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Using Principal Component Analysis to Assess Soil Chemical Properties in the Mwea Irrigation Scheme, Kenya: Implications for Rice Agronomic Management

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Sub-Saharan Africa faces significant challenges as a net importer of rice, with self-sufficiency rates plummeting to as low as 14% in countries like Kenya. The Mwea irrigation scheme shoulders the bulk of rice cultivation, contributing over 80% of the country’s production. However, productivity within the scheme has seen a concerning decline, dropping from 5.6 — 6.0 t ha^{-1} to 1.3 — 4.6 t ha^{-1} between 1977 and 2018. This decline could be attributed to site-specific nutritional deficiencies and/or toxicities, rendering generalized agronomic recommendations ineffective in certain areas. To address this problem, our study aimed to assess soil chemical properties variability within the Mwea irrigation scheme, identify clusters with similar nutritional status, and tailor area-specific agronomic recommendations. During May to September 2020, we collected and analyzed four hundred samples from five sections of the scheme for total organic carbon, soil pH, macro and micronutrients, and exchangeable cations. Principal component analysis was conducted on the mean values of the soil chemical properties to identify significant contributors to variation and establish zones with similar patterns. Principal components 1 to 4 collectively explained 72.2% of the total variability. Cluster analysis revealed four distinct clusters, namely MW, TB, KT, and WU. Within cluster MW, soil pH was below the optimum range for rice cultivation, suggesting a need for liming. Potassium deficiency was observed across all clusters, with rice straw incorporation recommended as a long-term solution. Furthermore, zinc deficiency was noted in cluster WU, necessitating zinc fertilizer application. Conversely, iron toxicity was a concern in cluster MW, suggesting the adoption of alternating wetting and drying techniques and cultivating tolerant varieties. By proving tailored recommendations based on localized soil conditions, we aim to bolster rice productivity within the Mwea irrigation scheme and contribute to regional food security efforts.

Keywords: Agronomic management; food security; rice; principal component analysis; soil chemical properties.

1. INTRODUCTION

Rice *(Oryza sativa)* is a staple food for more than half of the global population and constitutes a significant source of calories for many developing countries [1]. Particularly in sub-Saharan Africa, rice consumption exhibited remarkable growth, outpacing that of other commodities [2]. This surge in demand can be attributed to factors such as population growth, urbanization, and evolving consumer preferences. Notably, in Kenya, per capita rice consumption has experienced a substantial increase, soaring from 12 kg in 2016 to 25.3 kg in 2020 [3]. In the same year, the country’s milled rice production reached an estimated 85,000 MT, while consumption stood at 700,000 MT, resulting in a deficit of 86% (600,000 MT), necessitating substantial imports to meet local demand.

Rice production in Kenya primarily occurs within government and community-managed irrigation schemes, covering approximately 32,000 hectares, which span across central, western, and coastal regions [4]. Among these irrigation schemes, the Mwea irrigation scheme (MIS) in central Kenya, established between 1954 and 1973, stands as the largest government-managed scheme covering approximately 12,000 hectares and contributing roughly 80% of the nation’s total rice production [5]. Despite its prominence, rice productivity in the MIS, and across the country, has experienced a gradual decline over the years. Specifically, within the MIS, paddy rice productivity decreased from 5.6 to 6.0 tons per hectare during the period between 1967 and 1977, to a range of 1.3 to 4.6 tons per hectare between 2008 and 2018 [6]. Notably, varieties such as IR05N221 and AT054, with average yield potential of 7.5 tons per hectare, remain popular within the MIS [7]. To address this decline and enhance productivity within the MIS, there is a pressing need to characterize soil chemical conditions and nutrient status to pinpoint the underlying causes of these yield gaps.

Research findings from long-term fertility experiments in West Africa suggest that intensive rice farming systems may lead to a decline in soil chemical characteristics [8]. It is widely acknowledged that soil quality directly influences crop yield [9]. Continuous rice cultivation has been practiced in certain sections of the MIS [10,11], with multiple studies indicating adverse effects on soil quality, nutrient absorption, and crop yields [12]. In recent years, there has been a significant rise in the sale of rice straw for animal feed within the MIS. However, this continual exportation of crop residues may negatively impact organic matter content and other essential nutrients [13]. Consequently, intensive rice cultivation and farmer management practices leading to soil quality degradation likely contribute to the observed decline in rice yields over time in the MIS. Therefore, it is imperative to assess soil quality variability and categorize sections with similar characteristics within the MIS to devise sustainable rice fertilizer and water management strategies. This approach aims to enhance input efficiency and increase average rice yields within the MIS.

Several soil variables are essential for evaluating soil quality. These include soil pH, soil organic carbon, macronutrients (nitrogen, potassium, and phosphorus), exchangeable cations (magnesium, calcium, and sodium), and micronutrients (iron, manganese, zinc, and copper). These parameters are crucial for ensuring optimal rice growth and grain yield [14]. Soil pH significantly influences soil fertility by modulating nutrient availability and uptake, as well as the presence of toxins [15]. Soil organic carbon plays a pivotal role in enhancing soil nutrient properties and supporting crop production, while also contributing to the mitigation of agricultural ecosystems' impact on climate change [16,17]. Nitrogen is indispensable for synthesizing nucleotides, amino acids, and chlorophyll [18]. Potassium enhances plant vigor, reduces lodging, promotes cell division, and bolsters resistance to diseases [19]. According to Fageria et al. [20], phosphorus is crucial in rice cultivation, aiding in root development, ripening, early flowering, and tolerance to specific biotic and abiotic stresses, with its deficiency leading to delayed maturity and increased vulnerability to diseases. Exchangeable cations are vital for sustaining soil nutrients, furnishing essential elements for plant growth [21,22,23], and buffering soil acidification [24]. Although micronutrients are required in minute quantities, their adequate supply enhances nutrient availability and positively influences cell physiology that is reflected in yield [25].

Few studies have been conducted to characterize soil chemical properties in the MIS [26,27]. However, no efforts have been made to identify and group sections exhibiting similar trends and patterns in soil characteristics, which could inform site-specific recommendations within the MIS. Multivariate analysis offers researchers a comprehensive approach to extract insights from datasets, considering not only individual variables but also their interrelationships [28]. Among multivariate analysis methods, principal component analysis (PCA) stands out for its ability to reduce the number of variables by identifying the most significant variables in a large dataset [29]. This process simplifies complex data and uncovers underlying patterns, trends, and potential clusters [30], thereby facilitating informed decision-making in precision agriculture. Hence, the aim of this study was to assess the current chemical status of soils within the MIS using PCA-based multivariate analysis and to propose management practices for sustainable rice production within the scheme.

2. MATERIALS AND METHODS

2.1 Study Area

The study was conducted in the MIS, situated on the lower slopes of Mount Kenya in Kirinyaga County, central Kenya, from May to September 2020. The scheme has a total gazetted area of 30,350 acres, but only 28,600 of those are under irrigation [4]. The irrigation scheme lies within Mwea West and Mwea East Sub- counties, approximately 103 km northeast of Nairobi, at an altitude of 1190 m above the sea level, spanning latitudes 37°13′E and 37°30′E and longitudes 0°32′S and 0°46′S. The region experiences bimodal rainfall, with long rains occurring between March and May and short rains between October and December [31].

