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Evaluating Soil Fertility and Suitability for Sustainable Rice Cultivation in Central Tongu District, Volta Region, Ghana

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Abstract

In a bid to manage soil for sustainable rice production, a study was conducted at Mafi-Dove, Central Tongu district of the Volta Region, Ghana to address the issues of soil fertility and productivity management with regard to rice production and provide data-driven insights and actionable recommendations for successful continuous rice farming. A total of 70 soil samples were collected at the depth of 0 - 30 cm and 30 - 60 cm for analysis of major nutrients and micronutrients using standard protocols. The results showed low to very low levels of essential nutrients, including nitrogen (0.01% - 0.12%), available phosphorus (3.00 - 12.37 mg/kg), and exchangeable potassium (0.11 - 0.40 meq/100g. Soil organic carbon content was notably low (topsoil: 0.89%, subsoil: 0.72%). Heavy metal analysis showed iron (219.89 - 3980.82 mg/kg), zinc (63.47 - 174.14 mg/kg), and boron (20.36 - 35.74 mg/kg) concentrations within acceptable ranges for rice cultivation. Correlation analysis revealed significant relationships between the soil properties, particularly exchangeable calcium and total exchangeable bases (r = 0.91). Furthermore, there was predominantly clay loam topsoil transitioning to clay subsoil, with a slightly acidic pH (mean 6.1 - 6.2). It is therefore recommended that soil management practices such as organic amendments (e.g., manure, compost, rice straw), implement water management protocols and maintain pH levels using liming and gypsum to enhance soil fertility, high water-holding capacity and safeguard soil structure and balance cation exchange.

Keywords

Heavy Metal, Irrigated Rice, Nutrient Profiles, Soil Fertility, Sustainable

Agriculture

1. Introduction

The Ghanaian agricultural sector faces significant challenges, including erratic rainfall patterns, prolonged droughts, low soil fertility, and over-reliance on rainfall for crop irrigation [1]. Recent studies have reported a 20% crop yield reduction due to climate variability over the past decade [2], whereas approximately 70% of agricultural land suffers from some degree of soil degradation [3]. Therefore, effective soil fertility management is essential because inadequate practices can cause up to 30% of crop yield gaps in Ghana [3].

Previous soil surveys in the region, such as those conducted by Asiamah [4], classified the soils in the study area as part of the Amo-Tefle association (Gleyic Cambisol). This soil group is widely distributed across the Volta Region of Ghana and extends into three agroecological zones, including the coastal savannah, deciduous forest, and transition zones. These zones are significant for rice production and other agricultural systems, which makes the findings from this study relevant to similar environments. For instance, Dogbe *et al.* [5] found that tailored soil management strategies can increase rice yields by up to 40% in the Volta Region, underscoring the potentially significant impact of this assessment on the project's success and overall agricultural productivity in the study area and other similar areas. This study builds on existing literature on soil fertility assessment and management in Ghana's rice-growing regions. By addressing critical aspects such as nutrient dynamics, soil pH management, and heavy metal concentrations, this study establishes a methodological framework that can be applied to other regions with similar soil and climatic conditions.

Ghana grows a lot of rice utilizing diverse types that may adapt to different agroecological zones [6]. Global rice production has surpassed 500 million tons, according to FAO estimates, whereas global consumption was 500 million tons in 2017 [7].

Ghana's rice self-sufficiency ratio rose to almost 43% in 2020 after falling from 38% in 1999 to 24% in 2006, according to Agriculture Research for Sustainable Development [8]. For food security, import substitution, and foreign exchange savings, it is therefore imperative that stakeholders in the food and agriculture sectors guarantee increased and sustained domestic production of high-quality rice. Farmers and other stakeholders have become accustomed to using irrigation and fertilizer to increase rice production over the years, which can be harmful to the soil if the fertility level of the soil and potential toxic elements (PTEs), particularly iron toxicity in irrigated rice production areas, are not taken into consideration first. The mobility and availability of the main soil nutrients may be hampered by the presence of PTEs in the majority of fertilizers currently on the market.

Most of the studies on rice production carried out in the district have not addressed the case of sustaining rice production through soil fertility management. For instance, flagship projects in the district, such as increasing rice production levels and boosting yields by Prairie Volta Limited, Global Agricultural Development Company (GADCO) and Brazil Agro Business Limited, etc did not address the issues of soil fertility management. Their focus was on the irrigation of tracts of lands. We therefore conducted this study to:

1) Address the issues of soil fertility and productivity management with regard to rice production.

2) Provide data-driven insights and actionable recommendations for successful continuous rice farming at the project site in Mafi-Dove in the Central Tongu District of the Volta region.

Soil nutrients are necessary for food production to be abundant and maintain food security. To sustain food production and maintain a healthy ecosystem, these nutrients must be present at the proper levels [9]. The three most crucial soil nutrients for crop growth are potassium (K), phosphorous (P), and nitrogen (N). Therefore, it is appropriate to investigate into this subject and offer evidence to support the Sustainable Development Goals (Agenda 2030) of the UN as well as the achievement of the global goals for food security (SDG 2) and poverty reduction (SDG 1). The United Nations approved the Sustainable Development Goals (SDGs), sometimes referred to as the Global Goals, in 2015 as a global call to action to eradicate poverty, safeguard the environment, and guarantee that everyone lives in peace and prosperity by 2030. The 17 Sustainable Development Goals (SDGs) acknowledge that development must balance social, economic, and environmental sustainability and that actions in one area will impact results in other areas [10]. In order to control soil fertility management and guarantee sustainable rice production in the research area, the findings will necessitate immediate policy changes.

If information regarding soil fertility and productivity levels is assessed, we believe that farmers and other district stakeholders have the ability to boost rice production. PTEs may also have a negative impact on rice yield in paddy fields.

2. Materials and Methods

2.1. Description of Study Area

The study area was located in Mafi-Dove, Central Tongu district of the Volta Region, Ghana, covering approximately 1100 ha within the coastal savannah agroecological zone (**Figure 1**). The climate is characterized by two rainy seasons and high temperatures, ranging from 24˚C to 33.7˚C. The geology of the area comprises recent alluvial deposits interlaid with tertiary sand, supporting coastal savannah vegetation [11].

Historical land use and current farming practices, including sand-winning activities, significantly influenced the environmental conditions of the study area. Past rice cultivation conducted nine years ago may have left residual effects on soil properties.

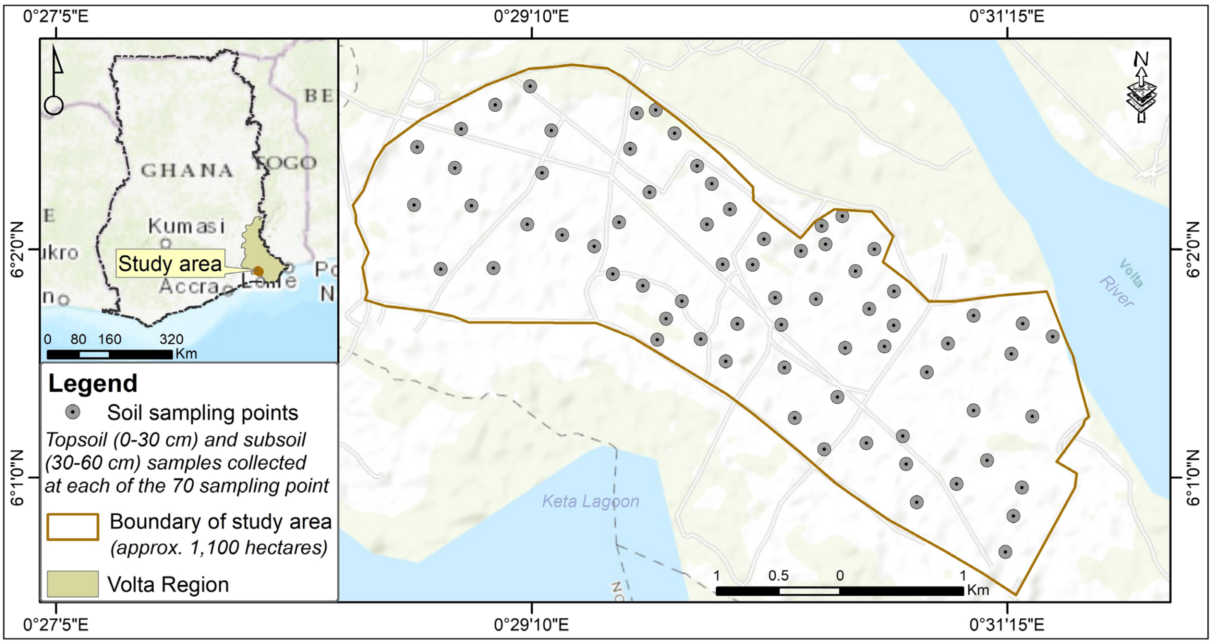


Figure 1. Study area and sampling design.

