



Soil Fertility Status in Bukoba, Missenyi and Biharamulo Districts in Kagera Region, Tanzania

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To cite this article:

Mgeta Steven Merumba, Ernest Semu, Johnson Mashambo Semoka, Balthazar Michael Msanya. Soil Fertility Status in Bukoba, Missenyi and Biharamulo Districts in Kagera Region, Tanzania. *International Journal of Applied Agricultural Sciences*. Vol. 6, No. 5, 2020, pp. 96-117. doi: 10.11648/j.ijaas.20200605.12

Received: September 5, 2020; **Accepted:** September 17, 2020; **Published:** September 23, 2020

Abstract: The study was conducted in three Districts of Kagera Region, Tanzania to assess the inherent soil fertility status of farmers' fields. Thirty-three fields, located three to five km apart, were selected and soil samples (0 – 20 cm depth) were taken, mixed thoroughly, air-dried, ground, sieved through 2 mm sieve, and analyzed in the soil laboratory based on standard laboratory analytical procedures. Correlation analyses among soil chemical properties were performed using IBM SPSS Statistic 20 and the mean values were calculated using Excel spreadsheet statistical package. Soil fertility index (SFI) and limiting nutrients were used to assess the fertility status of the fields. The results indicated that soil textures ranged from sandy clay loam to sandy clay, clay loam, clay to sandy. Soil pH ranged from strongly acid (5.1) to slightly acid (6.1) while EC levels were very low (0.03 - 0.17 dS m⁻¹). Total TN ranged from very low to medium (0.04 - 0.41%), extractable P ranged from low to high (0.44 - 86.44 mg kg⁻¹) and Exchangeable K ranged from very low to medium (0.08 - 0.98 cmol(+) kg⁻¹). Exchangeable S ranged from low to medium (2.27 - 12.14 mg kg⁻¹) while CEC ranged from very low to medium (5.20 - 23.00 cmol(+) kg⁻¹), extractable Zn ranged from medium to high (0.85 - 18.41 mg kg⁻¹), Cu from medium to high (0.47 - 2.81 mg kg⁻¹), and Mn and Fe were medium (2.24 - 70.34 mg kg⁻¹) and high (37.50 - 473.21 mg kg⁻¹), respectively. The results also indicated both positive ($r=+ve$) and negative ($r=-ve$) and both significantly ($p\leq 0.05$) and highly significantly ($p\leq 0.01$) correlations among the soil chemical properties in each districts. Based on SFI, the soil fertility status of the studied fields ranged from poor fertility to good fertility. The results on the limiting nutrients across the studied fields indicated that N and K were the most limiting nutrients (67%) followed by P (52%), S (32%), Mg and OC (18%) and the least was Ca (15%). The results also indicated that N and P were the most limiting nutrients in Bukoba District while N and S were the most limiting nutrients in Missenyi District and N, P and K were the most limiting nutrients in Biharamulo District. Therefore, specific soil fertility management practices are recommended based on limiting nutrients in those fields having inadequate levels of plant nutrients together with training of farmers on proper use of the appropriate soil fertility management practices.

Keywords: Soil Fertility Status, Soil Fertility Index, Physical and Chemical Properties, Soil Fertility Management, Limiting Nutrient (s), Kagera Region

1. Introduction

Agricultural production in the sub-Saharan Africa (SSA) has continued to decline due to increasing human population and land use intensification [1], due to decreased size of land

available to farmers, reduced soil fertility and low crop productivity [2]. However, smallholder farmers are continuing to cultivate the available land to ensure household

food security. Continued crop cultivation without replenishing the mined nutrients led to organic matter and soil nutrient depletion on smallholder farms [3-5], causing land degradation due to poor soil fertility [6, 7]. Tanzania, being among the sub-Saharan Africa (SSA) countries, is also affected by declining crop productivity at farm level [8] due to continued crop cultivation without replenishing the nutrients by external inputs [9]. For example, in Kagera region, average root yield of cassava in farmers' fields is about 7 MT ha⁻¹ [10, 9] as compared to the national current average root yield of 10 MT ha⁻¹ and potential yield of 25 to 60 MT ha⁻¹ [8]. The average yield of maize in Kagera region is 1.6 MT ha⁻¹ compared to the national current average yield of 4 MT ha⁻¹ [10]. The low yield is due among others, to the increased susceptibility of the crops to pests, and low soil fertility [11, 12]. The low soil fertility has been attributed to the extensive loss of nutrients through leaching especially in high rainfall zone (above 1800 mm), extensive weathering of the soils, low soil organic matter content and continuous crop removal of the nutrients from the soils without replenishment [13]. This suggests the need to use fertilizers in those soils to improve the soil fertility status for optimum and sustainable crop yields. However, before deciding on fertilizer use, farmers need to understand the inherent soil fertility status of their farms.