Kenya’s agro-climatic zoning classifies the MIS into three zones, with varying moisture availability ratios: 0.65 for zone III, tapering to 0.50 for the extensive area of zone IV, and further declining to 0.40 for the semi-arid zone V [32]. Characterized by generally hot conditions, the area maintains an average temperature of 23 °C. The MIS is subdivided into seven sections: Mwea, Tebere, Thiba, Wamumu, Karaba, Ndekia, and Curukia, serviced by the Thiba and Nyamidi rivers (Fig. 1).

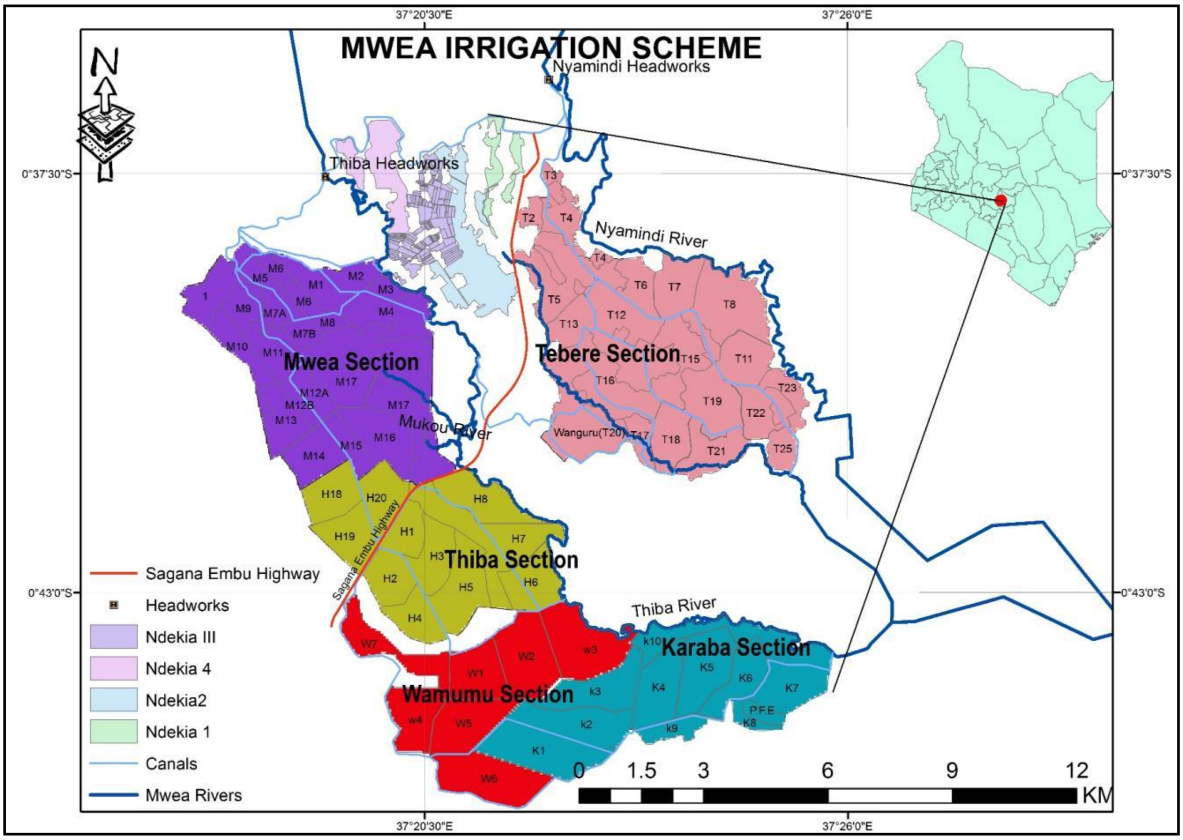

Fig. 1. Map of Mwea irrigation scheme, indicating the five sections where the soil sampling was conducted

Each section comprises multiple units: Mwea (17), Tebere (17), Thiba (11), Wamumu (7), Karaba (10), Ndekia (5), and Curukia (8). The present research focused on the first five sections, which have been under rice cultivation for over three decades. Among these, Tebere and Mwea are the largest, covering 3,285 and 3,110 acres under irrigation, respectively, and situated upstream of the two rivers [33]. Downstream are Thiba (3,019), Wamumu (2,880), and Karaba (2,650 acres).

2.2 Soil Sampling, Processing, and Analysis

A total of 400 soil samples were collected from the five selected sections within the MIS at the end of the 2020 cropping season (Table 1). Specifically, 108 samples were gathered from Mwea and 102 from Tebere, covering the seventeen units in each section. Additionally, 76 samples were obtained from the Thiba section across its eleven units, while 59 samples were collected in Karaba section, distributed among eight units. In Wamumu, 55 samples were distributed among seven units. Thus, the samples were systematically collected from all 60 units of the MIS across the five sections. The varying number of samples collected from each section was based on the relative number of units per section. Notably, fewer samples were collected from Tebere compared to Mwea, attributed to some farmers applying manure in preparation for the ensuing season.

Within each unit, 5 to 10 farmers were randomly selected, and soil samples were collected from a one-acre plot size for each farmer. These samples were obtained from the surface soil (0 – 20 cm) at nine locations within the designated plot area, as illustrated in Fig. 2. Subsequently, the nine samples from each plot were thoroughly mixed to create a composite sample, labelled, and stored in polythene bags before transportation to the laboratory for analysis.

Table 1. Distribution of 400 samples across five rice-growing sections and units in the Mwea irrigation Scheme collected at the end of the 2020 rice cropping season.

Rice growing section									
Karaba		**Wamumu**		**Thiba**		**Mwea**		**Tebere**	
Unit	**No. of samples**	**Unit**	**No. of samples**	**Unit**	**No. of samples**	**Unit**	**No. of samples**	**Unit**	**No. of samples**
K1	10	W1	7	H1	7	M1	5	T2	5
K2	8	W2	8	H2	5	M2	5	T5	5
K3	7	W3	8	H3	7	M3	6	T6	5
K4	7	W4	7	H4	7	M4	7	T7	7
K5	7	W5	7	H5	8	M5	6	T8	8
K6	7	W6	10	H6	6	M6	6	T11	7
K7	8	W7	8	H7	7	M7	6	T13	6
K8	5			H8	7	M8	6	T15	6
				H18	7	M9	7	T16	6
				H19	8	M10	7	T17	5
				H20	7	M11	7	T18	5
						M12	6	T19	6
						M13	6	T20	7
						M14	7	T21	7
						M15	6	T22	6
						M16	7	T23	6
						M17	8	T25	5

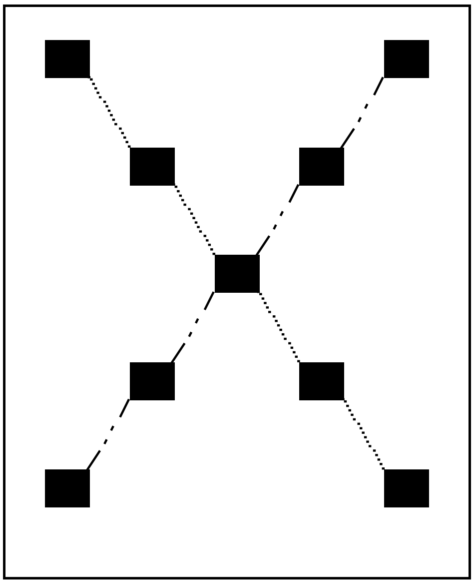

Fig. 2. Distribution of nine samples collected per acre of farmland to create a composite sample across the five sections of the Mwea irrigation scheme.

