Original Research Article

Multi-variate Analysis of the Soil Chemical Properties in the Mwea Irrigation Scheme, Kenya and its Implications on Agronomic Management

Abstract

Sub-Saharan Africa is a net importer ofrice with self-sufficiency rates of as low as 14% in countries such as Kenya. More 80% of the rice produced in the countryis cultivated in theMweairrigation scheme. Productivity in the irrigation scheme declined from 5.6 ─ 6.0 t ha^{-1} to 1.3 ─ 4.6 t ha^{-1} between 1977 and 2018 thatcould be attributed to site specific nutritional deficiencies and /or toxicities rendering the generalized agronomic recommendations inapplicable in some areas. This studyaimed to evaluate variability in soil chemical properties within the irrigation scheme, cluster areas with similar nutritional status and provide area-specific agronomic recommendations. Four hundred samples were collected from the five sections of the Mwea irrigation scheme and analyzed for total organic carbon, soil pH, macro nutrients, micro nutrients and exchangeable cations. Principal components (PC) 1 ─ 4 accounted for 72.2% of the total variability within the irrigation scheme. Four clusters were generated in a scatter plot between PC1 and 2 and there were significant differences among the clusters for all the elements evaluated except for Na. Soil pH, potassium and zinc levels were found to be below optimum while available phosphorus and iron were above the critical levels leading to deficiencies and /or toxicities. Based on the findings of cluster analysis and variability of each nutrient among the clusters, specific management strategies were suggested

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to guide in developing of a package of good agronomic practices to improve rice productivity in the irrigation scheme.

Key Words: Agronomic management, Nutrient, Rice, Principal component analysis

Introduction

Rice *(Oryza sativa)*is a staple food for more than half of the world's population and an important source of calories for many countries in the developing world (Fukagawa and Ziska 2019). In sub-Saharan Africa, rice consumption in most countries is growing faster than any other commodity (Arounaet al. 2021). This increase in consumption can be traced to population growth, urbanization and changing consumer preferences. In Kenya, the per capita consumption of rice has continued to rise sharply from 12kg in 2016 to 25.3 kg in 2020 (United Stated Department of Agriculture 2023). In 2020 alone the country's milled rice production was estimated at 85,000 MT while consumption was 700,000 MT forcing the country to import 86% (600,000 MT) of rice to meet local demand.

Rice production in Kenya is mainly carried out in government and community managed irrigation schemes covering about 32,000 ha and includes irrigation schemes in central, western and coastal regions (NIA 2023). Established between 1954 and 1973, the Mwea irrigation scheme (MIS), in central Kenya is the largest government managed scheme (28,600 ha), producing about 80% of the total rice output (MOALF 2020). However, over the years, paddy rice productivity in the country, particularly in the MIS, has experienced a gradual decline from 5.6 ─ 6.0 t ha^{-1} in the decade between 1967─77 to 1.3─4.6 t ha^{-1} in the decade between 2008─2018 (FAO 2021). This is despite the fact that

varieties such as BW196 and AT054 with a yield potential of 8 t ha^{-1} are popular in the MIS (Ng'endoet al. 2022). In order to increase productivity in the MIS there is a need to characterize the soil chemical conditions and nutrient status to identify causes of these yield gaps.

Findings from long-term fertility experiments in West Africa indicate that intensive rice farming systems could result in a deterioration of soil chemical characteristics (Haefeleet al. 2004). Soil quality has been reported to have a direct impact on crop yield (Yamagishiet al. 2003). Continuous rice cropping has been a common practice in some sections of the MIS (Gikonyoet al. 2018;Samejimaet al. 2020). Findings from several studies suggest that such continuous cropping patterns have a negative effect not only on soil quality but also on nutrient absorption and yield of several crops (Wacalet al. 2019). In the past few years, selling of rice straw for animal feed has become a booming business in the MIS. This continuous export of crop residues could have a negative impact on organic material and other nutrients (Muhunyu 2012). Thus, intensive rice cultivation and farmer management practices resulting in degradation in soil quality could be some of the key factors contributing the observed decline in rice yields over time in the MIS. Therefore, assessing variability of the soil quality and clustering sections with similar characteristics within the MIS is important in the design of sustainable rice fertilizer and water management practices; increase input efficiency and enhance average rice yield within the MIS.

Several soil variables are required to assess soil quality. These include soil pH, soil organic carbon, macro nutrients (nitrogen, potassium, and phosphorus), exchangeable cations (magnesium,calcium, and sodium), and micro nutrients

(iron, manganese, zinc, and copper), all of which are required in optimum amounts for proper rice growth and grain yield (Muhsinaet al. 2020). Multivariate analysis enables researchers to gather more information from a data set by taking into account not only a particular variable by itself but also in relation to other variables (Da Piedadeet al. 2019). Principal component analysis (PCA) is recognized as one of the most widely used multivariate analysis methods for reducing the number of variables by identifying those that are most significant in the data (Abdel-Fattah et al. 2021). Thus, PCA simplifies complex and huge data sets and reveals existing patterns, trends and potential clusters (Lever et al. 2017) that can be used to make informative decisions in precision agriculture.

Few studies have been conducted to characterize soil chemical properties in the MIS (Kunduet al. 2016,2017,2020). However, there have been no attempts to cluster sections with similar trends and patterns in soil characteristics that can be used to make site specific recommendations within the MIS. Therefore, the objective of the present study was to evaluate the current chemical status of the soils in the MIS using a multivariate analysis based on principal component analysis and to provide recommendations on management practices for sustainable rice production in the scheme.

