe [4,47]. As for the Zn content in the soil in the rice-growing area of Vinh Long province, it is assessed at the Zn deficiency threshold according to the rating scale of Dierolf *et al*. [48], with values only ranging from 5.23 ± 0 to 9.69 ± 0 meq/100 g in 3L areas [Figure 9b]. Therefore, during the cultivation process, it is necessary to add this essential trace source to ensure the productivity and quality of agricultural products.

3.3. Clustering Soil Quality in the Study Area

The CA results have formed two soil quality groups, in which I gathered the most locations, including D2, D3, D4, D5, D6, D8, D12, and D13. Group II included five sites, including D1, D7, D9, D10, and D11 [Figure 10].

Group I includes the soil sampling locations in the 3L, 2L-1M, and 1L-1M areas. Soil monitoring sites in this group could be reduced from 8 to 3 locations but still represent the soil properties monitoring.

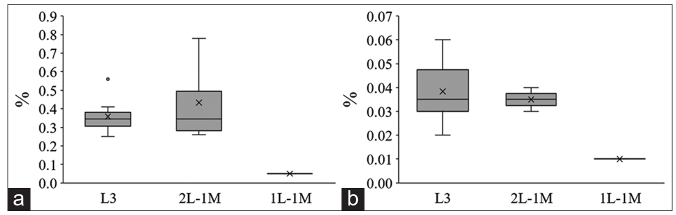

Figure 7: (a) Total sulfur and (b) total dissolved salts.

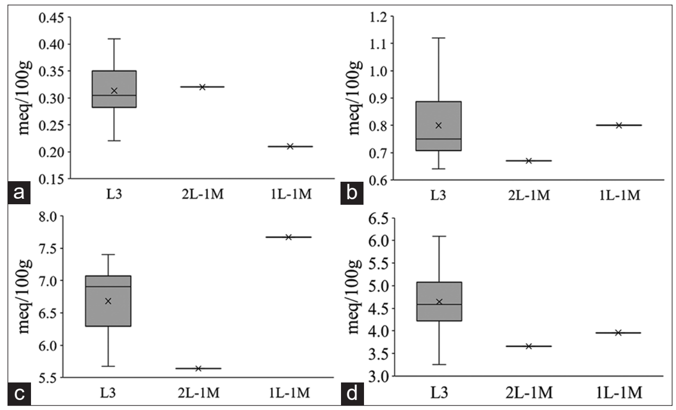

Figure 8: (a) Potassium ions; (b) sodium ions; (c) calcium ions; and (d) magnesium ions.

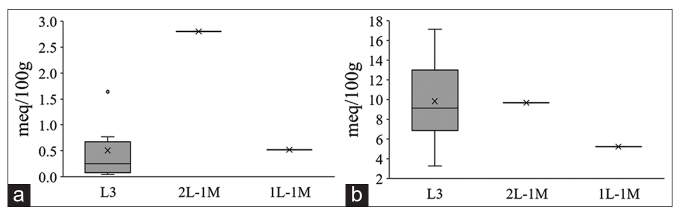

Figure 9: (a) Exchanged Al3+ and (b) Zinc.

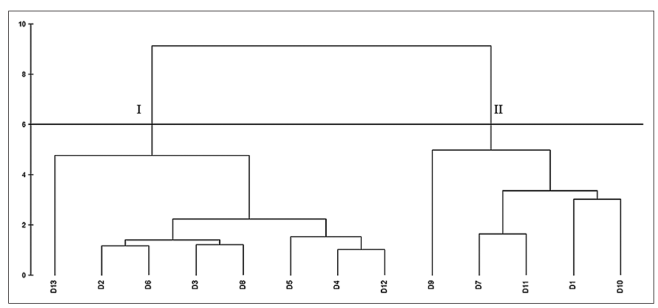

Figure 10: Clustering soil quality in the study area.

Group II comprises the soil sampling locations of the 3L and 2L-1M, where the monitoring sites could be reduced from 5 to 2 soil sampling locations. Through analysis, the CA) has suggested narrowing down from 13 initial monitoring locations to five sites, which could monitor and evaluate the physiochemical characteristics of soil in the study area, saving 61.54% of monitoring costs. In addition, the study also conducted numerical DA to find the difference between the two soil quality groups. The DA results showed the difference in soil quality mainly from exchanged Al^{3+}, EC, soil structure stability, and density with normalized coefficients of 0.613; 0.554; (−0.380); and 0.318. However, other variables also contribute to the difference, but to a lesser extent.

4. CONCLUSION

In the study area, the pH was low, and clay and silt content dominated the soil composition. Most of the physical parameters in rice cultivation soils (soil bulk density, density, and porosity) were within the appropriate thresholds for plant growth. However, soil structuredurability is assessed at a low level. The CEC value showed that the ability to hold and exchange nutrients in the arable soil was not high. EC, total soluble salts, and exchanged Al^{3+} were in the ranges of plant tolerance. The SOM, TN, phosphorus, and total potassium in rice cultivation soil were from moderate to good, rich, and average to rich, respectively. The total OM and phosphorus contents were the highest in the 3L soil. The TN and potassium were the highest in 1L-1M soil. The sulfur content in the soil was less to more in acidic soil and high in 2L-1M soil. In rice soil, base CEC was low for K^+ and Ca^{2+}, moderate for Na^+, and high for Mg^{2+}, but high cations content in 3L soil. The Zn content was relatively low for trace elements, which must be supplemented during cultivation. The CA showed that only five out of 13 locations were monitored in the study areas. The DA results showed that the difference in soil quality as constraints for rice crops was mainly from exchanged Al^{3+}, EC, soil structure stability, and density. Therefore, this work provides helpful information on soil constraints and could assist in planning the appropriate use of rice land in Vinh Long Province.

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6. AUTHORS' CONTRIBUTIONS

Vo Quang Minh: Concept and design, Data analysis/interpretation, Drafting manuscript, Critical revision of manuscript, Supervision, Final approval. PhamThanh Vu: Concept and design, Data acquisition, Data analysis/interpretation, Drafting manuscript, correspondent. Nguyen Thanh Giao: Concept and design, Data acquisition, Data analysis/interpretation, Drafting manuscript, Statistical analysis.

7. CONFLICTS OF INTEREST

The authors report no financial or any other conflicts of interest in this work.

8. ETHICAL APPROVALS

This study does not involve experiments on animals or human subjects.

9. DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author of the Department of Environment and Natural Resources of Vinh Long province, Viet Nam.

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