The collected samples underwent a series of standardized procedures for analysis. Initially, the samples were dried in an oven at 40 °C, ground and passed through a 2 mm sieve, and subsequently analyzed for total organic carbon, soil pH, macronutrients (total nitrogen, available phosphorus, and extractable potassium), micronutrients (iron, manganese, zinc, and copper), and exchangeable cations (magnesium, calcium, and sodium). Soil pH was determined in a 1:1 (w/v) soil – water suspension using a pH – meter. For soils with pH greater than 7.0, extractable phosphorus was determined instead of available phosphorus. The sodium adsorption ration (SAR) was calculated to assess whether sodium is a significant contributor to alkalinity in high-pH soils, using equation (1) below.

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}}$$

Where: Na^{+}, Ca^{2+}, and Mg^{2+} are respective soluble cation concentrations in mg/kg.

Total organic carbon in the dried samples was oxidized using acidified dichromate at 150 °C for 30 minutes, followed by addition of barium chloride and subsequent spectrophotometric analysis at 600 nm [34]. Total nitrogen was determined by digesting the soil sample with concentrated sulphuric acid containing potassium sulphate, selenium, and hydrated copper sulphate, followed by distillation and titration with diluted standardized sulphuric acid [35]. Extraction of potassium, phosphorus, calcium, magnesium, manganese, and sodium was conducted in a 1:5 ratio (w/v) with a mixture of 0.1 N HCl and 0.025 N H_2SO_4. Concentrations of potassium, calcium, and sodium were measured using a flame photometer, while phosphorus, magnesium, and manganese concentrations were determined spectrophotometrically [36].

For determination of extractable phosphorus, extraction was performed in a 1:20 ratio (w/v) with 0.5 M sodium bicarbonate solution at pH 8.5, followed by spectrophotometric analysis [37]. Iron, zinc, and copper were extracted in a 1:10 ratio (w/v) with 0.1 M HCl and their concentrations were determined using an atomic absorption spectrophotometer [36].

2.3 Statistical Analysis

Multivariate analysis was performed in R (version 4.0.2) [38]. Principal component analysis was employed to identify sources of variability in soil chemical composition and to establish clusters among sections within the MIS. Previous studies have highlighted the efficacy of PCA in detecting variations in physical and chemical soil parameters, as well as for establishing geochemical soil groupings [39,40]. To mitigate the potential bias towards variables with higher variances, the data was transformed prior to analysis [41]. Principal components (PCs), eigenvalues, eigenvectors, and 2-D biplots were obtained using FactoMineR and Factoextra packages. Eigenvectors, representing coefficients positively or negatively associated with each original variable, were considered significant if their values were ≥0.22 (regardless of sign).

The means of soil chemical properties among clusters generated by principal component analysis were compared using the least significant difference (LSD) test at a significance level of $p \leq 0.05$. Pearson correlation analysis was conducted to assess the relationship between soil properties. For this analysis, average values for each soil property in each unit were utilized, resulting in the sample size (*n*) equal to the number of units sampled (n = 60).

3. RESULTS

3.1 Principal Component Analysis

Principal component analysis (PCA) revealed 12 principal components (PCs) (Table 2). The first, second, third, and fourth principal components accounted for 29.2%, 21.9%, 11.7%, and 9.3% of the total variance in the MIS, respectively. These four PCs had eigenvalues >1 and cumulatively accounted for 72.2% of the total variance and were considered for further analysis (Table 2).

Table 2. Principal components, eigenvalues, proportion of explained variance, and cumulative proportions

Principal component	Eigenvalue (λ)	Variance	Cumulative variance
1	3.50	29.2	29.2
2	2.64	21.9	51.1
3	1.41	11.7	62.9
4	1.11	9.3	72.2
5	0.90	7.5	79.7
6	0.71	5.9	85.6
7	0.53	4.4	90.0
8	0.39	3.3	93.3
9	0.33	2.7	96.0
10	0.30	2.5	98.6
11	0.17	1.4	99.9
12	0.00	0.0	100

The direction and magnitude of contribution of different soil chemical properties to PC1 and PC2 are shown in Fig. 3 and Table 3, while those of PC3 and PC4 are shown in Fig. 4 and Table 3, respectively. PC1 exhibited a positive association with soil pH (0.41) and other soil properties, including total organic carbon (0.27), total nitrogen (0.28), available phosphorus (0.22), and extractable potassium (0.32), calcium (0.30), and sodium (0.35). In contrast, micronutrients such as copper (-0.33), iron (-0.30), and zinc (-0.35) exhibited a negative association with PC1 (Table 3).

The soil chemical property most strongly and positively correlated with PC1 was soil pH, while zinc exhibited the strongest negative correlated with PC1 (Table 3). According to [42], variables with coefficients above 0.22 significantly contribute to variation. This criterion applied to PC2, PC3, and PC4 to avoid redundancy.

PC2 demonstrated a strong negative association with total nitrogen (-0.49), total organic carbon (-0.48), and potassium (-0.30) (Table 3). Conversely, this PC displayed a strong positive association with Mn (0.36). PC3 and PC4 were primarily influenced by macro and micronutrients, as well as exchangeable cations, as outlined in Table 3. PC3 showed a strong positive association with Mg^{2+} (0.65), Mn^{2+} (0.35), and Ca^{2+} (0.32), while exhibiting a strong negative correlation with phosphorus (-0.36). On the other hand, PC4 displayed a robust negative correlation with phosphorus (-0.60), extractable potassium (-0.31), iron (-0.41), calcium (-0.30), and manganese (-0.39) (Table 3).

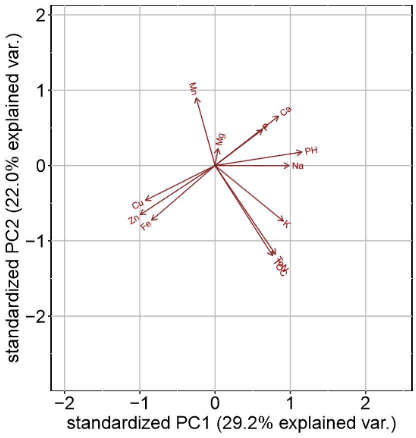

Fig. 3. Loading plot of the twelve soil chemical properties for PC1 and PC2 in the Mwea irrigation scheme

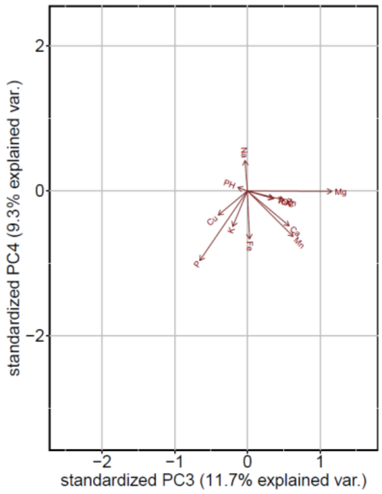

Fig. 4. Loading plot of the twelve soil chemical properties for PC3 and PC4 in the Mwea irrigation scheme

Table 3. Eigenvectors of the first four principal components axes for soil characteristics in the Mwea irrigation scheme