2. Materials and methods

2.0 Study area

The study was conducted in the MIS located on the lower slopes of Mt. Kenya in Kirinyaga County, central Kenya between May and September of 2020. The scheme has a total gazetted area of 30,350 acres but only 28,600 of those are under irrigation (NIA 2023). The irrigation scheme lies within Mwea West and

Mwea East Sub- counties, approximately 103 km North East of Nairobi, at an altitude of 1190 m above the sea level. It lies within latitudes 37°13′E and 37°30′E and longitudes 0°32′S and 0°46′S with a mean annual precipitation of about 950 mm. The area experiences bimodal rainfall with the long rains falling between March and May and short rains between October and December (Kihoroet al. 2013). According to Kenya’s agro-climatic zoning, the MIS traverses three agro-climatic zones with maximum moisture availability ratios ranging from 0.65 for zone III towards the highland slopes to 0.50 for the vast area covered by zone IV and to 0.4 for the semi-arid zone V (Sombroeket al. 1982). The area is generally hot with an average temperature of 23 °C. The MIS is divided into seven sections: Mwea, Tebere, Thiba, Wamumu, Karaba, Ndekia, and Curukia, served by Thiba and Nyamidirivers (Fig. 1).

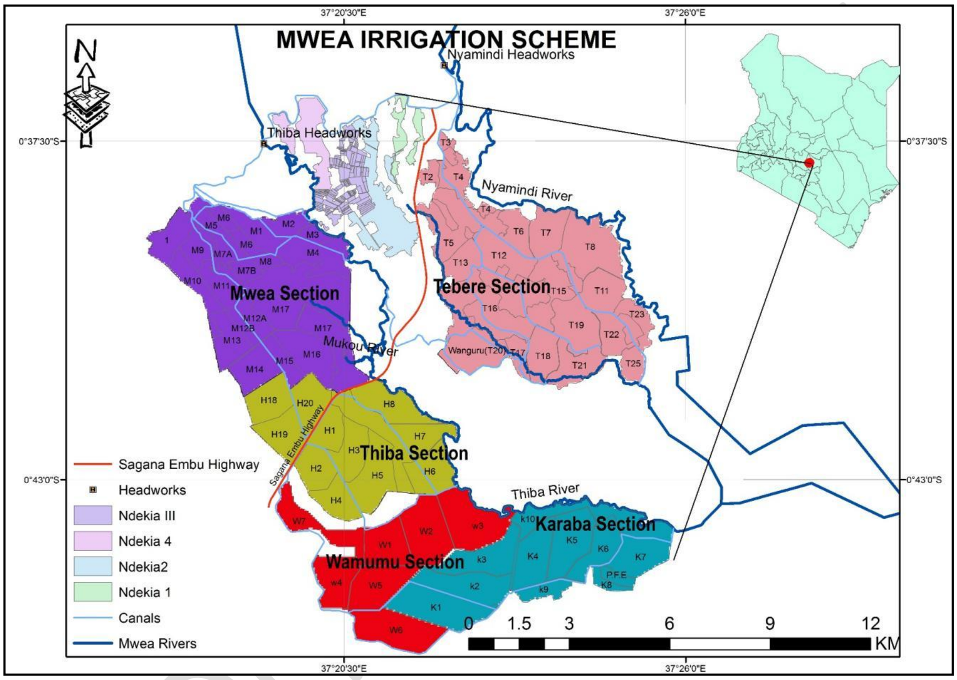

Fig. 1 Map of Mwea irrigation scheme showing the five sections

Each section is further divided into units: Mwea, 17; Tebere, 17; Thiba, 11; Wamumu, 7; Karaba, 10; Ndekia, 5 and Curukia 8 units. The current research was undertaken in the first five sections that have been under rice cultivation for over thirty years. Tebere and Mwea are the two largest sections within the scheme covering 3,285 and 3,110 acres under irrigation, respectively and located upstream of the two rivers (Kabutha and Mutero 2002). Further downstream are Thiba (3,019), Wamumu (2,880) and Karaba (2,650 acres).

2.1 Soil sampling, processing and analysis

Four hundred soil samples distributed across the five selected sections in the MIS were collected at the end of the cropping season in 2020 (Table 1). In Mwea and Tebere, 108 and 102 soil samples, respectively, were collected across the seventeen units for each section. A total of 76 samples were obtained from the Thiba section across eleven units. On the other hand, 59 samples were collected in Karaba section, distributed among eight units. In Wamumu, 55 samples distributed among seven units were obtained. Hence, the samples were collected from all the 60 units of the MIS scattered across the five sections. Different number of samples were collected from each of the five sections based on the relative number of units per section, however, fewer samples were collected in Tebere than in Mwea because some farmers had applied manures in preparation for the upcoming season.

Table 1 Distribution of the 400 samples across five rice growing sections and units in the MIS collected in May 2020.

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

In each unit, 5 to 10 farmers were randomly selected and soil samples collected from a one acre plot size for each farmer. In each of the one acre size of land, soil samples were collected at nine locations as shown in Fig. 2. The nine samples were mixed thoroughly to obtain a composite sample, kept in a labelled polythene bag and taken to the laboratory for analysis.

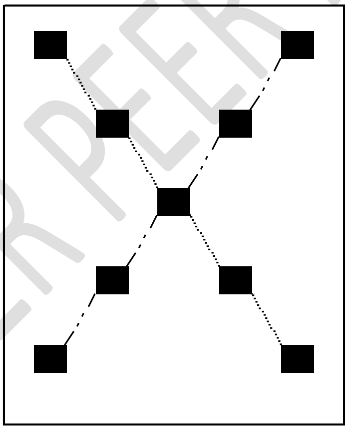

Fig. 2 Distribution of nine samples collected from each of the acre famers across the five sections of the Mwea irrigation scheme

The samples were oven dried at 40 °C, ground and passed through a 2 mm sieve, and subsequently analyzed for total organic carbon, soil pH, macro nutrients (total N, available P_2O_5, and extractable K), micro nutrients (Fe, Mn, Zn, and Cu), and exchangeable cations (Mg, Ca and Na). Soil pH was

determined in a 1:1 (w/v) soil – water suspension using a pH – meter. For soils with $pH > 7.0$, extractable rather than available phosphorus was determined. To determine whether sodium was a key element contributing to alkalinity in high pH soils the sodium adsorption ration (SAR) was determined by the following equation (1).