2.2. Soil Sampling and Preparation

The sampling strategy employed a systematic grid pattern with stratified random sampling to ensure comprehensive coverage of the study area. Our sampling design (70 points × 2 depths = 140 samples) was used to target both horizontal and vertical variability, with sampling locations stratified by topography and historical land use (**Figure 1**). The grid size was determined based on the topographical variation of the field and previous studies in similar agricultural settings [12, 13]. A sampling density of approximately one sample per 7.86 hectares was chosen to capture the spatial variability of soil properties across the landscape while maintaining statistical robustness [14]. Dual-depth sampling (0 - 30 cm and 30 - 60 cm) was prioritized to capture textural and nutrient stratification, as commonly recommended for irrigated rice systems [15] [16]. A total of 70 soil observation points were made, such that at each observation point, topsoil (0 - 30 cm) and subsoil (30 - 60 cm) samples were collected (**Figure 1**). The dual-depth sampling strategy was adopted to characterize the vertical heterogeneity of the soil and assess potential nutrient stratification, which is crucial for understanding root zone dynamics in rice cultivation [15]. Therefore, 140 soil samples were collected from various locations across a 1100-hectare field for analysis. A post-hoc spatial analysis (e.g., heatmaps, correlation matrices; see Results) confirmed this design's suitability to resolve variability. The soil samples were packaged, labelled and transported to the Department of Analytical Services of the CSIR-Soil Research Institute, Kumasi for analysis.

Each soil sample was appropriately labeled on its own tray after the polyethylene bags containing the samples were poured onto a shallow tray. The soil samples were air-dried for three days in a shaded, dry, open, and well-ventilated area with periodic stirring to guarantee full drying. After drying, the samples were passed through a 2 mm mesh screen to get rid of any last bits of fine material, such as crop leftovers, gravel, and roots. Samples of prepared soil were stored for analysis in the laboratory.

2.3. Analytical Procedure

A glass electrode pH meter (H19017Microprocessor) was used to measure the pH of the soil at a ratio of 1:2.5 soil to water. Two aqueous solutions with pH values of 4 and 7 were used to standardize the pH meter's glass electrode. The glass electrode was dipped into the supernatant to determine the samples' pH. Furthermore, the loss of ignition method was used to calculate the soil organic carbon (SOC) according to Agus *et al.* [17]. Available phosphorus, total nitrogen, basic cations and particle size distribution were analyzed using methods by FAO [18].

2.4. Quality Control, Data Treatment and Statistical Analyses

We employed blanks, standard solutions, and triplicate measurements for quality control, From the Global Soil laboratory network under the auspices of the Food and Agricultural Organization of the United Nations, Rome were also included in our standard reference materials.

Soil samples from the study area were compared using a one-way ANOVA. The Tukey's Honestly Significant Difference (HSD) test was used at $p < 0.05$. Before doing an ANOVA, we ran the Shapiro-Wilk Test to check that the data were normally distributed. In this situation, if $p > 0.05$ but not if $p < 0.05$, the variables were taken to have a normal distribution. We also used a Heatmap correlation matrix to investigate the relationships between the investigated soil chemical properties.

3. Results

3.1. Soil Physical Properties

The soil texture analysis indicated a predominance of clay loam in the topsoil and clay in the subsoil (**Figure 2(a)**, **Figure 2(b)**, and **Figure 3**). In the topsoil (0 - 30 cm), the textural triangle showed a clustered distribution primarily in the clay loam region, with particle size analysis indicating median values of approximately 29% sand, 42% silt, and 29% clay (**Figure 2(b)**). The subsoil (30 - 50 cm) samples showed a different distribution pattern, clustering higher in the clay region of the textural triangle, with median values of approximately 29% sand, 30% silt, and 41% clay.

The spatial distribution of soil texture classes (**Figure 3**) showed three distinct textural patterns across the study area. In the topsoil layer (0 - 30 cm), clay loam occupied approximately 61% of the area, followed by loam (33%), and clay (6%). The subsoil layer (30 - 50 cm) displayed a different distribution pattern, with clay dominating approximately 76% of the area, followed by clay loam (17%) and loam (7%).

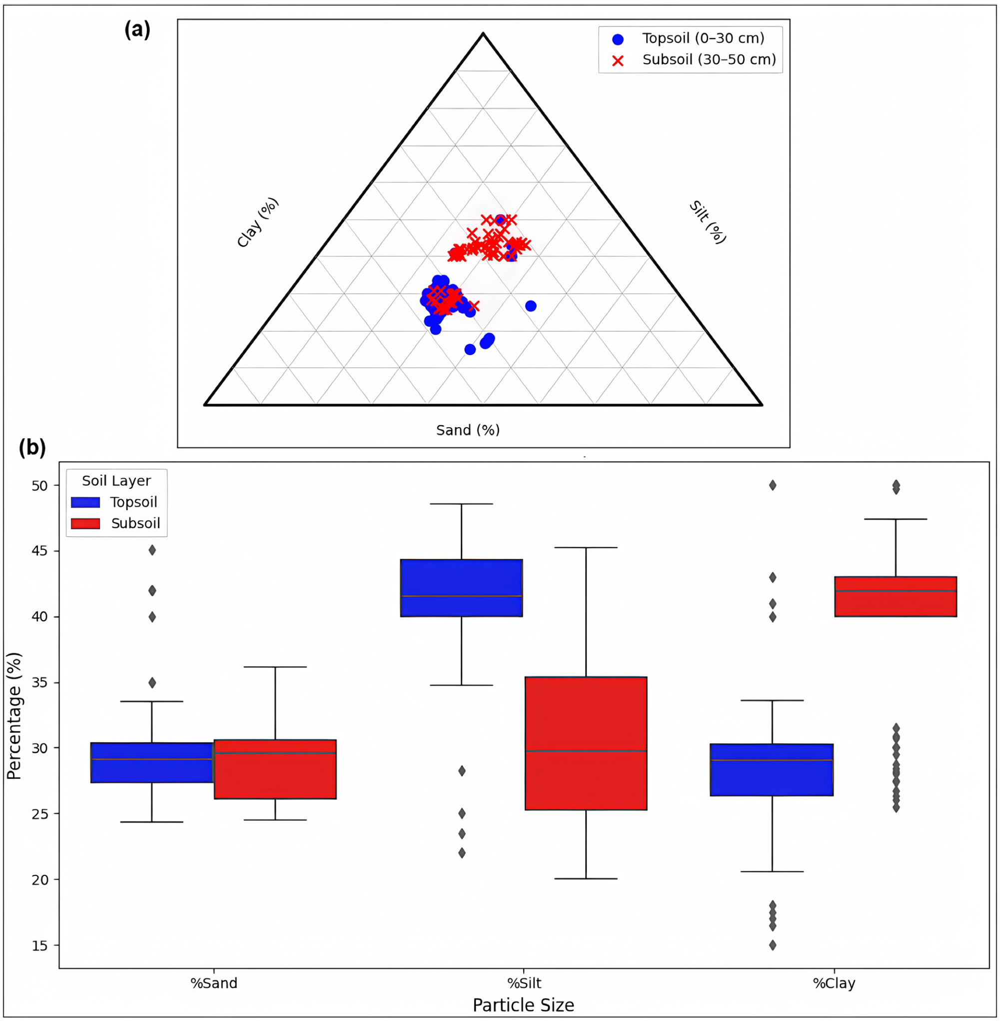


Figure 2. Soil physical properties of the study area, showing (a) textural class and (b) particle size distribution for topsoil and subsoil.

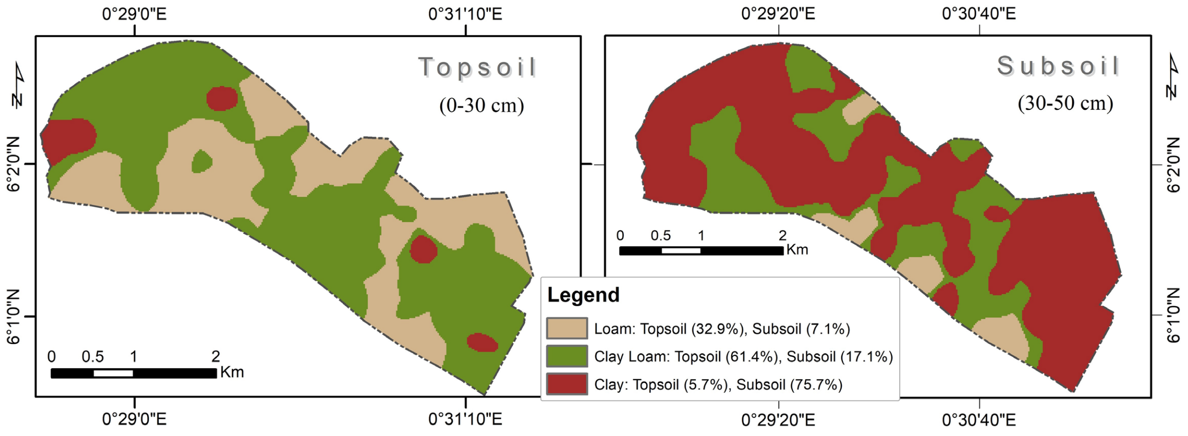


Figure 3. Spatial distribution of soil texture classes for topsoil and subsoil.