Category	Parameter	Principal Components			
		PC1	PC2	PC3	PC4
	pH	**0.41**	0.07	(–) 0.07	0.03
	ToC	**0.27**	(–) **0.48**	0.20	(–) 0.06
Macronutrients	TN	**0.28**	(–) **0.49**	0.20	(–) 0.07
	P	**0.22**	0.19	(–) **0.36**	(–) **0.60**
	K	**0.32**	(–) **0.30**	(–) 0.11	(–) **0.31**
Micronutrients	Cu	(–) **0.33**	(–) 0.19	(–) **0.22**	(–) 0.21
	Fe	(–) **0.30**	(–) **0.29**	0.02	(–) **0.41**
	Zn	(–) **0.35**	(–) **0.26**	**0.28**	(–) 0.08
	Mn	(–) 0.09	**0.36**	**0.35**	(–) **0.39**
Exchangeable cations	Ca^{2+}	**0.30**	**0.27**	**0.32**	(–) **0.30**
	Mg^{2+}	0.01	0.09	**0.65**	0.00
	Na^{+}	**0.35**	0.00	(–) 0.02	**0.26**

ToC: total organic carbon, TN: total nitrogen, P: phosphorus, K: potassium, Cu: copper, Fe: iron, Zn: zinc, Mn: manganese, Ca^{2+}: calcium, Mg^{2+}: magnesium, and Na^{+}: sodium. Numbers highlighted in bold were significant.

A scatter plot depicting the units within the five sections of the MIS, as determined by PC1 and PC2, is presented in Fig. 5. Notably, rice cultivation units within the Mwea, Tebere, and Thiba sections exhibited distinct clusters, demonstrating minimal overlapping. Additionally, the Wamumu section formed a discernable cluster, distinct from Thiba and appearing to be intermediate of Mwea and Tebere. Conversely, the Karaba section showed some overlap with Thiba. Grouping the five sections of the MIS based on PC1 and PC2 resulted in four distinct clusters i.e. Mwea (MW), Tebere (TB), Wamumu (WU), and Karaba with Thiba (KT) (Fig 5).

There was no clear separation of the five sections based on PC3 and PC4 except for the Wamumu section that was distinct from the other four sections (Fig. 6).

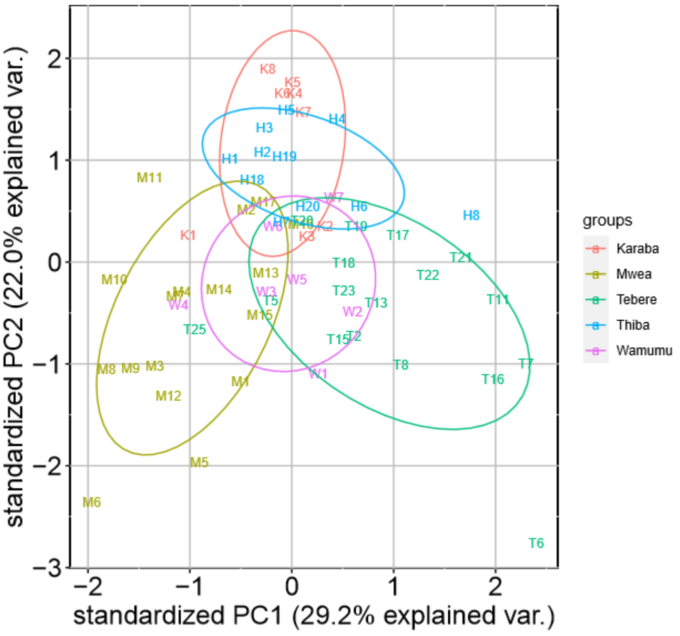

Fig. 5. Scatter plot of the first and second principal component scores of the units in the Mwea irrigation scheme based on total organic carbon, total nitrogen, phosphorus, potassium, copper, iron, zinc, calcium, magnesium, manganese, and sodium.

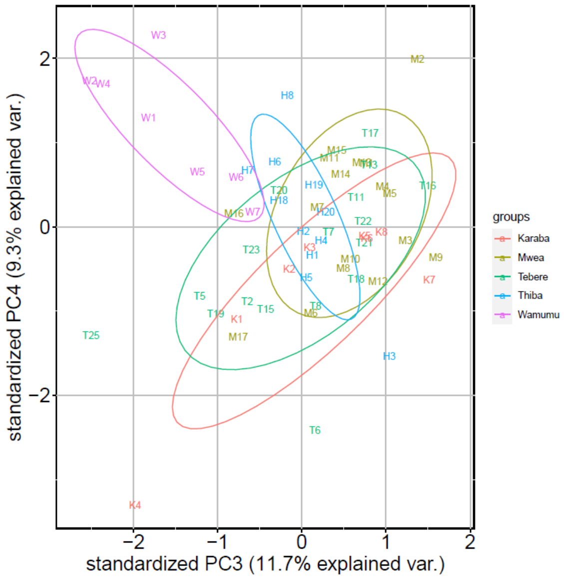

Fig. 6. Scatter plot of the third and fourth principal component scores of the units in the Mwea irrigation scheme based on total organic carbon, total nitrogen, phosphorus, potassium, copper, iron, zinc, calcium, magnesium, manganese, and sodium.

3.2 Soil Chemical Properties

3.2.1 Soil pH and total organic carbon

Our analysis revealed notable variation among the four clusters in soil pH and total organic carbon, as shown in Table 4. The average soil pH across the clusters ranged from 5.03 in cluster MW to 5.83 in cluster TB (Table 4). Cluster TB exhibited pH levels comparable to those observed in WU but significantly higher than those in clusters KT and MW. Conversely, cluster KT had pH levels comparable to WU but differed significantly from MW. Regarding total organic carbon, cluster TB recorded the highest average at 3.4%, while cluster KT had the lowest at 2.8% (Table 4). Upstream of the MIS, clusters TB and MW exhibited higher total organic carbon levels compared to clusters KT and WU, which showed a decrease in total organic carbon levels downstream within the MIS. The total organic carbon in cluster TB was statistically similar to that of cluster MW but different from that of clusters WU and KT. Cluster MW exhibited total organic carbon levels comparable to cluster WU but significantly different from cluster KT (Table 4).

3.2.2 Macronutrients

There were notable variations in paddy soil macronutrients, namely nitrogen, potassium, and phosphorus. Nitrogen exhibited the lowest coefficient of variation (CV) at 14.6%, while phosphorus and potassium displayed higher CV values of 55.5% and 52.5%, respectively (Table 4). The mean total nitrogen content was highest in cluster TB (0.32 mg/kg) and lowest in cluster KT (0.26 mg/kg) (Table 4). Total nitrogen levels in cluster TB significantly differed from those in the other three clusters. The average available phosphorus content was highest in cluster KT (23.43 mg/kg) and lowest in cluster MW (10.24 mg/kg) (Table 4). The average available phosphorus in cluster KT was statistically similar to that of cluster TB but significantly different from those in clusters WU and MW. Extractable potassium levels were highest in cluster TB (0.20 cmol+/kg) and lowest in cluster WU (0.03 cmol+/kg) (Table 4). In cluster TB, extractable potassium levels significantly differed from those in clusters MW, WU, and KT. However, the levels in clusters MW, WU, and KT were comparable.