$$SAR = \frac{Na^{+}}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \qquad (1)$$

Where: Na^{+}, $Ca^{2+}$and Mg^{2+}– respective soluble cation concentrations given in mg/kg. Total organic carbon (ToC) in the dried sample was oxidized by acidified dichromate at 150 °C for 30 minutes to ensure complete oxidation. Barium chloride was then added to the cool digested sample, mixed thoroughly and allowed to stand overnight. The carbon concentration was determined using a spectrophotometer at 600 nm (Anderson et al. 1993). Total nitrogen was determined by first digesting the soil sample with concentrated sulphuric acid containing potassium sulphate, selenium and hydrated copper sulphate at about 350 °C. The amount of nitrogen was measured by distillation followed by titration with diluted standardized H_2SO_4 (Page et al. 1982). Extraction of potassium, phosphorus, calcium (Ca^{2+}), magnesium (Mg^{2+}), manganese (Mn), and sodium (Na^{+}) was done 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 determined with a flame photometer while phosphorus, magnesium and manganese concentrations were measured spectrophotometrically (Mehlichet al. 1962). For determination of extractable phosphorus, extraction was performed in a 1:20 ratio (w/v) with 0.5M sodium bicarbonate solution at pH 8.5. Phosphorus in the extract was then measured spectrophotometrically (Watanabe et al. 1965). Iron, zinc and copper were extracted in a 1:10 ratio (w/v) with 0.1 M HCl. The concentration of these elements was determined using an atomic absorption spectrophotometer (Mehlichet al. 1962).

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2.2 Statistical analysis

Multivariate analysis was performed in R (4.0.2) (Hothorn and Everitt 2009). Principal component analysis was used to detect sources of soil chemical variability and to create clusters of the sections within the MIS. Since the original variables had different units, the data was transformed prior to analysis to avoid the risk of traits with higher variances being emphasized in the first principal components (Wilks 2006). Principal components (PCs), eigenvalues, eigenvectors, and 2-D biplots were obtained using FactoMineR and factoextra packages. Eigenvectors, i.e. coefficients associated positively or negatively with each original variable, with values ≥0.22 (regardless of + or -) were deemed significant. Means of soil chemical properties among clusters generated by principal component analysis were compared using the least significant difference (LSD) test at $p \leq 0.05$. Pearson correlation analysis was performed to determine the relationship between soil properties. In this aspect, average values for each soil property in each unit were used for the analysis. Hence, the sample size (*n*) for the correlation analysis was equal to the number of units where sampling was performed (n = 60).

3. Results

3.1.Principal Component Analysis

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

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 in PC1 and PC2 are shown in Fig. 3 and Table 3 while that of PC3 and PC4 are shown in Fig. 4 and Table 3, respectively. The first principal component had positive association with soil pH (0.41). Other soil properties which showed positive correlation with PC1 were total organic carbon (0.27);

all the major nutrients i.e. total nitrogen (0.28), available phosphorus (0.22), and extractable potassium (0.32); and two of the three exchangeable cations, i.e. Ca^{2+} (0.30) and Na^{+} (0.35). In contrast all the three micro nutrients, copper (-0.33), iron (-0.30), and zinc (-0.35) exhibited a negative association with PC1.

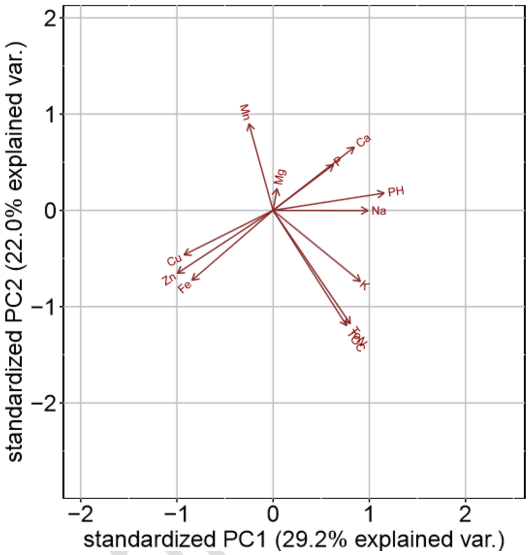

Fig. 3 Loading plot of the twelve soil chemical properties in the Mwea Irrigation Scheme

The soil chemical property that was most strongly and positively correlated with the PC1 was soil pH, while zinc was the most strongly and negatively correlated with PC1. According to Raji (2002) variables having coefficients above 0.30 are considered as having an effect large enough to contribute significantly to variation. To avoid redundancy, this criterion applied to PC2, PC3 and PC4.

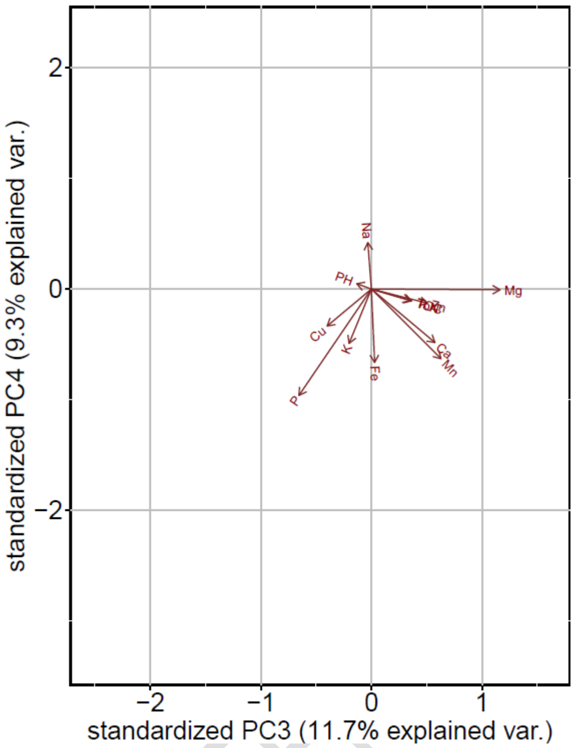

Fig. 4 Loading plot of the twelve soil chemical properties in the Mwea Irrigation Scheme

Principal component two had a strong negative association with total nitrogen (-0.49) followed by total organic carbon (-0.48) and potassium (-0.30). In contrast, this PC had a strong positive association with Mn (0.36). Principal components three and four were mainly influenced by macro and micro nutrients, and exchangeable cations. The former principal component had a strong positive association with Mg^{2+} (0.65) followed by Mn (0.35) and Ca^{2+} (0.32), and strong negative association with phosphorus (-0.36). On the other hand, PC4 had a strong negative association with phosphorus (-0.60), extractable potassium (-0.31), iron (-0.41), Ca^{2+} (-0.30) and Mn (-0.39).