Soil is a dynamic natural medium from which plants get nutrients and mechanical support. It is a complex system comprised of minerals, soil organic matter (SOM), water, and air in different proportions [14]. Soil quality comprises interactive attributes of physical, chemical, and biological properties, which affect processes in the soil that make it suitable for agricultural uses [15]. Some of the chemical properties of the soil include soil reaction (pH), organic matter, and macro- and micro-nutrients while physical properties include soil colour, soil texture, and structure. These properties vary spatially and temporally from a field to a larger region scale and are influenced by soil formation factors. These factors include soil parent materials, living organisms, time and relief (intrinsic factors), as well as soil management practices, fertilization and crop rotation (extrinsic factors) [16]. Physical and chemical soil properties play an important role for the soil fertility and are determined after soil testing [17].

Soil fertility assessment is the measurement of available plant nutrients and estimation of capacity of soil to maintain a continuous supply of plant nutrients for crops. It is the most basic decision making tool on a particular land use system [18] and it provides information regarding nutrient availability in soils, which forms the basis for fertilizer recommendations for economic and sustainable crops production [5]. It also helps to establish appropriate soil fertility management strategies for farmers, extension staff, and policy makers to improve soil fertility and crop productivity. Thus, understanding soil fertility status of the land at a particular location will help agricultural stakeholders including farmers to make decisions on how to use and manage the respective land for sustainable crop

production. However, there is scanty information on the current fertility status of the soils in Kagera Region. It is for this reason that this study was conducted for the objective of assessing the fertility status of some selected fields as proxy to the soil fertility status of Bukoba, Missenyi and Biharamulo Districts. This will lead to formulation of recommendations on appropriate soil fertility management strategies to improve crop productivity at farm level and the region as whole, thereby improving household food security and income.