3.2.3 Micronutrients

The status of zinc, iron, copper, and manganese is shown in Table 5. Coefficients of variation for these soil micronutrients were 83.8%, 42.0%, 41.8%, and 47.7%, respectively, indicating variability in soil micronutrients levels in the MIS.

Zinc levels in cluster MW were more than two-fold higher than, and significantly different from those in clusters TB, WU, and KT. Zinc levels in clusters TB, WU, and KT were comparable but significantly lower than those in cluster MW.

Iron levels exhibited a tendency to decrease downstream in the MIS, with clusters KT and WU displaying lower levels compared to clusters TB and MW located upstream of the MIS. Iron levels ranged from 183 mg/kg in cluster KT to 320 mg/kg in cluster MW. Levels of iron in clusters TB, WU, and KT were comparable but significantly lower than those in cluster MW (Table 5).

Average copper levels ranged from 2.66 mg/kg in cluster TB to 4.11 mg/kg in cluster WU. Copper levels in cluster WU were not significantly different from those in cluster MW; however, both were significantly higher than those in clusters TB and KT. No differences in copper levels were observed between clusters TB and KT. Manganese levels were the highest in cluster KT at 0.95 (mg/kg soil) and the lowest in cluster WU at 0.31 (mg/kg soil). Manganese levels in cluster KT were significantly higher than those in all the other three clusters. Cluster MW had higher manganese levels than cluster TB, but these differences were not significant. However, cluster MW was found to have significantly higher manganese levels than cluster WU. There were no significant differences in manganese levels between clusters TB and WU.

3.2.4 Exchangeable cations

The levels of magnesium (Mg^{2+}), calcium (Ca^{2+}), and sodium (Na^{+}) are shown in Table 5. Significant variations were observed among clusters for magnesium and calcium, but not for sodium. The coefficients of variation for these soil exchangeable cations were 12.4%, 29.1%, and 25.8%, respectively. Magnesium levels ranged from 5.16 cmol+/kg in cluster WU to 6.16 cmol+/kg of soil in cluster MW. Clusters MW, TB, and KT exhibited comparable magnesium levels, while cluster WU had significantly lower levels than the other three clusters (Table 5). Calcium levels ranged from 8.6 cmol+/kg in cluster WU to 15.9 cmol+/kg in cluster KT. Clusters KT and TB had comparable calcium levels, significantly higher than clusters MW and WU, which did not differ significantly in calcium content. Although, sodium levels were higher in clusters TB and WU compared to clusters MW and KT, these differences were not statistically significant (Table 5). The SAR value was similar in clusters MW, TB, and KT but significantly lower than that in cluster MW.

Table 4. Mean soil pH, total organic carbon, and macronutrient levels across four clusters in the Mwea irrigation scheme

			Macronutrients		
Cluster	**Soil pH**	**Total organic carbon (%)**	**Total nitrogen (mg/kg)**	**Available phosphorus(mg/kg)**	**Extractable potassium (cmol+/kg)**
MW	5.03±0.3 c	3.1 ab	0.29 b	10.24 c	0.09 b
TB	5.83±0.7 a	3.4 aa	0.32 a	23.08 ab	0.20 a
WU	5.65±0.6 ab	2.9 bc	0.27 bc	16.16 bc	0.03 b
KT	5.53±0.6 b	2.8 cc	0.26 c	23.43 a	0.09 b
LSD	0.29	0.27	0.03	6.98	0.04
CV (%)	8.5	13.3	14.6	55.5	52.5

Same letter indicates means across clusters for specific parameters are not significantly different at P < 0.05.
MW: Mwea, TB: Tebere, WU: Wamumu, KT: Karaba and Thiba.

Table 5. Mean micronutrient and exchangeable cation levels across four clusters in the Mwea irrigation scheme

Cluster	**Micronutrients (mg/kg)**				**Exchangeable cations (cmol+/kg)**			
	Zn	**Fe**	**Cu**	**Mn**	**Mg^{2+}**	**Ca^{2+}**	**Na^{+}**	**SAR**
MW	7.03 a	320.1 a	3.89 a	0.67 b	6.16 a	11.0 b	0.87 a	0.03 b
TB	2.06 b	241.9 b	2.66 b	0.50 bc	6.03 a	15.3 a	1.05 a	0.03 b
WU	1.66 b	196.6 b	4.11 a	0.31 c	5.16 b	08.6 b	1.07 a	0.04 a
KT	2.50 b	183.4 b	2.79 b	0.95 a	6.06 a	15.9 a	0.97 a	0.02 b
LSD	1.70	73.5	1.06	0.20	0.55	2.39	0.21	
CV (%)	83.8	42.0	41.8	47.7	12.4	29.1	25.8	

Same letter indicates means across clusters for specific parameters are not significantly different at P < 0.05.
MW: Mwea, TB: Tebere, WU: Wamumu, KT: Karaba and Thiba.
Zn: zinc, Fe: iron, Cu: copper; Mn: Manganese, Mg^{2+}: magnesium, Ca^{2+}: calcium, Na^{+}: sodium, SAR: sodium adsorption rate.

Table 6. Pearson's Correlations of the twelve soil chemical properties.

	PH	TN	ToC	P	K	Ca^{2+}	Mg^{2+}	Mn	Cu	Fe	Zn	Na^{+}
PH	1.00	0.26^{ns}	0.21^{ns}	0.31^{*}	0.38^{**}	0.44^{**}	0.13^{ns}	-0.18^{ns}	-0.20^{ns}	-0.47^{**}	-0.55^{**}	0.46^{**}
TN		1.00	1.00^{**}	-0.06^{ns}	0.60^{**}	0.06^{ns}	0.02^{ns}	-0.37^{**}	-0.18^{ns}	0.09^{ns}	0.05^{ns}	0.30^{*}
ToC			1.00	-0.07^{ns}	0.59^{**}	0.04^{ns}	0.00^{ns}	-0.37^{**}	-0.16^{ns}	0.10^{ns}	0.07^{ns}	0.28^{*}
P				1.00	0.27^{*}	0.34^{**}	-0.18^{ns}	0.13^{ns}	-0.13^{ns}	-0.14^{ns}	-0.47^{**}	0.11^{ns}
K					1.00	0.12^{ns}	-0.10^{ns}	-0.29^{*}	-0.15^{ns}	-0.03^{ns}	-0.19^{ns}	0.22^{ns}
Ca^{2+}						1.00	0.25^{ns}	0.36^{**}	-0.41^{**}	-0.37^{**}	-0.30^{*}	-0.29^{*}
Mg^{2+}							1.00	0.20^{ns}	-0.11^{ns}	-0.03^{ns}	0.06^{ns}	-0.07^{ns}
Mn								1.00	-0.17^{ns}	-0.01^{ns}	0.03^{ns}	-0.11^{ns}
Cu									1.00	0.54^{**}	0.49^{**}	-0.35^{**}
Fe										1.00	-0.49^{**}	-0.31^{*}
Zn											1.00	-0.37^{**}
Na^{+}												1.00

TN: total nitrogen, ToC: total organic carbon, P: phosphorus, K: potassium, Ca^{2+}*: calcium,* Mg^{2+}*: magnesium,* Mn^{2+}*: manganese, Cu: copper, Fe: iron, Zn: zinc, and Na: sodium. (n=60)*

3.3 Correlation among Soil Chemical Properties

The Pearson correlation coefficients among the twelve soil chemical properties measured in the MIS are shown in Table 6. Soil pH exhibited a significant positive correlation with macronutrients, including total nitrogen (r = 0.23*), phosphorus (r = 0.31*), and potassium (r = 0.38**), as well as with exchangeable cations such as calcium (r = 0.44**) and sodium (r = 0.46**). Conversely, soil pH demonstrated a significant negative correlation with micronutrients, notably iron (r = -0.47**) and zinc (r = -0.55**).