Table 3 Eigenvectors (factor scores) of the first four principal components axes to variation in 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
Macro-nutrients	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
Micro-nutrients	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	0.30	0.27	0.32	(–) 0.30
	Mg	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, Ca: calcium, Mg: magnesium, Mn: manganese, and Na: sodium. Number highlighted in bold were considered to be significant.

A scatter plot of units within the five sections of the MIS based on PC1 and PC2 is shown in Fig. 5. Rice cultivation units within the Mwea, Tebere and Thiba sections formed clear separate clusters from each other with minimal overlapping. The Wamumu section formed a distinct cluster from Thiba and appeared to be intermediate of Mwea and Tebere. On the other hand, Karaba section appeared to overlap with Thiba. Based on the first and second principal components the five sections of the MIS were grouped into four

clusters i.e. Mwea (MW), Tebere (TB), Wamumu (WU), and Karaba with Thiba (KT).

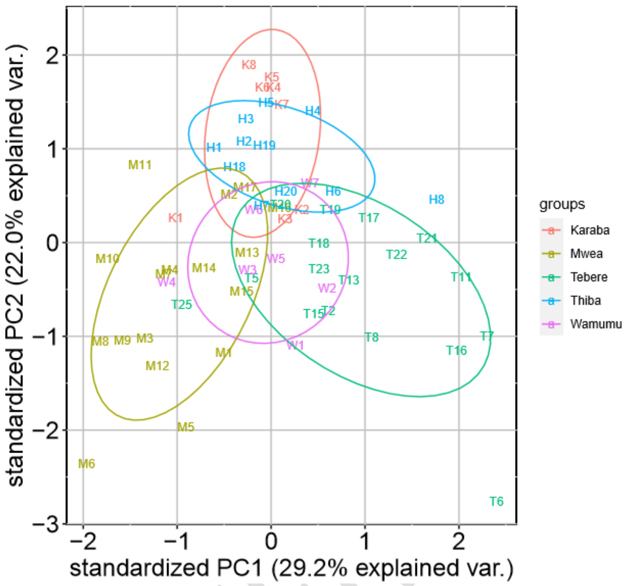

Fig. 5 Scatter plot of the first and second principal component scores of the units in the Mwea Irrigation Scheme based on total organic carbon, total nitrogen, phosphorus, potassium, copper, iron, zinc, calcium, magnesium, manganese, and sodium.

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

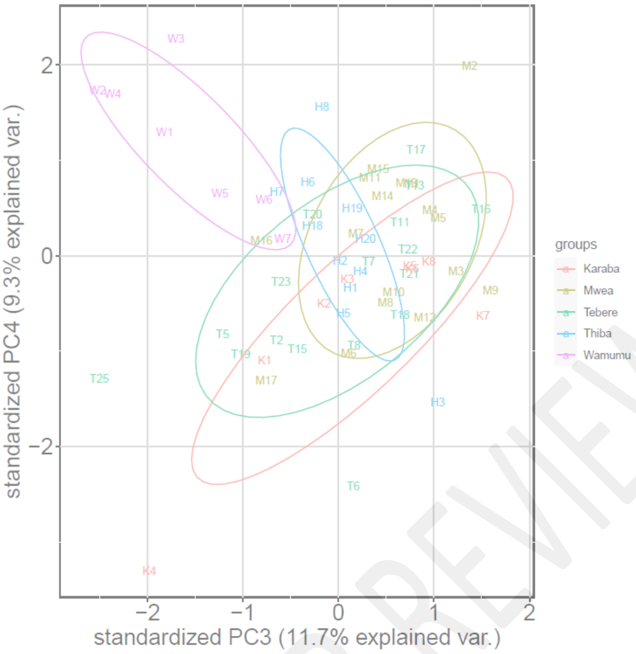

Fig. 6 Scatter plot of the third and fourth principal component scores of the units in the Mwea Irrigation Scheme based on total organic carbon, total nitrogen, phosphorus, potassium, copper, iron, zinc, calcium, magnesium, manganese, and sodium.

3.2 Soil chemical properties

3.2.1 Soil pH and total organic carbon

Variation among the four clusters in soil pH and total organic carbon are shown in Table 4. Average soil pH ranged from 5.03 in cluster MW to 5.83 in cluster TB (Table 3). Soil pH levels in cluster TB were comparable to those in WU but significantly higher than those found in clusters KT and MW. Cluster KT had comparable pH levels to those found in WU but significantly different from those in MW. The average total organic carbon was highest in cluster TB (3.4%) and the lowest in cluster KT with 2.8% (Table 4). The total organic carbon in cluster TB was statistically similar to that of cluster MW but different

from that of clusters WU and KT. The total organic carbon in cluster MW was statistically similar to that of cluster WU but different from that of clusters KT. In cluster MW and TB the total organic carbon were comparable.