2. Materials and Methods

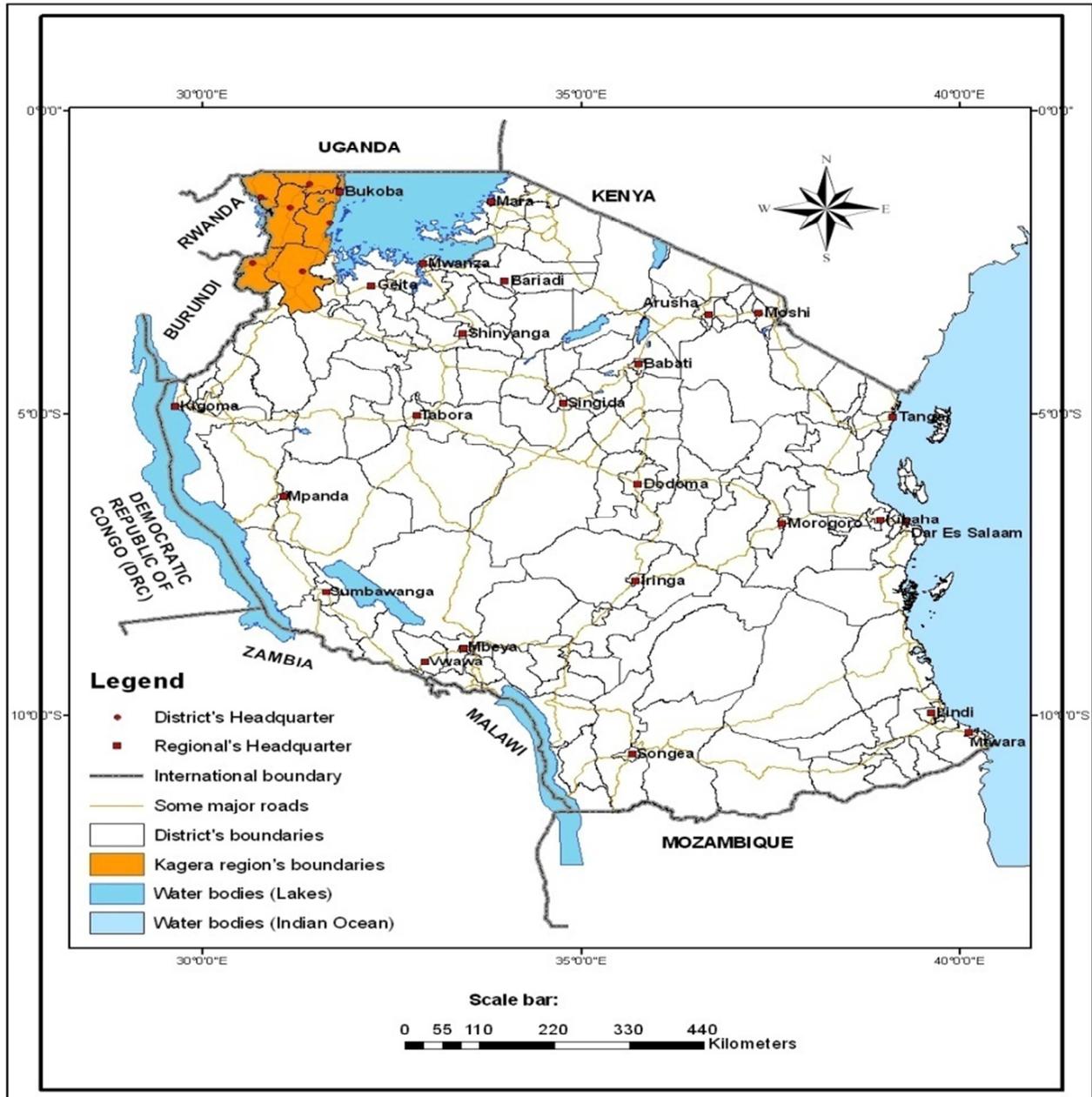
2.1. Description of the Study Area

2.1.1. Location of the Study Area

Kagera region is located on the north-western corner of Tanzania bordering the western shore of Lake Victoria (Figure 1). It lies between latitudes 1°00' and 2°45' south of the Equator and between longitudes 30°25' and 32°40' east of the Greenwich. It is the fifteenth largest region in Tanzania with an area of about 3,568,600 ha of land, which accounts for approximately 3.3% Tanzania's total land area. However, out of region area, about 10,173 ha are enclosed by water of the Lake Victoria, Ikimba and Burigi, and the Ngoni and Kagera rivers [19, 20]. Administratively, the region has seven districts, namely Bukoba, Biharamulo, Muleba, Karagwe, Ngora, Kyerwa, and Missenyi and borders three countries, namely Uganda, Rwanda and Burundi, (Figure 1). This study was conducted in three districts, namely Bukoba, Missenyi and Biharamulo. Bukoba District covers an area of 284,100 ha and is situated between latitudes 01° 00' and 03° 00' S and between longitudes 030° 45' and 031° 00' E, with altitude ranging from 1200 - 1400 meters above sea level. Missenyi District covers an area of 270,875 ha and is situated between latitudes 01° 00' and 01° 30' S and between longitudes 030° 48' and 031° 49' E, with altitude ranging from 1100 - 1400 meters above sea level. Biharamulo District covers an area of 374,400 ha and is situated between latitudes 02° 15' and 03° 15' S and between longitudes 031° 00' and 032° 00' E, with altitude ranging from 1100 - 1700 meters above sea level [21, 20].

2.1.2. Climate and Soils of the Study Area

The study area experiences bimodal rain seasons ranging from September to December (short rains) and from March to June (long rains). The average annual rainfall ranges from 900 - >2500 mm in Bukoba District, from 600 - 2000 mm in Missenyi District and from 700 - 1000 mm in Biharamulo District [21, 9, 20]. Based on rainfall intensity, three agro-ecological zones, namely high (Bukoba), medium (Missenyi), and low (Biharamulo) rainfall zones are found in Kagera Region [13]. Average annual temperature ranges from 16 - 28°C, with Missenyi District having higher annual temperature (28°C) than Bukoba and Biharamulo Districts (26°C). The soils range from sandy clay loam to sandy clay and clay [21].



Source: [20]

Figure 1. Location of Kagera Region and its Districts, Tanzania.