3.2. Soil Chemical Properties

The soil pH was slightly acidic, with values averaging 6.2 ± 0.27 in the topsoil (0 -

30 cm) and 6.1 ± 0.29 in the subsoil (30 - 60 cm), with a combined depth average of 6.1 ± 0.28 (**Table 1**). The topsoil pH ranged from 5.5 to 6.8 (strongly acidic to neutral), while the subsoil ranged from 5.2 to 6.5 (strongly acidic to slightly acidic). Thus, these values are predominantly within the slightly acidic range of 6.1 - 6.5, as visualized in **Figure 4(a)**. Approximately 80% of the topsoil (880 ha) and 78% of the subsoil (858 ha) areas fall within this category (**Figure 5(a)**). Localized areas in the topsoil (15%, 165 ha) and subsoil (20%, 220 ha) showed moderately acidic conditions (pH 5.6 - 6.0), while 5% (55 ha) of the topsoil was neutral (pH 6.6 - 7.3). In the subsoil, 2% (22 ha) covering the northern portion of the study area displayed strongly acidic conditions (pH 5.1 - 5.5).

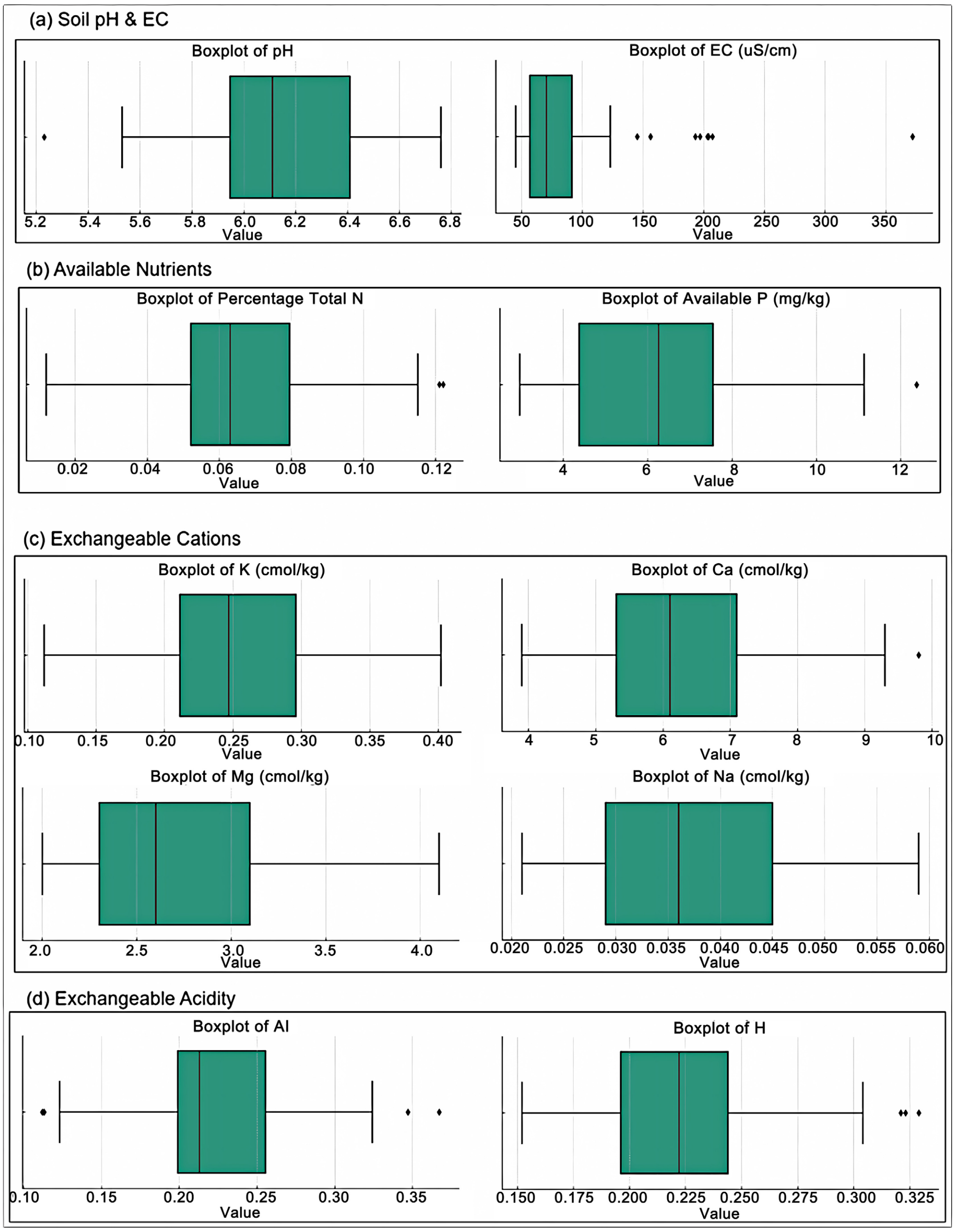
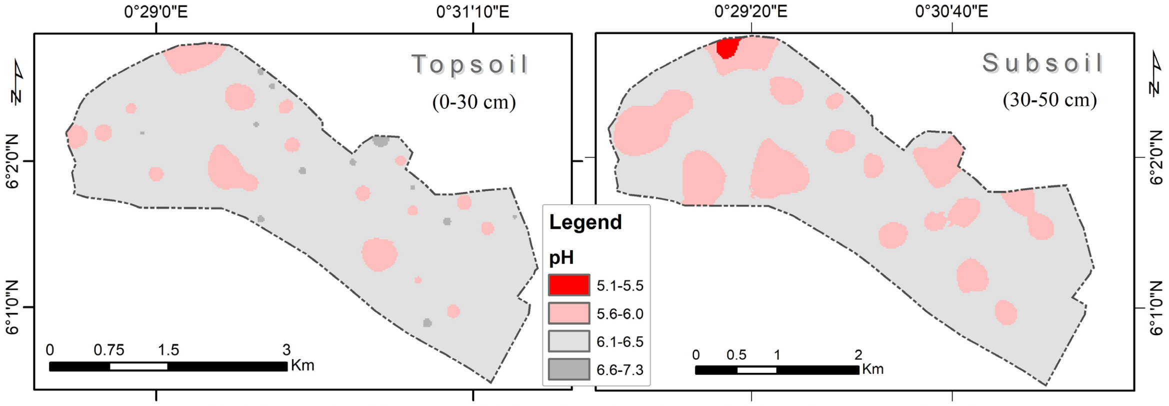


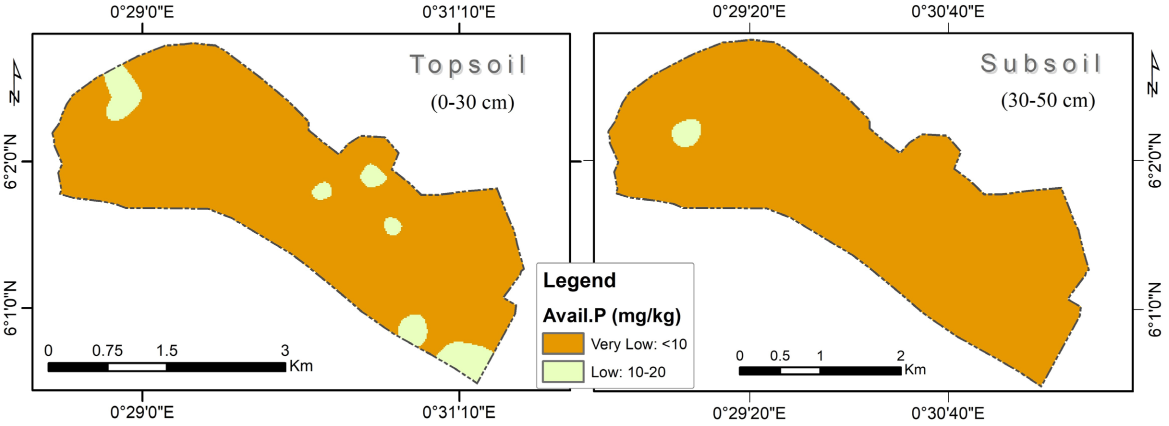
Figure 4. Distribution of soil chemical properties.