3.2.2 Macro nutrients

There were variations in paddy soil macro nutrients. Nitrogen had the lowest CV values of 14.6% compared to 55.5% and 52.5 for soil phosphorus potassium, respectively (Table 4). The mean total nitrogen was highest in cluster TB (0.32 mg/kg) and lowest in cluster KT (0.26 mg/kg) (Table 4). Total nitrogen amounts in cluster TB were significantly different from those in the other three clusters. The average available phosphorus was highest in cluster KT (23.43 mg/kg) and lowest in cluster MW (10.24 mg/kg) (Table 4). The average available phosphorus recorded in cluster KT was statistically similar to that of cluster TB but significantly different from that of cluster WU and MW. The average 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 the extractable potassium levels were significantly different from levels recorded in clusters MW, WU and KT. In these three clusters, the extractable potassium levels were comparable.

Table 4 Mean values of soil pH, total organic carbon, and macro nutrients for the four clusters in the Mwea irrigation scheme.

		Macro-nutrients		
	Total organic	Total nitroge	Available phosphor	Extractable potassium

Cluster	Soil pH	carbon (%)	n (mg/kg)	us (mg/kg)	(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 a	0.32 a	23.08 ab	0.20 a
WU	5.65±0.6 bc	2.9 bc	0.27 bc	16.16 bc	0.03 b
KT	5.53±0.6 b	2.8 c	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

3.2.3 Micro nutrients

The status of zinc, iron, copper, and manganeseis shown in Table 5. The coefficients of variation for these soil micro nutrients were 83.8, 42.0, 41.8 and 47.7%, respectively indicating that variability exist in soil micro nutrients in MIS. Zinc levels in clusters TB, WU, and KT were comparable but significantly lower than those in cluster MW.

Table 5 Mean values of micro nutrients and exchangeable cations for the four clusters in the Mwea irrigation scheme.

Cluster	Micro-nutrients (mg/kg)				Exchangeable cations (cmol+/kg)			SAR
	Zn	Fe	Cu	Mn	Mg	Ca	Na	
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 b	0.31 c	5.16 b	8.6 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

Zinc levels in cluster MW were more than two-fold those in clusters TB, WU, and KT. Iron levels in clusters TB, WU, and KT were comparable but significantly lower than those in cluster MW (Table 5). The average levels of copper ranged from 2.66 mg/kg in cluster TB to 4.11 mg/kg in cluster WU. The copper levels in clusters WU were not significantly different from those in cluster MW; however, copper levels in these two clusters were significantly higher than those in clusters TB and KT. There were no differences in copper levels between clusters TB and KT. Iron levels in clusters TB, WU, and KT were comparable but significantly lower than those in cluster MW. Manganese levels were the highest in cluster KT at 0.95 (cmol+/kg soil) and the lowest in cluster WU at 0.31 (cmol+/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

Levels of magnesium (Mg^{2+}), calcium (Ca^{2+}) and sodium (Na^{+}), are shown in Table 5. Coefficients of variation for these soil exchangeable cations were 12.4, 47.7, 29.1, and 25.8%, respectively. The levels of magnesium among the clusters ranged from 5.16 in cluster WU to 6.16 cmol+/kg of soil in cluster MW. Magnesium levels in clusters MW, TB, and KT were comparable. In contrast, magnesium levels in cluster WU were significantly lower than the other three clusters. Calcium levels varied from 8.6mg/kg in cluster WU to 15.9mg/kg in

cluster KT. Clusters KT and TB had comparable calcium levels, however, these two clusters had significantly higher calcium amounts than MW and WU. The latter two clusters did not differ significantly in their calcium levels. Sodium levels were higher in clusters TB and WU than in WU and KT although these differences were not significant (Table 5). The SAR value was similar in clusters MW, TB and KT but significantly lower than that in cluster MW.

3.3 Correlation among soil chemical properties

The Pearson coefficients of correlation among the twelve soil chemical properties measured in MIS are shown in Table 6. Soil pH had a significant positive association with all the macro nutrients (total nitrogen (r = 0.23*), phosphorus (r = 0.31*), and potassium (r = 0.38**), and exchangeable cations calcium (r = 0.44**) and sodium (r = 0.46**). Conversely, soil pH had a significant negative correlation with the micro nutrients iron (r = -0.47**) and zinc (r = -0.55**). Total carbon had a significant perfect positive correlation with nitrogen (r = 1.00**), significant positive correlation with potassium (r = 0.59**) and sodium (r = 0.28*), and negative correction with manganese (r = -0.37**). Among the macro nutrients, nitrogen, showed a significant positive correlation with potassium (r = -0.60**) and sodium (r = 0.30*), and 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 had 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*), and negative correlation with calcium (r = -0.29*), copper (r = -0.35**), iron (r = -0.31*), and zinc (r = -0.37**).

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

Table 6 Pearson’s Correlations of the twelve soil chemical properties

	PH	TN	ToC	P	K	Ca	Mg	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						1.00	0.25 ns	0.36 **	-0.41 **	-0.37 **	-0.30 *	-0.29 *
Mg							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).

4. Discussion

i. Clustering of soils in the Mwea Irrigation Scheme (MIS) using principal component analysis

In this study, principal component analysis was used to identify important soil properties that could describe 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). All the twelve soil properties that were analyzed, except magnesium, were significantly correlated with either PC1 or 2 or both (Table 3). This suggests that most of the variation within the MIS for the measured soil properties can be attributed to the first two principal components. PC1 had a positive and significant correlation with soil pH, total organic carbon, macro nutrients (nitrogen, phosphorus and potassium), and exchangeable cations (Ca^{2+} and Na^{+}) (Table 3). This suggests that these parameters vary together such that when one category increases the other would tend to also increase (Da Piedadeet al. 2019). A scatter plot for PC1 and 2 showed that the Mwea (cluster MW), Tebere (cluster TB), Wamumu (cluster WU) sections were clearly distinct while Karaba and Thiba (cluster KT) appeared to overlap and hence were grouped together (Fig. 5). Moreover, significant differences were found among clusters in all the soil properties evaluated except for sodium (Tables 4 and 5). This indicates principal component analysis was adequate in the clustering of the sections of the MIS.