Total organic carbon displayed a perfect positive correlation with nitrogen (r = 1.00**), and a significant positive correlation with potassium (r = 0.59**) and sodium (r = 0.28*), while exhibiting a negative correction with manganese (r = -0.37**). Nitrogen, among the macronutrients, exhibited a significant positive correlation with potassium (r = -0.60**) and sodium (r = 0.30*), and a negative correction with manganese (r = -0.37**). Phosphorus showed a significant positive correlation with both potassium (r = 0.27*) and calcium (r = 0.34**), and negative correlation with zinc (r = -0.47**). Potassium exhibited a significant negative association with manganese (r = -0.29*).

Among the exchangeable cations, sodium showed a positive and significant correlation with total nitrogen (r = 0.30**) and total organic carbon (r = 0.28*), while displaying a negative correlation with calcium (r = -0.29*), copper (r = -0.35**), iron (r = -0.31*), and zinc (r = -0.37**).

Zinc, classified as a micronutrient, displayed a significant positive correlation with copper (r = 0.49**) and iron (r = 0.49**), and a negative correlation with calcium (r = -0.30*). Manganese showed a significant positive correlation with calcium (r = 0.36**) but was negatively correlated with total nitrogen (r = -0.37**), total organic carbon (r = -0.37**), and potassium (r = -0.29*).

4. DISCUSSION

4.1. Clustering of Soils in the Mwea Irrigation Scheme (MIS) Using Principal Component Analysis

In this study, principal component analysis was employed to identify important soil properties describing variation in the MIS. Principal components (PC) 1 ─ 4 accounted for over 72% of the variation in soil chemical properties in the MIS (Table 2). Except for magnesium, all the twelve analyzed soil properties showed significant correlations with either PC1 or 2, or both (Table 3), indicating that most of the variation within the MIS for the measured soil properties can be attributed to these two principal components. PC1 exhibited a positive and significant correlation with soil pH, total organic carbon, macronutrients (nitrogen, phosphorus, and potassium), and exchangeable cations (Ca^{2+} and Na^{+}) (Table 3), suggesting that these parameters vary in tandem; an increase in one category corresponds to an increase in the others [27].

A scatter plot for PC1 and 2 depicted clear distinctions among the Mwea (cluster MW), Tebere (cluster TB), Wamumu (cluster WU) sections, while Karaba and Thiba sections appeared to overlap and hence were grouped together in cluster KT (Fig. 5). Furthermore, significant differences were observed among clusters in all evaluated soil properties except for sodium (Tables 4 and 5), indicating that principal component analysis adequately clustered the sections of the MIS.

4.2 Variation in Chemical Properties among Clusters and Recommendations for Agronomic Management

a. Soil pH and total organic carbon

The coefficient of variation (CV) for soil pH was calculated to be 8.5% (Table 4), indicating minimal variability within the MIS. This finding is consistent with previous research [26], which reported low variability in soil pH within the MIS, with CV values of 12% for $pH_{(water)}$ and 15% for $pH_{(KCl)}$. Principal component analysis revealed that soil pH had the most significant positive impact on PC1, making it a key factor contributing to the variation in soil chemical properties in our study (Fig. 3 and Table 3). The optimal soil pH for lowland rice cultivation typically falls within the range of 5.5 to 7.0 [43]. In clusters TB, WU, and KT, soil pH varied, showing acidic levels in some areas and optimal levels in others. Conversely, in cluster MW, predominantly comprising units in the Mwea section, pH values were below the optimal range for rice growth under flooded field conditions (Table 4). Literature suggests that fertilizer management practices can influence soil pH levels. In irrigated lowland rice systems, urea and ammonium sulphate are the commonly used nitrogen sources [19]. Studies evaluating the impact of these nitrogen sources on soil pH have shown that ammonium sulphate is more acidifying than urea [44]. A survey conducted in the Mwea irrigation scheme revealed that approximately 85% of farmers applied ammonium sulphate during the first and second top-dressing stages [45]. Therefore, the observed low pH levels, particularly in cluster MW (Table 4), where rice cultivation has been practised since 1954 [4], may partly be attributed to the prolonged use of highly acidifying nitrogenous sources. Such low soil pH levels result from release of hydrogen, aluminum, manganese, and iron to toxic levels [46], hampering plant growth primarily by inhibiting root development and growth [47]. The acidity of soils within the rice cultivation areas under cluster MW can be ameliorated by applying lime to enhance soil fertility [48]. However, this intervention should be carefully implemented, as excessive addition of lime can significantly decrease the availability of micronutrients, particularly iron, zinc, and copper, leading to deficiencies in these essential plant nutrients [49]. The utilization of carbonated rice husk as biochar presents a cost-effective solution for amending acidic soils in the MIS. This option is particularly advantageous due to the widespread availability of the product, which is abundantly generated as a by-product in several mills situated near the scheme. Often, these rice husks are indiscriminately disposed of along roadsides or openly incinerated within the scheme’s fields [50,51]. Furthermore, the utilization of biochar offers additional benefits such as creation of a carbon sink to mitigate global warming, enhancement of soil water holding capacity, reduction of greenhouse gas emissions, and stabilization of mobile heavy metals and other organic pollutants in soil [52,53,54,55,56].

Organic carbon significantly influences the physical, chemical, and biological attributes of soil [57,58]. In this study, we observed a coefficient of variation of 13.3% for total organic carbon, indicating minimal variability within the study area (Table 4). The critical threshold for total organic carbon is estimated at 2% [59]. Across the four clusters examined, total organic carbon levels exceeded this critical threshold, averaging at 3% (Table 4). However, variations were evident among the clusters, with cluster TB and MW exhibiting higher levels compared to the other clusters. Land topography is recognized as one of the factors affecting soil organic carbon levels [60,61]. In this study, total organic carbon content was found to be higher in upstream clusters MW and TB than in downstream clusters WU and KT (Fig. 1 and Table 4). This disparity can be attributed to consistent flooding experienced by upstream clusters during the rice growing season, as a result of their proximity to the water intake [62]. Previous research suggests that anaerobic paddy soils exhibit lower decomposition rates of organic matter compared to aerobic conditions [63], implying that differences in water management practices among clusters may contribute to the observed variations in total organic carbon levels. Nevertheless, it is crucial to prevent deficiencies, especially in clusters downstream of the MIS. Application of farmyard manure emerges as cost-effective method for enhancing soil organic carbon content [56].