(a) Soil pH



5.1–5.5: Strongly acidic, 5.6–6.0: Moderately acidic, 6.1–6.5: Slightly acidic, 6.6–7.3: Neutral

(b) Available Phosphorous (mg/kg)



(c) Total Nitrogen

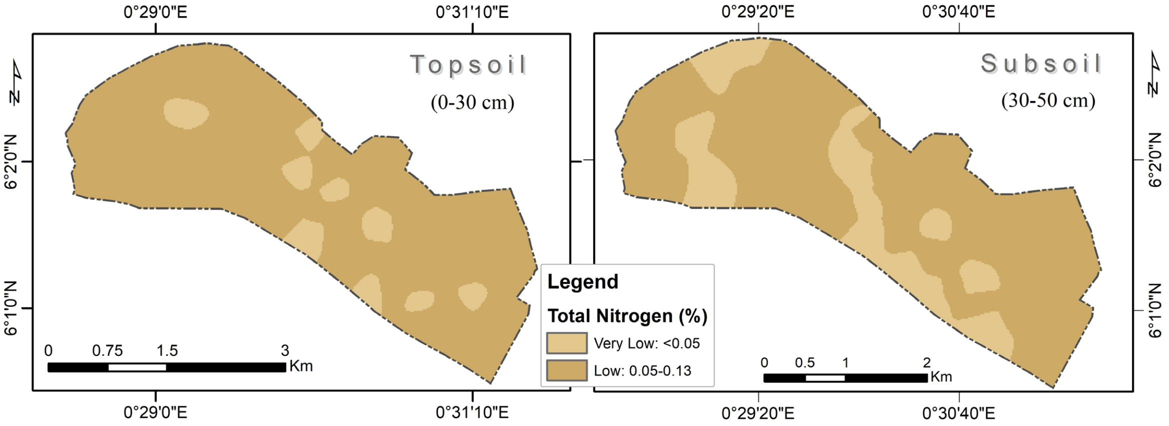


Figure 5. Spatial distribution maps of key soil chemical properties.

Exchangeable acidity analysis (Table 1 and Figure 4(d)) corroborated the soil pH observations, with exchangeable aluminum (Exch. Al) averaging 0.24 ± 0.05meq/100g in the topsoil (0 - 30 cm) and 0.22 ± 0.05 meq/100g in the subsoil (30 - 60 cm). Similarly, exchangeable hydrogen (Exch. H) averaged 0.22 ± 0.04 meq/100g in the topsoil and 0.23 ± 0.04 meq/100g in the subsoil (Table 1). The

Exch. Al values ranged from 0.11 to 0.37 meq/100g, while Exch. H ranged from 0.15 to 0.33 meq/100g (**Table 1** and **Figure 4(d)**), indicating relatively stable levels of exchangeable acidity throughout the field. These values align with the slightly acidic pH conditions recorded in the study area.

Table 1. Soil chemical properties (Mean, Range, ± SD) for topsoil, subsoil, and combined depths.

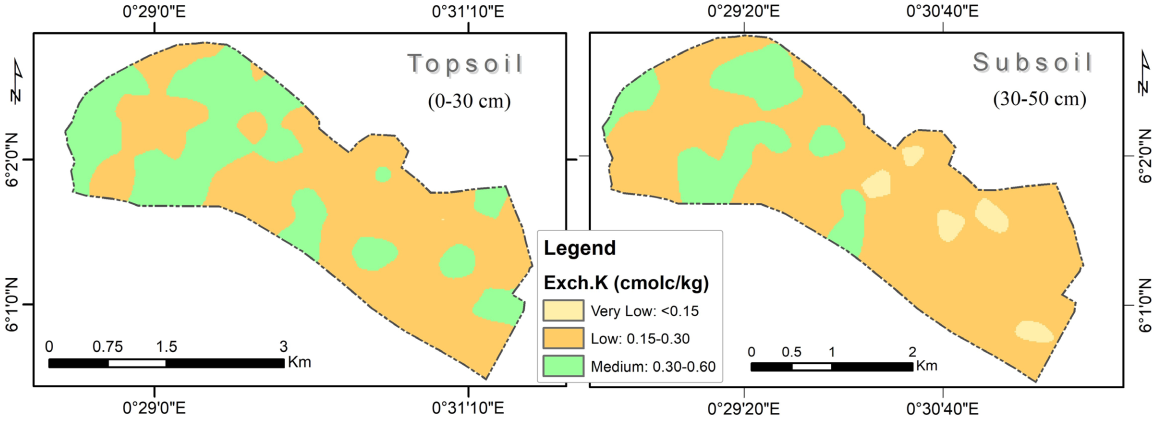
Soil Property	Unit	Topsoil (0 - 30 cm)	Subsoil (30 - 60 cm)	Topsoil & Subsoil (0 - 60 cm)
		($n = 70$)	($n = 70$)	($n = 140$)
pH	-	6.2 (5.5 - 6.8) ± 0.27	6.1 (5.2 - 6.5) ± 0.29	6.1 (5.2 - 6.8) ± 0.28
EC	µS/cm	90.6 (49 - 372) ± 49.32	72.1 (45 - 197) ± 26.74	81.36 (45 - 372) ± 40.61
Avail.P	mg/kg	6.97 (3.00 - 12.37) ± 2.13	5.67 (3.00 - 10.26) ± 1.82	6.32 (3.00 - 12.37) ± 2.08
Tot.N	%	0.07 (0.01 - 0.12) ± 0.02	0.06 (0.03 - 0.12) ± 0.02	0.07 (0.01 - 0.12) ± 0.02
Exch.K	meq/100g	0.28 (0.17 - 0.40) ± 0.07	0.24 (0.11 - 0.39) ± 0.06	0.26 (0.11 - 0.40) ± 0.07
Exch.Ca		6.56 (3.9 - 9.3) ± 1.20	5.92 (4.2 - 9.8) ± 1.11	6.24 (3.9 - 9.8) ± 1.20
Exch.Mg		2.9 (2 - 4.1) ± 0.57	2.69 (2 - 4.1) ± 0.53	2.77 (2 - 4.1) ± 0.55
Exch.Na		0.04 (0.02 - 0.06) ± 0.01	0.04 (0.02 - 0.06) ± 0.01	0.04 (0.02 - 0.06) ± 0.01
TEB		9.74 (6.84 - 13.09) ± 1.35	8.89 (6.84-14.05) ± 1.34	9.31(6.84-14.05) ± 1.41
Exch. Al		0.24 (0.12 - 0.37) ± 0.05	0.22 (0.11 - 0.32) ± 0.05	0.23 (0.11 - 0.37) ± 0.05
Exch. H		0.22 (0.15 - 0.32) ± 0.04	0.23 (0.15 - 0.33) ± 0.04	0.22 (0.15 - 0.33) ± 0.04
% OC	%	0.89 (0.42 - 2.13) ± 0.32	0.72 (0.30 - 1.52) ± 0.27	0.81 (0.30 - 2.13) ± 0.30
% OM		1.53 (0.72 - 3.67) ± 0.54	1.25 (0.51 - 2.62) ± 0.46	1.39 (0.51 - 3.67) ± 0.52

The soil electrical conductivity (EC) analysis (**Table 1** and **Figure 4(a)**) revealed a range of values across the study area, from 45 to 372 µS/cm, with a mean of 90.6 ± 49.32 µS/cm in the topsoil (0 - 30 cm) and 72.1 ± 26.74 µS/cm in the subsoil (30 - 60 cm). All the EC values were well below 2000 µS/cm, indicating non-saline conditions across the entire study area for both topsoil and subsoil.

The analysis of available nitrogen (Total N) and available phosphorus (Avail. P) revealed spatial variability across the study area (**Figure 5(b)** and **Figure 5(c)**). Total N concentrations averaged 0.07 ± 0.02% in the topsoil (0 - 30 cm) and 0.06 ± 0.02% in the subsoil (30 - 60 cm), with values ranging from 0.01 to 0.12% across all depths (**Table 1** and **Figure 4(b)**). Available P levels averaged 6.97 ± 2.13 mg/kg in the topsoil and 5.67 ± 1.82 mg/kg in the subsoil, with values ranging from 3.00 to 12.37 mg/kg in the combined depths (0 - 60 cm). The boxplots (**Figure 4(b)**) show Total N values centered near 0.06%, with most between 0.04% and 0.08%, and outliers above 0.10%. Avail. P has a median of around 6 mg/kg, ranging from 5 to 8 mg/kg, with outliers from 3 to 12 mg/kg, indicating variability across the area. The spatial distribution maps (**Figure 5(b)** and **Figure 5(c)**) classify Total N concentrations as predominantly low across the study area, while Avail. P levels vary from low to high, with localized zones showing higher concentrations. These classifications reflect the range of nutrient availability across the sampled profiles.