Variation in chemical properties among clusters and recommendations for agronomic management

a. Soil pH and total organic carbon

Soil pH had a coefficient of variation value of 8.5% (Table 4) indicating that very low variability exists for soil pH in MIS. These results are in agreement with findings by Kunduet al. (2016) who reported that variability for soil pH in MIS was low with CV values of 12% for water and 15% for KCl. Principal component analysis showed that soil pH had the largest positive effect on PC1 and therefore considered the key contributor of the variation found in soil chemical properties in this study (Fig. 3 and Table 3). The optimum soil pH for lowland rice ranges between 5.5 and 7.0 (Ilaganet al. 2014). In clusters TB, WU and KT, the soil pH tended to be acidic in some areas and optimum in others while in cluster MW, which was mainly comprised of units in the Mwea section, pH values were below the optimum levels for the growth of rice under flooded field conditions (Table 4). Evidence in literature indicates that fertilizer management practices could have an impact on soil pH levels. In irrigated lowland rice systems urea and ammonium sulphate are the two common sources of nitrogen (Fageriaet al. 2003). Findings from a survey conducted in the Mwea irrigation scheme showed that about 85% of the farmers applied ammonium sulphate during the first and second top-dressing (Onderi and Danga 2022). In studies conducted to evaluate the effect of the two sources of nitrogen on soil pH, ammonium sulphate was found to be more acidifying than urea (Fageriaet al. 2010).Hence the low pH particularly in cluster MW (Table 4), where rice cultivation has been practised since 1954 (NIA 2023), could partly be attributed to continuous use of highly acidifying sources of nitrogen for rice cultivation for a prolonged period of time. Low soil pH is caused by free release of hydrogen, aluminum, manganese, and iron to toxic levels (Das 1996). Soil acidity hampers plant growth primarily by causing the inhibition of root

development as well as root retardation (Rout et al. 2021). Application of lime in acids soils is one of the strategies that are commonly used to change soil pH and also improve soil fertility (Reddy and Subramanian 2016). However, excessive addition of lime can cause a significant decrease in the availability of micronutrients, especially iron, zinc and copper leading to deficiencies of those plant nutrients (Haynes 1982). The application of biochar as an alternative method of soil amendment has been reported to confer additional advantageous effects to acidic soils such as creating a carbon sink to mitigate global warming, increasing soil water holding capacity, reducing greenhouse gas emissions and stabilizing mobile heavy metals, and other organic pollutants in soil (Lehmann et al. 2006; Van Zwietenet al. 2010; Inyanget al. 2011; Abdul-Halim et al. 2018;Bereket al. 2018). In this aspect, the use of carbonated rice husk as biochar could be low-cost option in the MIS considering that the product is a freely available by-product from a number of mills nearby the scheme and is mostly found dumped along the road or openly burnt in the fields within the scheme (Bogonko 2020; Ndirangu and Oyange 2019).

Organic carbon plays a key role in determining the physical, chemical, and biological properties of soil (Yang et al. 2004; Reeves et al. 1997). In this study the coefficient of variation for total organic carbon was 13.3% indicating very low variability for organic carbon in the MIS (Table 4). The critical level for total organic carbon is 2% (Musinguziet al. 2013). In the four clusters the total organic carbon was greater than the critical levels recording a mean of 3% (Table 4). Nonetheless, variation was found among the clusters with cluster TB followed by MW having higher levels that the other two clusters. Land

topography is one of the several factors that have been reported to impact levels of soil organic carbon (Hao and Kravchenko 2007; Wang et al. 2012). In this study, total organic carbon was higher in upstream clusters MW and TB than WU and KT that are located downstream (Table 4 and Fig. 1). Due to the close proximity to the water intake, the upstream clusters seldom experience water shortages and hence soils here tend to be under flooded water conditions during the rice growing season (Mohammed et al. 2003). Findings from previous studies indicate that decomposition of soil organic matter tends to be low under anaerobic than aerobic paddy soils (Katoh 2003). This suggests that the higher total organic carbon in clusters TB and MW than in WU and KT could be as result of differences in water management practices among clusters. Still, there is need to take precaution to avoid deficiency particularly in clusters situated downstream of the MIS. Application of farmyard manure is one of the most cost effective ways of improving organic carbon in the soil (Yang et al. 2004).

b. Macro-nutrients

In rice-based systems, nitrogen is typically the most limiting nutrient to crop productivity. In the absence of inorganic fertilizer application, total nitrogen accumulation depends of indigenous sources such as soil, irrigation water, crop residues and manure application (Nguyen et al. 2008). Variation for total nitrogen amounts was very low and above the critical level of 0.2% (Olaleyeet al. 2009) in all the four clusters (Table 4). Nonetheless, total nitrogen tended to be higher in upstream clusters of MW and TB than in clusters downstream the MIS. Again, in contrast to upstream clusters, downstream clusters are frequently exposed to cycles of dry and wet soil conditions that are more pronounced during peak irrigation water requirement (Mohammed et al. 2003).

The inorganic fertilizers that farmers mainly use in the MIS release mineral nitrogen in the form of NH_4^+, which is stable in flooded anaerobic environments. The nitrogen is usually applied in three splits whereby about 30% of the total nitrogen is applied as basal with the remaining amount applied in two equal splits at the active tillering and panicle initiation stage (Oyangeet al. 2019). Soil aeration due to draining of water cause changes in nitrogen from NH_4^+ to NO_3^-; the latter nitrogen form is unstable under flooded anaerobic conditions and can quickly be lost through denitrification (Ishii et al. 2011). The lower total nitrogen levels in clusters downstream of the MIS (Table 4) could be attributed to nitrogen losses caused by fluctuations in soil water conditions leading to the formation and loss of unstable forms of nitrogen. Adequate supply of water particularly during the timing of fertilizer application could mitigate against such nitrogen losses and also enhance nitrogen use efficiency.