2.1.3. Farming Systems of the Study Area

The farming systems of the study area are largely banana/coffee based [22], with three distinct land use types classified in local parlance “Haya” as *Kibanja* (*Bibanja* in plural). This is the most fertile land that usually surrounds the residential houses, and is permanently planted with the perennial crops, mainly banana (*Mussa spp.*), and coffee (*Coffea canephora*). The permanent crops are seasonally intercropped with annual crops, mainly beans (*Phaseolus vulgaris*), maize (*maize (Zea mays)*), taro (*Colocasia esculent*), cassava (*Mahihot esculenta*) and various types of trees but the major crops being banana, coffee and beans. Another land

use type is *Kikamba*, the area for annual crop cultivation found near *Kibanja*. Crops grown in *Kikamba* include cassava, maize, sweet potato (*Ipomea potatos*), yams (*Dioscorea spp.*) and occasionally taro, which are grown solely or mixed. The last land use type is *Rweya*, the grassland further away, serving as communal grazing land, source of mulch, thatch grass and area for shifting cultivation. Crops cultivated on *Rweya* under shifting cultivation include cassava, sweet potato and yams while tea (*Cammelia sinensis*) and trees like *Eucalyptus spp.* and *Pinus spp.* are permanently grown [13, 22, 20]. Soil sampling for this study therefore was done on *Kikamba* land use type, as it is the land where annual crops are grown.

2.2. Site Selection and Soil Sampling

This study was conducted in Bukoba, Missenyi and Biharamulo Districts. In each District, two wards were selected. In each selected ward, one village was selected, thus giving two villages per each District. In each of the selected villages, five farmers' fields were selected to give 10 farmers' fields per District, which gave 30 farmers' fields in the three districts. In addition, one field in each district for the establishment of cassava experimental trial was selected to give 33 fields in the study area. The experimental trial sites were Tanzania Agricultural Research Institute (TARI), Maruku Centre in Bukoba District, Mabuye Primary school in Missenyi District and Rukaragata Farmers Extension Centre in Biharamulo District. The distance from one field to the other ranged from 3 - 5 km depending on the size of the villages. The size of the fields ranged from 0.4 - 1.2 ha. In each of the selected fields, a soil sample (0 – 20 cm depth) was collected using a zig-zag pattern over the whole field area using soil auger from at least 20 spots within the field, which were then thoroughly mixed to get one composite soil sample. At least one kg of each composite soil sample, obtained through the quartering procedure, was air-dried, ground, sieved to pass through 2 mm sieve, packed, and labeled for laboratory analysis. A global positioning system (GPS) (model GARMIN *etrex* 20) was used to locate the geographical position of each selected field. A map showing the location of the evaluated fields was produced.

2.3. Laboratory Soil Analysis

Laboratory analysis was done at Sokoine University of Agriculture (SUA) Soil Science Laboratory. The parameters analyzed were particle size distribution, soil pH, organic carbon (OC), total nitrogen (TN), available phosphorus (P), exchangeable bases (Ca, Mg, K and Na), cation exchange capacity (CEC), extractable sulphur (S), iron (Fe), manganese (Mn), zinc (Zn) and copper (Cu). Particle size distribution was determined by the Bouyoucos hydrometer method [23, 24] after dispersing the soils with sodium hexametaphosphate followed by determining textural classes using the USDA textural triangle [25].

Soil pH in water and electrical conductivity (EC) were measured potentiometrically [24, 26] in a soil: water ratio of 1:2.5 weight to volume basis using a soil pH-meter for soil pH and an EC-meter for electrical conductivity. Organic carbon (OC) was determined by the Walkley- Black wet oxidation method [27] and the OC values were converted to organic matter (OM) by multiplying OC values by a factor of 1.724 [28, 17]. Total nitrogen (TN) was determined by the micro-Kjeldahl digestion method [29]. Extractable phosphorus (P) was determined by the Bray and Kurtz-1 method [30] followed by colour development by the molybdenum blue method [31]. An ultraviolet visible (UV/VIS) spectrophotometer [32] was used to determine the quantity of available P in the soil.

The cation exchange capacity (CEC) of the soil and exchangeable bases (Ca^{+2} , Mg^{+2} , K^+ and Na^+) were extracted

by the ammonium acetate (NH_4OAc)-pH 7 saturation method [33] and determined using an atomic absorption spectrophotometer (AAS) [32] for Ca^{+2} and Mg^{+2} and flame photometer for K^+ and Na^+ [24]. The adsorbed NH_4^+ was displaced by K^+ using 1 M KCl followed by determination of CEC [34] by the micro-Kjeldahl distillation method [29, 24]. Extractable sulphur ($\text{SO}_4^{2-}\text{-S}$) was extracted using calcium monophosphate [$\text{Ca}(\text{H}_2\text{PO}_4)_2 \cdot \text{H}_2\text{O}$], following the development of particle suspensions (intensity of a beam of light) by the turbidimetric method (Moberg, 2001). An ultraviolet visible (UV/VIS) spectrophotometer [32] was used to determine the quantity of extractable $\text{SO}_4^{2-}\text{-S}$ in the soil [24]. Micronutrients (Cu, Fe, Zn, and Mn) extracted by the diethylene-triamine-penta-acetic acid (DTPA) method [35, 33, 24] were determined using an atomic absorption spectrophotometer [32].