Exchangeable potassium (K) concentrations averaged 0.28 ± 0.07 meq/100g in the topsoil (0 - 30 cm) and 0.24 ± 0.06 meq/100g in the subsoil (30 - 60 cm), ranging from 0.11 to 0.40 meq/100g across depths (Table 1). Figure 6(a) indicates low to medium levels, with relatively higher concentrations in the western and northern zones of the topsoil and scattered medium levels in the subsoil. The boxplot (Figure 4(c)) shows a relatively narrow variability overall, with most values clustered between 0.20 and 0.30 meq/100g. Exch. Ca levels averaged 6.56 ± 1.20 meq/100g in the topsoil and 5.92 ± 1.11 meq/100g in the subsoil, with a range of 3.90 - 9.80 meq/100g (Table 1). Boxplots (Figure 4(c)) show minimal outliers and relatively even distribution across both depths, with slightly lower concentrations in the subsoil. Exch. Mg concentrations averaged 2.90 ± 0.57 meq/100g in the topsoil and 2.69 ± 0.53 meq/100g in the subsoil, with a combined range of 2.00 - 4.10 meq/100g (Table 1). Boxplots (Figure 4(c)) depict a consistent spread, with slightly higher median values observed in the topsoil. Exch. Na levels were uniform across depths, averaging 0.04 ± 0.01 meq/100g, with a range of 0.02 - 0.06 meq/100g (Table 1). Boxplots (Figure 4(c)) reveal minimal variability and an overall low spread for this parameter.

(a) Soil Exchangeable Potassium (cmolc/kg)



(b) Soil Organic Carbon (%)

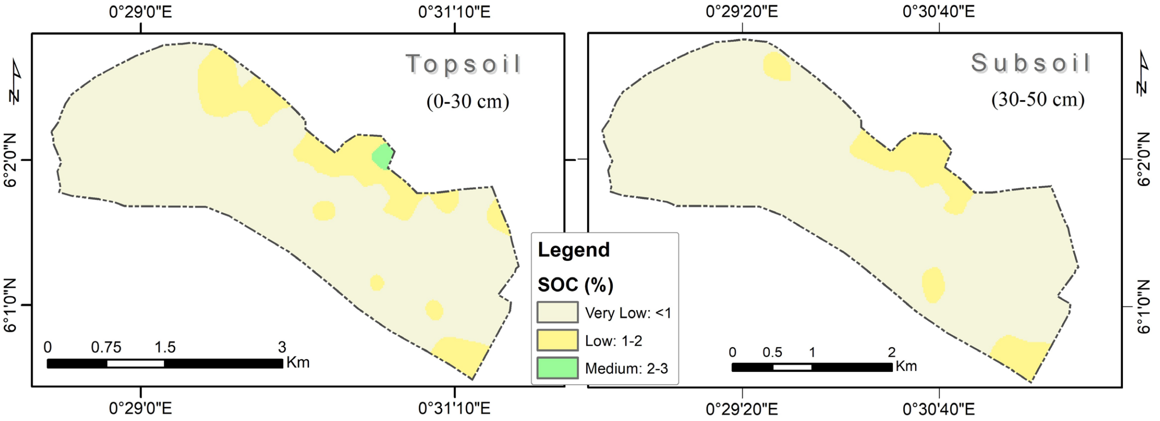
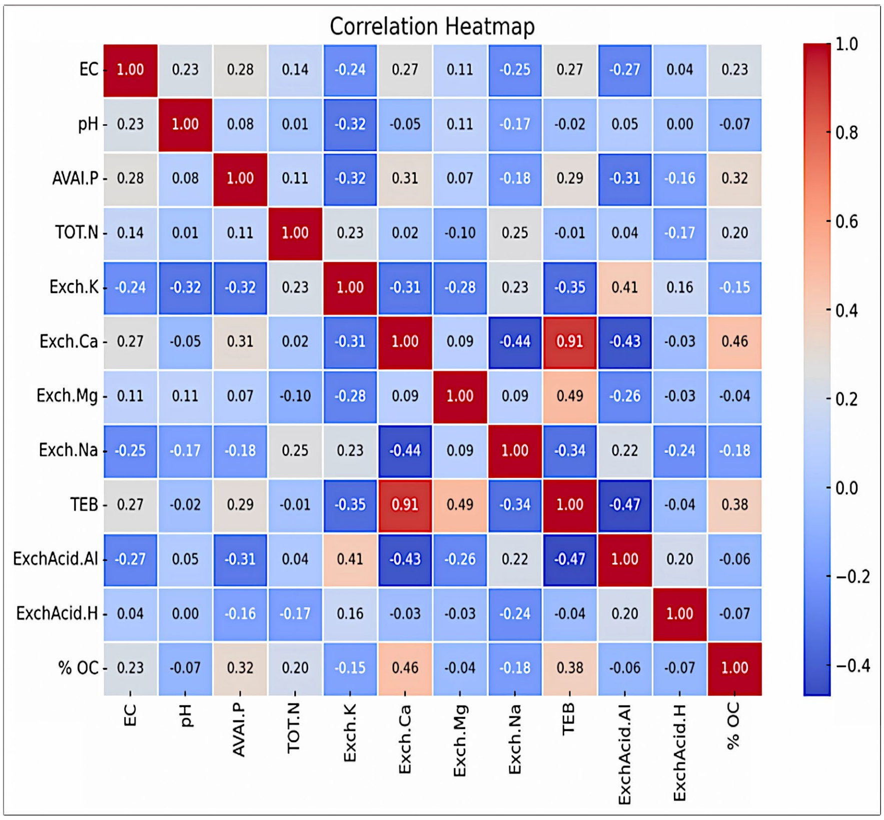


Figure 6. Supplementary distribution maps of soil chemical properties.

Soil organic carbon (SOC) levels averaged 0.89 ± 0.32% at 0 - 30 cm, with values ranging from 0.42 to 2.13% in the topsoil (**Table 1**). The SOC map in **Figure 6(b)** shows predominantly low to medium SOC levels, with higher concentrations in the northwest and central parts of the study area. In the subsoil (30 - 60 cm), SOC averaged 0.72 ± 0.27%, ranging from 0.30 to 1.52% (**Table 1**). The map highlights predominantly low SOC levels, with a few scattered medium concentrations. Across the full 0 - 60 cm depth, SOC averaged 0.81 ± 0.30%, ranging from 0.30 to 2.13% (**Table 1**). The distribution maps show that topsoil organic carbon levels were mostly low to medium across the area, with some higher concentrations in the northwest and central regions. The subsoil (30 - 60 cm) had predominantly low organic carbon levels, with pockets of very low levels in the eastern part and significant portions of medium levels in the western part of the study area (**Figure 6(b)**).

3.3. Relationship between Chemical Properties

Figure 7 illustrates the relationships among the soil properties using a correlation matrix. A strong positive correlation (r = 0.91, $p < 0.001$) was observed between exchangeable calcium (Exch.Ca) and total exchangeable bases (TEB), which indicates calcium's substantial contribution to base saturation in these soils.



	EC	pH	AVAI.P	TOT.N	Exch.K	Exch.Ca	Exch.Mg	Exch.Na	TEB	ExchAcid.Al	ExchAcid.H	% OC
EC	1.00	0.23	0.28	0.14	-0.24	0.27	0.11	-0.25	0.27	-0.27	0.04	0.23
pH	0.23	1.00	0.08	0.01	-0.32	-0.05	0.11	-0.17	-0.02	0.05	0.00	-0.07
AVAI.P	0.28	0.08	1.00	0.11	-0.32	0.31	0.07	-0.18	0.29	-0.31	-0.16	0.32
TOT.N	0.14	0.01	0.11	1.00	0.23	0.02	-0.10	0.25	-0.01	0.04	-0.17	0.20
Exch.K	-0.24	-0.32	-0.32	0.23	1.00	-0.31	-0.28	0.23	-0.35	0.41	0.16	-0.15
Exch.Ca	0.27	-0.05	0.31	0.02	-0.31	1.00	0.09	-0.44	0.91	-0.43	-0.03	0.46
Exch.Mg	0.11	0.11	0.07	-0.10	-0.28	0.09	1.00	0.09	0.49	-0.26	-0.03	-0.04
Exch.Na	-0.25	-0.17	-0.18	0.25	0.23	-0.44	0.09	1.00	-0.34	0.22	-0.24	-0.18
TEB	0.27	-0.02	0.29	-0.01	-0.35	0.91	0.49	-0.34	1.00	-0.47	-0.04	0.38
ExchAcid.Al	-0.27	0.05	-0.31	0.04	0.41	-0.43	-0.26	0.22	-0.47	1.00	0.20	-0.06
ExchAcid.H	0.04	0.00	-0.16	-0.17	0.16	-0.03	-0.03	-0.24	-0.04	0.20	1.00	-0.07
% OC	0.23	-0.07	0.32	0.20	-0.15	0.46	-0.04	-0.18	0.38	-0.06	-0.07	1.00

Figure 7. Correlation heatmap showing the interrelationship of soil properties.