b. Macronutrients

In rice-based agricultural systems, nitrogen is typically the most limiting nutrient to crop productivity. Without the application of inorganic fertilizers, the accumulation of total nitrogen relies on indigenous sources such as soil, irrigation water, crop residues, and manure [64]. Variation in total nitrogen content was found to be minimal and consistently above the critical threshold of 0.2% across all four clusters (Table 4). However, total nitrogen content tended to be higher in upstream clusters MW and TB compared to downstream clusters within the MIS. In contrast to upstream clusters, downstream clusters are subject to frequent cycles of dry and wet soil conditions, particularly pronounced during periods of peak irrigation demand. The primary inorganic fertilizers utilized by farmers in the MIS, i.e. urea and ammonium sulphate, release mineral nitrogen in the form of NH_4^+, which remains stable in flooded anaerobic environments. The nitrogen is applied in three splits, with approximately 30% applied as a basal dose, and the remaining amount divided equally and applied during the active tillering and panicle initiation stages [65]. Changes in soil aeration resulting from water drainage lead to the conversion of nitrogen from NH_4^+ to NO_3^-, with the latter form being unstable under flooded anaerobic conditions and susceptible to rapid loss through denitrification [66]. The lower levels of total nitrogen observed in clusters downstream of the MIS (Table 4) may be attributed to nitrogen losses caused by fluctuations in soil water conditions, leading to the formation and subsequent loss of unstable nitrogen forms. The cropping calendar in the MIS starts with sowing in July and ends with harvesting in December, using medium duration varieties [10]. This calendar is characterized by dry spells from July to September, succeeded by short rains from October to December. Ensuring sufficient irrigation water supply, particularly during the initial topdressing phase coinciding with the dry period of the cropping calendar, could mitigate nitrogen losses and enhance nitrogen use efficiency.

Soil pH dynamics have a notable influence on phosphorus availability as compared to other nutrients required for rice cultivation [67]. Soil pH levels below 5.5 restrict phosphorus availability due to fixation by iron and aluminium, while levels above 7.0 lead to phosphorus deficiency in rice crops as phosphorus becomes bound to calcium. In this study, soil phosphorus levels in cluster MW were substantially lower compared to the other three clusters (Table 4). Conversely, iron levels were the highest in cluster MW (Table 5), indicating that the low pH levels in this cluster resulted in phosphorus predominantly binding to iron [68]. When employing the Mehlich III procedure for available phosphorus determination, as conducted in this study, phosphorus levels are categorized as low (< 7 mg/kg), medium (7 ─ 15mg/kg), and high (> 15 mg/kg) [69]. Accordingly, recommended phosphorus rates are 30 ─ 60, 15 ─ 30, and 0 ─ 15 P_2O_5 kg/ha for low, moderate, and high phosphorus levels, respectively. Based on this classification, soil phosphorus levels in clusters MW and WU were categorized as moderate, while those in clusters TB and KT were classified as high (Table 4). According to [64], a phosphorus application rate of 60 kg P_2O_5 ha^{-1} is recommended for rice cultivation in the Mwea irrigation scheme. This indicates an excessive application of phosphorus across the scheme, highlighting the necessity to reassess current rates for sustainable rice production and to prevent adverse environmental impacts.

Potassium plays a critical role in numerous plant processes essential for seed quality, including protein synthesis, carbon assimilation, photosynthesis, and enzyme activation [70]. For rice to adequately sustain these growth processes, the extractable potassium level in the soil must exceed 0.2 cmol+/kg of soil [71]. However, the findings of this study reveal potassium deficiency across all clusters within the scheme, with clusters MW, WU, and KT exhibiting more severe deficiencies (Table 4). Key factors contributing to this widespread deficiency include the use of insufficient potassium fertilizer amounts and the removal of rice straw after harvest in the MIS [25]. Previous research suggests that 10 kg K ha^{-1} is required per ton of rice grain harvested [72]. Considering that IR05N221 and Basmati370 are the predominant rice varieties cultivated within the MIS, with yield potentials of 7.5- and 3.5- tons ha^{-1}, respectively [10,7], application rates of 75 kg and 35 kg K ha^{-1} would be deemed adequate to meet crop requirements for IR05N221, and Basmati370, respectively. Furthermore, for efficient potassium utilization, [73] recommended a split application at early tillering and at panicle initiation, corresponding to 45−50 and 60−65 days after sowing, respectively, for both IR05N221 and Basmati370. This approach has been reported to enhance rice yields compared to a single dose basal application. Rice straw contains approximately 1.4 to 2.0% K_2O [74], indicating that long-term potassium management strategies within the scheme should also involve the incorporation of rice straw into the paddy fields.

c. Micronutrients

Micronutrients play a crucial role in rice growth and development [26]. Principal component analysis revealed that zinc had the largest loading values for the first principal component, indicating its significance as the most important soil micronutrient in the MIS (Fig. 3 and Table 3). Similar observations have been made in studies conducted in lowland rice-growing areas, where zinc deficiency was found to be widespread after nitrogen and phosphorus deficiencies [75,76]. A zinc concentration of 2.0 mg/kg (i.e. 2 ppm) in 0.1N HCl is considered critical for rice production [71,77]. Our study revealed that zinc levels in cluster WU were below the critical levels, while those in clusters TB and KT were only slightly above deficiency levels (Table 5). Currently, zinc fertilizers are not included in the recommended package for rice cultivation in the MIS [44], resulting in a need for application rates of 25 kg ha^{-1}, particularly in cluster WU, in the form of zinc sulphate before flooding or after transplanting [71,78]. Furthermore, zinc absorption in rice has been shown to increase with adequate nitrogen and phosphorus application [79,80]. Specifically, nitrogen application promotes lateral root growth and development [81,82], while sufficient phosphorus application facilitates the distribution of plant roots in deeper soil layers [83], thereby enhancing nutrient absorption efficiency. These findings suggest that effective management of zinc fertilizers, combined with appropriate nitrogen and phosphorus application, could serve as an efficient strategy to mitigate zinc deficiencies in the MIS.

In cluster MW, zinc levels were more than three times higher than those in the other three clusters (Table 5). [84] found that soil pH negatively correlated with available zinc levels. In the MIS, instances of continuous waterlogging due to inadequate drainage infrastructure have been reported, particularly in areas with black cotton soils containing high clay content [85]. Such persistent flooding prevalent in cluster MW, is commonly associated with low soil pH [86,74]. The elevated zinc levels in cluster MW may be attributed to the acidic soil conditions prevailing in this area (Table 4). However, these heightened zinc levels in cluster MW may not benefit rice cultivation in low soil pH environments due to the occurrence of aluminium and iron toxicity, which can impair root development and nutrient uptake [46].

Iron is a vital component of porphyrins and ferredoxins, essential elements in the light phase of photosynthesis [71]. For normal growth and functioning of rice, soil iron levels ranging from 2 to 300 mg/kg are necessary [71]. Cluster MW exhibited significantly higher iron levels compared to the other three clusters (Table 5). Furthermore, the iron levels in cluster MW exceeded the recommended range (Table 7), indicating potential nutritional toxicity due to excessive iron, which could hinder rice growth and yield in this cluster. The accumulation of iron to toxic levels is influenced by low pH and continuous waterlogging. Strategies such as adopting alternate wet and dry water-saving technology, currently being promoted in the scheme [87], should be coupled with prioritizing the breeding of tolerant rice varieties, which is essential for mitigating the effects of iron toxicity in the affected zone.