Phosphorus availability for rice is influenced to a greater extent by soil pH dynamics as compared to other nutrients (Rakotoson 2022). Soil pH levels < 5.5 limit phosphorus availability due to fixation by iron and aluminium while those > 7.0 cause deficiency for the rice crop as a result of the phosphorus being bound to calcium. In this study, soil phosphorus in cluster MW was substantially lower than that of the other three clusters (Table 4). In contrast, Fe levels were the highest in cluster MW. These findings suggest that the low pH levels in cluster MW resulted in most of phosphorus to be fixed to iron (Abou-Seedaet al. 2020). When using the Mehlich III procedure for the determination of available phosphorus, as was the case in this study, phosphorus levels can be categorized as low (< 7 mg/kg), medium (7 –

15mg/kg) and high (> 15 mg/kg) (Nwileneet al. 2000). Consequently, the recommended phosphorus amounts 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 the soil phosphorus levels for cluster MW and cluster WU were categorized as moderate while those in clusters TB and KT were high (Table 4). According to Oyangeet al. (2019) phosphorus application rate of 60 kg P_2O_5 ha^{-1} is recommended for rice cultivation in the Mwea irrigation scheme. This shows that there is excess application of phosphorus across the scheme and there is need to review the current rates for sustainable rice production to avoid causing detrimental impact to the environment.

Potassium is an essential nutrient in several plant processes that have a direct influence on the quality of seed such as protein synthesis, carbon assimilation, photosynthesis, and enzyme activation (Marschner 2012). The extractable potassium level in the soil has to be above 0.2 cmol+/kg of soil for rice to obtain adequate amounts to sustain plant growth processes (Olaleyeet al. 2009). The findings of this study indicate that there was potassium deficiency across all the clusters in the scheme, but this was more severe in clusters MW, WU, and KT (Table 4). Use of inadequate potassium fertilizer amounts coupled with removal of rice straw after harvest in the MIS have been cited as key factors that have contributed to the widespread deficiency (Kunduet al. 2016). Findings from previous research show that 10 kg K ha^{-1} is required per ton grain rice harvested (Dobermann and Fairhurst 2000). Within the MIS, farmers cultivate different varieties with different yield potentials (Samejimaet al. 2020). Thus, the potassium application amounts need to be adjusted to meet the specific crop requirements. Moreover, for efficient utilization of applied

potassium split application at early tillering and at panicle initiation have been reported to enhance rice yields than single dose basal application (Manzooret al. 2008). Rice straw contains 1.4 to 2.0% K_2O (Dobermann and Fairhurst 2002), hence long term potassium management strategies within the scheme should also include incorporation of rice straw to the paddy fields.

c. Micronutrients

Micro nutrients play an important role in the growth and development of rice (Kundu et al. 2019). Principal component analysis revealed that among micro nutrients zinchad the largest loading values for the first principal component (Fig. 3 and Table 3). This indicates that zinc is the most important soil micro nutrient in the MIS. Similar findings have been reported in studies conducted in lowland rice growing areas that found zinc to be the most wide spread nutrient disorder after nitrogen and phosphorus deficiency (Quijano-Guertaet al. 2002; Singh et al. 2003). Zinc concentration of 2.0 mg/kg (i.e. 2 ppm) 0.1N HCl is considered the critical level for deficiency in rice production (DobermannandFairhurst 2000; Fairhurstet al. 2007). The findings of this study showed that zinc levels in cluster WU (i.e. units mainly in the Wamumu section of the Mwea irrigation scheme) were below the critical level while those in clusters TB and KT were only slightly above deficiency levels (Table 5). In zinc deficient soils, an application rate of 25 kg/ha in the form of zinc sulphate before flooding or after transplanting has been recommended in irrigated lowland rice (Dobermann and Fairhurst 2000; Kalalaet al. 2017). However, at present, only a few farmers in the MIS use zinc fertilizers because these have not been included in the recommendation package for rice cultivation (Onderi and Danga 2022). On the other hand, zinc absorption in rice has also been

reported to be enhanced at sufficient nitrogen and phosphorus application (Erenogluet al. 2011; Lalet al. 2000). A number of previous studies have reported the functional role of nitrogen application in promoting lateral root growth and development in both lowland and upland rice ecosystems (Tran et al. 2014;Mengeet al. 2019). Moreover, Saneokaet al. (1990) showed that plant roots were distributed in deeper soil layers at higher than lower phosphorus levels. These findings indicate that the use of appropriate zinc fertilizers particularly in clusters TB and KT, should be coupled with proper management of nitrogen and phosphorus application could be an efficient strategy to alleviate these deficiencies in the MIS.

In cluster MW zinc levels were more than threefold of those in the other three clusters (Table 5). Qi (1987) reported that the available zinc in soils correlated negatively with soil pH. In the MIS, few incidences of continuous water logging due to poor drainage infrastructure has been reported especially in places with black cotton soils that have high clay content (Wamariet al. 2016). Perennial flooding are among the key factors that are often associated with low soil pH (Qadar 2002; Quijano-Guertaet al. 2002). The high zinc levels in cluster MW could be attributed to acidic soil conditions prevalent in this cluster (Table 4). However, these high zinc levels in cluster MW may not be beneficial to rice at low soil pH levels due to occurrence of aluminium and iron toxicity that affect root development and hence nutrient uptake (Rout et al. 2021).

Iron is an important constituent of porphyrins and ferredoxins, both of which are critical components of the light phase of photosynthesis (Dobermann and Fairhurst 2000). For normal growth and function of rice, soil iron levels of 2–300 mg/kg are required (Dobermann and Fairhurst 2000). Cluster MW had

significantly higher iron levels than those found in the other three clusters (Table 5). Moreover, the iron levels in cluster MW were above the recommended range (Table 7).