The analysis also revealed several moderate positive correlations. For example, exchangeable calcium and organic carbon (r = 0.46, $p < 0.01$), exchangeable magnesium and TEB (r = 0.49, $p < 0.01$), and exchangeable potassium and exchangeable aluminium (r = 0.41, $p < 0.01$). Significant negative correlations emerged between exchangeable calcium and sodium (r = −0.44, $p < 0.01$), TEB and exchangeable aluminium (r = −0.47, $p < 0.01$), and pH with exchangeable potassium (r = −0.32, $p < 0.05$).

However, the majority of the correlations were weak (r < ±0.30), suggesting limited interdependence among most of the soil properties in the study area.

3.4. Heavy Metal Concentrations

The heavy metal analysis conducted across the topsoil (0 - 30 cm) of the study site revealed varying concentrations of iron (Fe), zinc (Zn), and boron (B). Fe concentrations ranged from 219.89 to 3980.82 mg/kg, with a mean of 1384.45 ± 1118.70 mg/kg. The distribution of Fe values showed a bimodal pattern, with one peak around 600 - 800 mg/kg and another around 3000 - 3500 mg/kg (**Figure 8**).

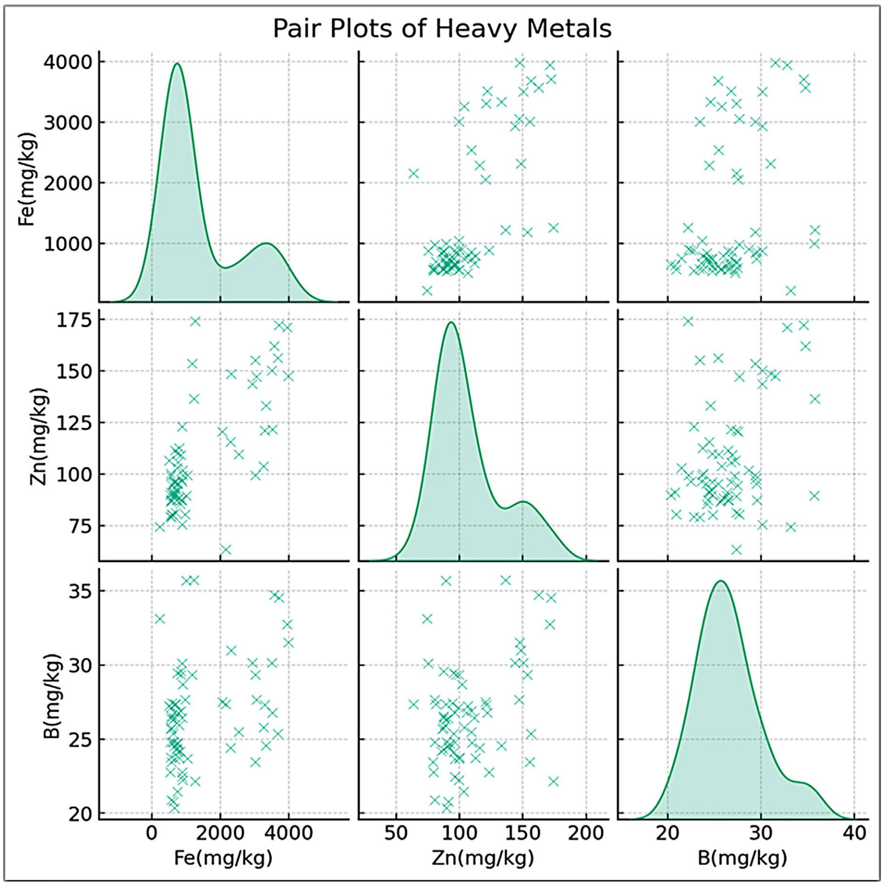


Figure 8. Pair plots for the selected metals.

Zn concentrations ranged from 63.47 to 174.14 mg/kg, with a mean of 106.93 ± 26.74 mg/kg. The distribution of Zn values was relatively normal and unimodal, peaking around 90 - 110 mg/kg (**Figure 8**). The median concentration was 96.94

mg/kg, slightly lower than the mean, suggesting a slight skew toward higher Zn values.

B concentrations ranged from 20.36 to 35.74 mg/kg, with a mean of 26.57 ± 3.49 mg/kg. The distribution of B values was relatively normal and unimodal, peaking around 25 - 30 mg/kg (**Figure 8**). The median concentration was 26.38 mg/kg, closely aligned with the mean, indicating a balanced and symmetrical distribution without significant skewness.

4. Discussion of the Results

4.1. Overview of Soil Nutrient Status and Implications for Rice Farming

The nutrient status of soils in the study area demonstrates the critical need for targeted interventions to address specific nutrient deficiencies that constrain rice farming. The findings of this study, conducted on Amo-Tefle soils (Gleyic Cambisol), provide valuable insights not only for Mafi-Dove but also for other parts of Ghana and beyond where similar soils occur. Asiamah [11] reported that these soils are prevalent across the Volta Region and are representative of the coastal savannah, deciduous forest, and transition zones. This broad distribution enhances the relevance of the study, offering a template for soil management practices in comparable agroecological settings. The results of this study are important for targeted soil fertility management approaches in addressing nutrient deficiencies, which are critical for rice productivity and sustainable agricultural development.

The nutrient challenges observed in this study may reflect broader trends affecting rice production in similar agroecological environments, given the widespread occurrence of the Gleyic Cambisol soils. Addressing these challenges requires a thorough understanding of essential nutrients critical for crop growth and productivity. Nitrogen (N), phosphorus (P), and potassium (K) are essential for rice productivity, while calcium (Ca), magnesium (Mg), and micronutrients such as iron (Fe), boron (B), and zinc (Zn) significantly influence crop health and yield [19]-[22]. The observed nutrient levels in both topsoils and subsoils present challenges and opportunities to refine management practices and improve rice yields through site-specific nutrient management strategies in the study area and its environs within the coastal savannah regions of Ghana.

Nitrogen is fundamental for vegetative growth and yields in rice. The very low to low observed total nitrogen levels in topsoils and subsoils, ranging from 0.01% in subsoils to 0.12%, are within the range reported for similar soils in the savannah region [16] [23] [24]. For instance, Bayala and Ouedraogo [24] observed nitrogen levels in topsoils ranging from 0.06% to 0.14%, while subsoils show even lower levels, ranging from 0.01% to 0.07%. These low levels remain insufficient to support the nutrient demands of high-yielding rice varieties without supplementation. Nitrogen deficiencies, often characterized by stunted growth and yellowing leaves in the early vegetative stages, have been reported in similar low-input rice farming systems in Ghana. These deficiencies are particularly pronounced in fields with limited organic matter content or insufficient crop residue incorporation [25] [26]. Segda *et al.* [26] found a positive correlation between increased nitrogen in rice crops and improved yields. For example, they studied irrigated rice systems in Burkina Faso to confirm the significance of nitrogen for rice yields, noting that nitrogen uptake was a major yield-limiting factor. Split applications of nitrogen fertilizer are suggested to provide a steady nutrient supply throughout the crop [26]. Split nitrogen fertilizer treatments can be used to provide a consistent supply of nutrients during the crop cycle.

Phosphorus, essential for root development and energy transfer in plants, is often limiting in rice-growing soils across the Volta Basin and most Ghanaian soils [4] [27]. The soils of the study area display very low phosphorus levels (averaging 6.32 mg/kg), which aligns with widespread phosphorus deficiencies reported across acidic soils, especially from irrigated rice fields in Ghana's Ashanti and Northern regions [16] [28] and other savannah agroecological zones [24]. If left unaddressed, such deficiencies could impede early rice establishment and overall yield potential, necessitating the use of phosphorus-rich fertilizers or soil amendments like rock phosphate. This phenomenon is affirmed by Issaka *et al.* [28], who categorized phosphorus as a "major problem" in Ghanaian soils, emphasizing the need for phosphorus fertilizer application to enhance crop production. Studies emphasize the application of phosphorus-rich fertilizers or rock phosphate to mitigate these deficiencies, particularly in soils with pH values that limit phosphorus availability [4]. Balancing phosphorus inputs with environmental safeguards against leaching remains imperative for sustainable productivity. Additionally, to remedy shortages and improve early rice establishment, phosphorus-rich fertilizers or soil amendments such as rock phosphate can be used.

Potassium, which is recognized as essential for rice grain filling [29]-[31], appears to be relatively limited in the study area's soils (0.11 to 0.40 meq/100g), with concentrations ranging from low to moderate levels. The K nutrient trend therefore varies spatially across given fields, which aligns with low K concentration levels observed by Segda *et al.* [26] and Buri *et al.* [16], and even widespread deficiency, particularly in topsoils and subsoils [32] [33]. Consequently, potassium fertilization is recommended, especially in areas with lower potassium levels, to ensure proper grain development [25] [34]. This is because continuous rice cultivation without adequate replenishment of potassium can deplete reserves, as observed in other West African rice production systems [21] [35]. This highlights the need for balanced fertilization practices, including potassium inputs, to sustain soil fertility and ensure optimal yields.