The rice crop requires approximately 8 grams of copper to produce one ton of rough rice, including straw [88]. Copper deficiency in the soil can lead to increased sterility in rice grains, resulting in reduced yields [89]. Soil copper levels exceeded critical thresholds in all clusters within the MIS (Tables 5 and 7). Specifically, clusters MW and WU exhibited higher copper levels compared to clusters TB and KT (Table 5), with the latter two clusters demonstrating elevated available phosphorus levels (Table 4). Existing literature indicates antagonist interactions between copper and phosphorus in both soil and plant tissues [90], suggesting that the high phosphorus levels in clusters TB and KT may have negatively influenced copper availability. Although we have previously discussed the need for downward adjustment of phosphorus rates based on the current nutritional status, farmers need to be sensitized on the importance of conducting regular soil testing to avoid phosphorus accumulation to levels detrimental to availability of micronutrients such as copper. While varying levels of manganese were observed among clusters, no deficiency was detected across the irrigation scheme.

Table 7. Key for classifying the various soil parameters evaluated in the Mwea irrigation scheme

Category	Parameter	Critical level	Reference
	pH	5.5 – 7.0	Ilagan et al., 2014
	ToC	<2%	Musinguzi et al., 2013
Macronutrients	TN	0.2%	Olaleye et al., 2009
	P	7 mg/kg	(Nwilene et al., 2000)
	K	>0.2 cmol+/kg	Olaleye et al., 2009
Micronutrients	Cu	0.1 mg/kg	Dobermann and Fairhurst, 2000
	Fe	2 – 300 mg/kg	Dobermann and Fairhurst, 2000
	Zn	2 mg/kg	Dobermann &Fairhurst, 2000; Fairhurst et al., 2007
	Mn	3-30 mg / kg	Dobermann and Fairhurst, 2000
Exchangeable cations	Ca^{2+}	1 cmol+/kg	Dobermann and Fairhurst, 2000
	Mg^{2+}	3 cmol+/kg	Dobermann and Fairhurst, 2000
Salinity	SAR	13	Richards, 1954

TOC: total organic carbon, TN: total nitrogen, P: phosphorus, K: potassium, Cu: copper, Fe: iron, Zn: zinc, Mn: Manganese, Ca^{2+}: calcium, Mg^{2+}: magnesium, SAR: sodium adsorption ratio.

d. Exchangeable cations

Significant variations in the levels of magnesium and calcium ions were observed among clusters (Table 5). However, regardless of the cluster, the concentrations of these ions exceeded the critical levels, i.e. 3 and 1 cmol+/kg for magnesium and calcium, respectively [71]. These findings agree with those reported by [25], indicating that deficiencies of these nutrients are rare in irrigated lowland rice. Sodium concentration in the soils did not show significant differences among the four clusters (Table 5). The assessment of different sodium levels' impact on plant growth is generally based on the sodium adsorption ration (SAR). Soils with SAR values exceeding 13 typically have sodium as the primary cation contributing to saline conditions [91]. In the Mwea irrigation scheme, SAR values were significantly lower than the critical levels, suggesting that the sodium amounts in these soils are unlikely to contribute to salinity issues based on the current soil status.

4.3 Correlation among Soil Properties

The analysis of variance revealed wide variations in soil pH, phosphorus, potassium, iron, and zinc levels, with some exceeding optimal thresholds for rice cultivation (Tables 4, 5, and 7). Consequently, our focus was on examining the correlation between these five and other soil characteristics assessed in this study. Correlation analysis identified a significant negative correlation between soil pH and iron (Table 6), suggesting that the low pH particularly in cluster MW may be partly attributed to high iron concentrations, primarily in the form of Fe^{3+}. Previous studies have shown that frequent wet and dry soil cycles can reduce Fe^{3+} levels, thus promoting rice growth [92]. Therefore, transitioning from continuous flooding to alternate wetting and drying (AWD) practices is crucial for mitigating Fe^{3+} accumulation to toxic levels in the MIS.

Additionally, a positive significant correlation between phosphorus and calcium was observed (Table 6). In soils with pH ≥ 7, applied phosphorus forms phosphate complexes with calcium, rendering it unavailable to rice plants [67]. Despite all the clusters in the MIS showing pH levels below 7, thus poising no immediate risk of phosphorus deficiency due to calcium binding, a survey conducted by [44] revealed that few farmers applied calcium-rich fertilizers such as calcium ammonium nitrate (CAN). This, coupled with prolonged water shortages, particularly in KT and WM [61], could elevate soil pH and calcium levels, limiting phosphorus availability. Conversely, zinc exhibited a negative correlation with calcium (Table 6). Although calcium levels were within normal ranges (Table 5), the significant negative correlation with zinc suggests isolated instances where high calcium levels may have hindered zinc bioavailability. Given the heterogeneous nature of the soil environment due to diverse farming practices, site-specific soil testing would be essential for identifying such occurrences and providing appropriate recommendations.

Furthermore, soil potassium showed a positive and significant relationship with total nitrogen, total organic carbon, phosphorus, and calcium (Table 6). The correlation coefficient between potassium and nitrogen (0.59) was stronger than that between potassium and phosphorus (0.27) (Table 6), indicating that factors influencing potassium availability would also affect nitrogen to a greater extent than phosphorus. We have previously emphasized that rice straw removal could significantly impact soil health in the MIS. [71] reported that every 1 ton of rice straw removed results in the export of 5 – 8 kg N, 14 – 20 kgs of K_2O, and 1.6 – 2.7 kgs of P, suggesting that continuous straw removal in the MIS could have short-term impacts on nitrogen and potassium and long-term impacts on phosphorus. Mitigation measures could include the application of organic manure, supported by the strong relationship found between total organic carbon and total nitrogen (1.00), and total organic carbon and potassium (0.60) (Table 6).

5. CONCLUSION

In this study, four hundred soil samples were collected from five sections in the MIS, and twelve soil chemical parameters were evaluated. Principal component analysis (PCA) was employed to identify the most significant soil characteristics and cluster areas within the MIS. PC 1 – 4 accounted for 72.2% of the variability within the MIS. A scatter plot based on PC 1 and 2 generated four clusters. The first three clusters, namely MW, TB, and WU, comprised of units in Mwea, Tebere, and Wamumu, respectively, while cluster KT consisted of units in both Thiba and Karaba sections. Significant variations in soil pH, phosphorus, potassium, iron, and zinc levels among clusters was observed, with some clusters exhibiting levels unsuitable for rice production. Within cluster MW, soil pH was below the optimal range for rice cultivation, suggesting a need for liming. Potassium deficiency was observed across all clusters, with rice straw incorporation recommended as a long-term solution. Conversely, zinc deficiency was noted in cluster WU, necessitating zinc fertilizer application. Conversely, iron toxicity was a concern in cluster MW, suggesting the adoption of alternating wetting and drying techniques and tolerant varieties. Through this analysis, tailored recommendations based on localized soil conditions were provided. Implementation of these recommendations is expected to enhance rice productivity within the Mwea irrigation scheme and contribute to regional food security efforts. Future research directions should prioritize addressing identified gaps in soil management strategies. This could include studies on the effectiveness of different liming techniques in alleviating soil acidity. Investigations into alternative methods for phosphorus supplementation in clusters with low pH, where phosphorus application may become bound to aluminium. Additionally, emphasis should be placed on the development and utilization of tolerant rice varieties for addressing iron toxicity within the MIS. Moreover, continuous monitoring efforts are essential to assess the long-term effectiveness of the recommended soil management practices in enhancing rice productivity in the MIS. However, these findings may not be universally applicable, warranting further studies for specific recommendations in other irrigation schemes in Kenya.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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