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
Macro-nutrients	TN	0.2%	Olaleye et al., 2009
	P	7 mg/kg	(Nwilene et al., 2000)
	K	>0.2 cmol+/kg	Olaleye et al., 2009
Micro-nutrients	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	1 cmol+/kg	Dobermann and Fairhurst, 2000
	Mg	3cmol+/kg	Dobermann and Fairhurst, 2000
Salinity	SAR	13	Richards, 1954

TOC: Total organic carbon, TN: total nitrogen, SAR: sodium adsorption ratio

This suggests that there could be nutritional toxicity as a result of excessive iron amounts with the potential of limiting rice growth and yield in cluster MW. Accumulation of iron to toxic levels is influenced by low pH and continuous water logging. Adoption of alternate wet and drying water saving technology that is currently being disseminated in the scheme (RiceMAPP 2016); and use tolerant rice varieties are among the strategies that can be adopted in the affected zone to mitigate the effects of iron toxicity.

The rice crop removes approximately 8 grams of copper for the production of one ton of rough rice including straw (Choudhury et al. 2009). Copper deficiency in the soil increases sterility in rice grain resulting in a decrease in

the yield (Ambak and Tadano 1991). Soil copper levels were above the critical levels in all the clusters within the MIS (Tables 5 and 7). Copper levels in clusters TB and KT tended to be lower than those in clusters MW and WU (Table 5). Conversely, the former two clusters were found to have high levels of available phosphorus (Table 4). There is accumulated evidence in the literature of antagonist effects between copper and phosphorus in soil and plant tissues (Zhang et al. 2020). This suggests that the high phosphorus levels in clusters TB and KT, in part, negatively affected the availability of copper in the soils of the MIS. Farmers should be advised to apply phosphorus fertilizers based on soil test results to avoid the accumulation of this nutrient to levels detrimental to availability of other nutrients. Although there were varying levels of manganese among the clusters, no deficiency was detected across the irrigation scheme.

d. Exchangeable cations

There were significant variations among clusters on the levels of magnesium and calcium ions (Table 5). Regardless of cluster however, the concentrations of these ions were higher than the critical levels i.e. 3 and 1 cmol+/kg for magnesium and calcium respectively (Dobbermann and Fairhurst 2000). These findings are in agreement with those reported by Kunduet al. (2016) who reported that deficiency of these nutrients is rare in irrigated lowland rice. There were no significant differences in sodium concentration in the soils among the four clusters (Table 5). The criterion for assessing the impact of different sodium levels in the soil on plant growth is generally based on the sodium adsorption ration (SAR). In soils with SAR values higher than 13, sodium is the main cation contributing to saline conditions (Richards 1954). In

the Mwea irrigation scheme, the SAR values were significantly lower than the critical levels suggesting that the sodium amounts in these soils are less likely to contribute to occurrence of salinity based on the current soil status.

iii. Correlation among soil properties

Among the parameters analyzed only soil pH, phosphorus, potassium, iron and Zn amounts showed wide variations extending to levels not suitable for rice cultivation (Tables 4, 5 and 7). Therefore, we focused on correlation between these five and other soil parameters evaluated in this study. Correlation analysis revealed that there was a significant negative correlation between soil pH and Fe (Table 6). This suggests that the low pH in MW could partly be attributed to high concentration of Fe mainly in the form of Fe^{3+}. Frequent cycles of wet and dry soil conditions have been reported to cause a reduction of Fe^{3+} and thus favoring rice growth (Dobermann 2004). A shift in water management practices from the conventional continuous flooding to alternate wetting and drying (AWD) is a key strategy in ameliorating Fe^{3+} accumulation to toxic levels in the MIS.

In this study, we found a positive significant correlation between phosphorus and Ca^{2+} (Table 6). In soils with pH ≥ 7 applied phosphorus forms phosphate complexes with Ca^{2+} and hence becomes unavailable to the rice plant (Abou-Seedaet al. 2020). Based on the current soil pH levels all the clusters in the MIS had pH less than 7 and hence there is no immediate risk of phosphorus deficiency as a result of this nutrient being bound to Ca^{2+}. However, in a survey conducted by Onderi and Danga (2022) to access the most commonly used fertilizers in the MIS, it was reported that few farmers applied calcium rich fertilizers such as calcium ammonium nitrate (CAN). This coupled with

long periods of water shortage particularly in KT and WM (Mohammed et al. 2003) could cause increases in soil pH and Ca^{2+} levels limiting P availability. In contrast, zinc showed negative correlation with calcium (Table 6). Although we found Ca^{2+} to be within normal ranges (Table 5), the significant negative correlation with zinc could suggest presence of few isolated cases where Ca^{2+} levels were high to the extent that bioavailability of zinc was hampered. Since the soil environment is highly heterogeneous as a result of different farmer practices, site specific soil testing would be able to identify such soil and give appropriate recommendations. Soil potassium showed a positive and significant relationship with total nitrogen, total organic carbon, phosphorus and calcium (Table 6). The correlation coefficient for the relationship between potassium and nitrogen (0.59) was stronger than phosphorus (0.27) (Table 6). This suggests that factors that affect potassium availability would also affect nitrogen to a greater extent than phosphorus. We have emphasized before that rice straw removal is likely to have serious implications of soil health status in the MIS. Dobernmann and Fairhurst (2002), reported that for 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. This indicates that the continuous straw removal in the MIS is likely to have a greater impact on nitrogen and potassium in the short term and phosphorus in the long term. Mitigation measures could include among others the application of organic manure. This is supported by the strong relationship that was 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 across five sections in the MIS and twelve soil chemical parameters evaluated. Principal component analysis was used 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 inMwea, Tebere, and Wamumu, respectively; while cluster KT consisted of units in both Thiba and Karaba sections. Soil pH, phosphorus, potassium, iron and zinc showed significant variation among clusters and levels unsuitable for rice production found in some clusters. Several agronomic management practices such as water, type of fertilizer, straw removal were discussed as possible causes of differences in nutritional status within the Mwea irrigation scheme. Based on these differences specific nutrient management and agronomic practices were recommended.

6. Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author upon reasonable request.

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