Our sampling density of approximately one sample per 7.86 hectares (70 points × 2 depths = 140 samples across 1100 ha) aligns with established protocols for rice soil surveys in West Africa. This includes Buri *et al.* [16], who employed 1 sample/5 ha for nutrient mapping in Ghana's Voltaian Basin, and Tsujimoto *et al.* [34], who resolved pH/fertility trends with 60 points across 900 ha in similar coastal savannah agroecologies. This design ensured a statistically robust characterization of spatial variability while accommodating field constraints.

Micronutrients, particularly zinc, play a significant role in rice growth and grain development. Zinc deficiency, a common problem in submerged soils used for rice, has been identified in several rice-growing regions in Ghana [36] [37]. Such deficiencies manifest as poor seedling vigor and chlorosis, especially under conditions of prolonged flooding or high soil pH. Incorporating zinc-enriched fertilizers or foliar sprays could mitigate these challenges and enhance productivity. The average zinc levels (106.93 mg/kg) in the studied soils are generally within the acceptable range for rice cultivation comparable to similar works in the region [38] with levels of 0.04 - 0.18 mg/kg. However, areas with lower zinc levels might require zinc supplementation to prevent stunted growth, yellowing of leaves, and reduced tillering in rice plants, as supported by Alloway [39].

The iron levels in the studied soils, ranging from 220 to 3981 mg/kg, fall within the typical range for most soils, and toxicity concerns are not a significant issue, consistent with findings by Opuni *et al.* [38], who reported levels between 0.43 and 12.49 mg/kg. Nevertheless, high iron concentrations can impact the availability of other essential nutrients, emphasizing the need for regular monitoring to maintain optimal nutrient balance. In areas with elevated iron levels, selecting rice varieties tolerant to high iron conditions could be beneficial.

As a trace element, boron requires meticulous management in rice cultivation, given its narrow threshold between deficiency and toxicity. Fortunately, the average boron level of 26.57 mg/kg in the studied soils falls within the normal range. Nevertheless, regular monitoring of boron levels and adjustments to fertilization practices are crucial to prevent adverse effects on rice growth, as emphasized by Lordkaew *et al.* [40]. Regular monitoring of heavy metal concentrations, particularly iron and zinc, can be conducted to prevent potential toxicity and ensure balanced nutrient availability. In regions where iron levels are high, rice cultivars that can withstand high iron circumstances can be used.

4.2. Role of Soil Physical Properties in Rice Farming

Soil texture analysis in this study indicated a predominance of loam in the topsoil and clay in the subsoil, suggesting the beginning of the downward movement of clay minerals through the soil profile. The accumulation of this illuviated clay may influence soil structure, drainage, and nutrient availability, which are critical factors for optimizing soil management strategies in irrigated rice cultivation [41].

Particle size and texture significantly influence water dynamics in rice fields. Clayey soils, dominant in the subsoil of the study area, tend to have smaller pore spaces, resulting in slower water infiltration and higher water holding capacity. This characteristic can be beneficial for rice cultivation, which requires prolonged periods of soil saturation or flooding [42]. However, excessive clay content can lead to poor drainage, creating conditions of waterlogging that may negatively impact root growth and nutrient availability [33]. On the other hand, loamy topsoil, as observed in the study, offers a balance between drainage and water retention, promoting healthy root development and efficient nutrient uptake.

Managing this soil texture for continuous rice cropping requires careful consideration. Continuous rice cropping, particularly with practices like puddling, can further modify soil texture, especially in the topsoil. Puddling, a common practice in rice cultivation, breaks down soil aggregates and increases the proportion of finer particles [16]. While puddling can improve water retention and nutrient availability in the short term, it can also lead to soil compaction and reduced permeability over time [16] [27]. Therefore, incorporating organic matter is crucial to mitigate the potential negative impacts of continuous puddling and maintain a favourable soil structure for rice production. This is especially important in the long term, as while puddling might influence topsoil structure in the short term, significant changes in soil texture generally occur over extended periods.

The results of the soil's physical characteristics, particularly the particle size analysis and texture, align with those reported by other scholars for the study area. For instance, research in the Voltaian Basin of Ghana by Senayah *et al.* [42] identified *Volta series* (Gleysol) as moderately suitable for rice due to its higher clay content, while *Lima series* (Planosol) demonstrated marginal suitability because of its sandy loam topsoil. This finding underlines the importance of considering soil texture during variety selection and implementing appropriate management practices to address specific soil limitations.

4.3. Soil Organic Carbon and Its Implication for Rice Farming

Soil organic carbon (SOC) is a crucial component of sustainable farming, significantly influencing soil fertility and overall agricultural productivity. The results indicate that the average SOC level in the topsoil of the study area was 0.89% and 0.72% in the subsoil, which indicates low average levels of SOC. These levels align with similar studies of the regions of the savannah agroecology [16] [23]. Comparing these findings to other rice farming studies in the region reveals that the Mafi-Dove community generally shows similar or slightly higher SOC levels in certain areas. For instance, in the Jolo Kwaha watershed, located in the savannah agroecological zone of Ghana, the mean organic carbon level in the lowlands was reported to be 0.61%, slightly lower than the Mafi-Dove area's average [16]. However, the Mankran watershed in the forest agroecological zone of Ghana reported a mean organic carbon value of 1.2% [16], which is higher than the Mafi-Dove area.

The low levels of SOC in the Mafi-Dove study area could be attributed to several factors including the following: (1) high temperatures (24˚C - 33.7˚C) accelerate organic matter decomposition, leading to rapid SOC loss [19] [23]; (2) removal of crop residues for livestock feed or fuel deprives the soil of organic matter inputs [4] [27] [43]; (3) sand-winning activities disrupt the soil profile, removing nutrient-rich topsoil, compacting the soil, altering water dynamics, and worsening erosion and its effects [4] [44]; (4) historical rice cultivation followed by the cultivation of cassava, maize, and pepper without sufficient replenishment of organic matter has contributed to SOC depletion [27] [43]; (5) limited use of organic amendments, such as farmyard manure or compost, results in a gradual decline of SOC [23] [27]; and (6) while the predominance of loam in the topsoil and clay in the subsoil provides potential for better SOC retention, inadequate organic matter management likely limits this benefit. Additionally, spatial variability in SOC levels suggests the influence of localized factors such as soil type, topography, and management practices. Several studies have emphasized the critical role of soil organic matter in improving soil structure, water-holding capacity, and nutrient availability in savannah agroecological zones [4] [19] [45].

4.4. Soil Acidity and Nutrient Availability

The soil pH in the Mafi-Dove study area, averaging 6.1 to 6.2, generally falls within the optimal range for rice cultivation. While rice can grow within a broader pH range of 4.2 - 8.5 [46], the most favourable range for nutrient availability and uptake is 5.5 - 7.0 [38]. The slightly acidic pH in the study area supports healthy growth, minimises the risk of aluminium toxicity, and contributes to potentially good yields [32] [47].

Localized variations in pH, ranging from 5.2 to 6.8, were observed across the study area. Soils with pH below 5.5 may increase aluminium availability, which can inhibit root development and nutrient uptake, while soils with pH above 7.0 may limit the availability of essential nutrients like iron and zinc [47].

The findings align with observations in Ghana and West Africa, where lowland soils, including those used for rice cultivation, often exhibit low fertility and slightly to strongly acidic pH levels. By comparison, soils in drier savannah zones, such as the Volta and Lima soil series, are strongly acidic with pH levels below 5.0 [16]. Mafi-Dove's slightly acidic soils reflect the distinct environmental influences of the coastal savannah zone, differing from the stronger acidity of inland savannah soils [16] [42].

The study highlights the critical link between soil pH and nutrient availability for rice cultivation. Maintaining a pH range of 5.5 - 7.0 is essential for nutrient uptake and minimizing risks like aluminium toxicity. Regular soil testing and lime-based amendments, such as ground or dolomitic limestone, can help neutralise acidity and sustain optimal pH levels [48]. Adding organic matter, such as compost or crop residues, can further enhance soil buffering capacity and stabilize pH in the long term [5]. These measures will ensure the continued suitability of Mafi-Dove soils for sustainable rice farming. Additionally, it is possible to neutralize soil acidity and maintain ideal pH values for rice production by regularly testing the pH of the soil and using lime-based supplements, such as ground limestone.

4.5. Correlation between Soil Properties and Implications for Soil Fertility

The strong positive correlation between exchangeable calcium and TEB (r = 0.91) demonstrates calcium's dominance in the soil exchange complex, which is characteristic of tropical agricultural soils [49]. This implies that, especially in Ghana's wetland environments, strategic calcium management techniques like the split application of calcium-rich supplements could improve base saturation and overall soil fertility for rice agriculture.

The moderate correlation between organic carbon and exchangeable calcium (r = 0.46) stresses organic matter's role in improving cation exchange capacity (CEC). This relationship suggests that incorporating rice straw and other organic residues could enhance both nutrient retention and calcium availability in these soils [50].

The negative correlation between exchangeable sodium and calcium (r = −0.44) indicates the presence of potential cation antagonism, which could impact soil structure and nutrient uptake by rice plants. Regular monitoring of sodium levels and maintaining adequate calcium through gypsum application may be necessary to prevent soil structural degradation and ensure optimal nutrient balance [51]. Additionally, the inverse relationship between TEB and exchangeable aluminium (r = −0.47) demonstrates the critical need for pH management in these tropical soils in the study area. Therefore, implementing a careful liming programme could help minimise aluminium toxicity risks while promoting nutrient availability for rice growth [52].

The predominance of weak correlations among most of the other properties (**Figure 7**) indicates that changes in one soil property may not significantly affect others, requiring individualized management approaches. Therefore, to achieve sustainable rice farming in Ghana's wetland conditions, it is essential to develop a comprehensive soil management plan that addresses specific nutrient requirements while accounting for their limited interactions. Given this, it would be essential to conduct routine soil testing and apply targeted amendments to ensure that the soil fertility levels are maintained at an optimal level for the continuous production of rice.

4.6. Heavy Metal Concentrations and Environmental Concerns

The heavy metal analysis from the Mafi-Dove study area in the Central Tongu district of the Volta Region, Ghana, focused on the topsoil (0 - 30 cm) and revealed varying concentrations of iron (Fe), zinc (Zn), and boron (B). While Ghana lacks national soil quality guidelines, the World Health Organization (WHO) provides guidelines for heavy metals in drinking water but not for soils; permissible limits in soil are usually set by national or regional agricultural and environmental bodies. For rice cultivation, general thresholds include zinc (Zn) at 10 - 300 mg/kg [53], with the Codex Alimentarius Commission [54]-[56] setting grain limits (Zn: <50 mg/kg; B: <10 mg/kg) for food safety. Iron (Fe), a micronutrient, commonly ranges from 20,000 - 550,000 mg/kg (2 - 55% by soil weight) and rarely causes toxicity but may disrupt the nutrient balance [57].

These heavy metal concentrations were evaluated in relation to their possible bioaccumulation in rice grains and their implications for food safety, to comprehensively assess potential risks. While Fe concentrations in the soil in this study fall within acceptable limits, Fe^{2+} accumulation under flooded conditions in paddy fields may pose toxicity risks to rice plants, as well as potential bioavailability concerns for rice grains. Zn concentrations, although within safe thresholds, require monitoring given their propensity to bioaccumulate in edible parts of crops. To fully assess food safety risks, future studies should include direct measurements of heavy metals in rice grains grown in these soils. Particular focus could be on elements like Cd and Pb that were not analyzed in this study but are known to accumulate in rice.

Total iron (Fe) concentrations in Mafi-Dove soils ranged from 219.89 to 3980.82 mg/kg, with a mean of 1384.45 mg/kg. Typical Fe concentrations in soils are reported to range between 20,000 and 550,000 mg/kg [57], and all values in Mafi-Dove fall below this range, indicating a generally low Fe content compared to global averages. Despite this, significant spatial variability was observed. The relatively low Fe levels suggest a potential risk of Fe deficiency for crops, including rice. However, under waterlogged paddy conditions, Fe^{2+} toxicity rather than deficiency may become a more pressing concern due to redox-induced solubility [47]. This is because Fe^{2+}, which forms under reducing conditions, can accumulate to levels toxic to rice plants, causing physiological stress and yield reductions. The clay loam topsoil and clay subsoil, coupled with the slightly acidic pH (mean 6.2), are conducive to such Fe^{2+} accumulation. Regional studies (e.g., Opuni *et al*., 2020) report minimal Fe transfer to rice grains at similar soil concentrations, but site-specific grain testing is recommended to confirm food safety. While regional studies (e.g., [38]) show minimal Fe transfer from soil to rice grains, we recommend periodic testing of both soluble Fe^{2+} in paddy water and Fe levels in mature grains to fully evaluate food safety risks under local growing conditions. These findings emphasize the need for mitigation strategies, such as controlled flooding and organic matter application, to manage Fe dynamics effectively. Further investigation into the bioavailable Fe fraction, specifically soluble Fe^{2+}, considering factors such as soil pH, organic matter, nutrient interactions, local background levels, and redox potential in flooded conditions, is essential for accurately assessing Fe status and guiding management strategies for rice cultivation in the area.

Zinc (Zn) concentrations ranged from 63.47 to 174.14 mg/kg, with a mean of 106.93 mg/kg, which falls within the normal Zn levels in soils (10 - 300 mg/kg) as reported by Kabata-Pendias [53]. These concentrations are well below the critical toxicity threshold of 300 - 400 mg/kg, above which Zn can become toxic to plants, causing stunted growth, chlorosis, and reduced yields [53]. For rice production, these levels indicate no immediate risk of Zn toxicity; however, Zn availability may be influenced by soil factors such as pH and organic matter content. It is noteworthy that the European Union soil quality guidelines suggest potential contamination risks at Zn levels exceeding 200 - 300 mg/kg [58], further affirming that Zn concentrations in Mafi-Dove soils are within safe limits for rice cultivation. Given that Zn can accumulate in rice grains even at moderate soil concentrations, we propose establishing a monitoring program that analyzes Zn levels in rice grains at harvest, particularly in fields where soil Zn exceeds 100 mg/kg, to ensure compliance with Codex Alimentarius food safety standards [56].

Boron (B) concentrations within the soils of the study area ranged from 20.36 to 35.74 mg/kg, with a mean of 26.57 mg/kg. These concentrations fall within the typical background range for total B in soils, reported as 10 - 70 mg/kg [53], and are moderate within this range. The neutral to slightly acidic soil pH (mean 6.1) suggests favorable conditions for B availability, as B solubility typically declines in strongly acidic or alkaline soils [59]. The clay loam texture in the topsoil and clay in the subsoil may further enhance B retention, given the high adsorption potential of clay minerals. Because B shows limited translocation to rice grains under these soil conditions [59], food safety concerns are minimal, though monitoring for potential B deficiency in rice plants is advised, particularly in coarse-textured soil zones.

While higher sampling densities could theoretically be used to resolve microscale variability, our farm-scale design was used to prioritize actionable recommendations for soil management, balancing statistical rigor with practical constraints common to tropical soil studies [14]. The risk assessment framework presented here, which combines international standards with site-specific considerations of metal bioavailability, provides a strong foundation for sustainable rice production while identifying key areas for ongoing monitoring.

5. Conclusion and Recommendation

Continuous rice cultivation is feasible with specific interventions to ensure sustainable production and support Ghana's food security. Low soil fertility (nitrogen, phosphorous, and potassium) and low organic carbon are the main issues, necessitating the use of both organic additions and inorganic fertilizers in an integrated approach to soil fertility management. Although careful monitoring is required to prevent waterlogging, the site's advantageous physical characteristics, such as clay loam topsoil and slightly acidic pH, support water retention and nutrient management. The fact that there is no heavy metal contamination suggests that the location is suitable for growing rice. Maintaining soil pH within the optimal range of 5.5 to 7.0 is crucial for minimizing aluminium toxicity risks. This can be achieved through targeted liming practices, as supported by the observed negative correlation between total exchangeable bases and exchangeable aluminium ($r = -0.47$). Additionally, gypsum application is necessary to maintain calcium levels and prevent sodium-induced structural degradation, considering the antagonistic relationship between calcium and sodium ($r = -0.44$). These measures will safeguard soil structure and promote a balanced cation exchange. Water management should leverage the high water-holding capacity of clayey subsoils while ensuring adequate drainage to prevent waterlogging. Incorporating organic matter into the soil is vital to mitigate compaction resulting from continuous rice cropping under puddling conditions. The moderate positive correlation between organic carbon and exchangeable calcium (r = 0.46) highlights the importance of organic amendments in maintaining soil structure and improving water infiltration. Although the study is focused on a specific locality, the occurrence of the Amo-Tefle association (Gleyic Cambisol) across different agroecological zones in Ghana enhances the relevance of the findings. Nonetheless, agroecological variations may influence specific soil conditions, and similar assessments are recommended in areas with differing soil types and climatic factors. These strategies, informed by thorough spatial sampling (70 points × 2 depths) consistent with methodologies applied in comparable West African rice systems, collectively ensure sustainable rice production while minimizing adverse environmental impacts.

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Ethical Compliance

This study complies with the ethical guidelines for scientific research and publishing as outlined by Elsevier's Publishing Ethics Policy. All the data were collected and analyzed in accordance with ethical standards, and proper citations were provided for all sources that were used in this work.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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