The total exchangeable base (TEB) was calculated as the sum of the four exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ and Na^+) for a given soil sample. The C:N ratio, silt: clay ratio, exchangeable sodium percentage (ESP) and percentage base saturation (BS %) were calculated using formulas by [36].

2.4. Statistical Analysis

Correlation analysis of the soil parameters was performed using IBM SPSS Statistic 20 and the mean values of the soil parameters were calculated using the Excel spreadsheet statistical package.

2.5. Soil Fertility Status Determination Using the Soil Fertility Index

There are direct and indirect ways of evaluating soil fertility status. Direct evaluation is carried out in the field, greenhouses or laboratory by means of experiments carried out under given climatic and management conditions [37]. Indirect evaluation consists of developing and applying models of varying complexity. One of the most suitable models is the soil fertility index (SFI) model [37-39], which uses the parametric approach for each soil to identify its fertility status using SFI classes. Each soil is evaluated based on factor ratings ranging between 10 and 100 using a rating value of each soil parameter [37] (Table 1). The least favourable value of factor rating is 10 and the most beneficial value of factor rating is 100. Therefore, soil fertility index in this study was calculated using the values of factor rating for each soil parameter using the SFI model (Formula 1).

$$\text{SFI} = \text{Rmax} \times \sqrt{\sum_{n=1}^{n=13} \frac{F}{100}} \quad (1)$$

Where:

F=Factor rating of each soil parameter

$$\text{Rmax (maximum ratio)} = \frac{V_1 + V_2 + V_3 + V_4 + V_5 \dots V_{13}}{13}$$

V=Rating value for each soil parameter

Thereafter, the soil fertility status of the studied fields was

identified based on classes and values of the soil fertility index (Table 2).

Table 1. Factor ratings and rating values of soil parameters.

Soil parameter	Factor rating				
	100	80	50	20	10
pH (1:2.5; soil: water)	6.5-7.5	7.4-8.5	5.5-6.4	4.5-5.4	<4.5->8.5
EC (dS m ⁻¹)	0-2	2.1-4	4.1-6	6.1-8	>8
SOM (g kg ⁻¹)	>30	20.1-30	10.1-20	5.1-10	0-5
TN (g kg ⁻¹)	>3.20	1.71-3.20	0.91-1.70	0.45-0.90	<0.45
P (mg kg ⁻¹)	>80	25.1-80	8.1-25	2.5-8.0	<2.5
Ca (cmol (+) kg ⁻¹)	17.6-50	5.76-17.5	1.19-5.75	>50	<1.19
Mg (cmol (+) kg ⁻¹)	>12.5	4.1-12.5	1.34-4.0	0.42-1.33	<0.42
K (cmol (+) kg ⁻¹)	0.29-0.74	0.75-2.56	0.13-0.28	>2.56	<0.13
Na (cmol (+) kg ⁻¹)	0-0.20	0.21-0.30	0.31-0.70	0.71-2.0	>2.0
Zn (mg kg ⁻¹)	0.71-2.41	2.4-8.0	0.2-0.7	>8	<0.2
Fe (mg kg ⁻¹)	2.1-4.5	1,1-2.0	0.2-1.0	>4.5	<0.2
Mn (mg kg ⁻¹)	15-50	4-14	50-170	>170	<4
Cu (mg kg ⁻¹)	>0.2				<0.2
Soil Textural class	CL, SCL, SiCL	vfSL, L, SiL, Si	C, SC, SiC	SL, fSL	S, LS

Source: [37].

Chemical property: EC=electric conductivity, SOM=soil organic matter, TN=total nitrogen, C:N=carbon: nitrogen ratio, P=phosphorus, SO₄-S=sulphate sulphur, Ca=calcium, Mg=magnesium, K=potassium, Na=sodium, CEC=cation exchange capacity, ESP=exchangeable sodium percentage, BS=base saturation, Zn=zinc, Fe=iron, Mn=manganese, Cu=copper,

Textural class: CL=clay loam, SCL=sandy clay loam, SiCL=silty clay loam, vfSL=very fine sandy loam, L - loam, SiL=silty loam, Si=silt, C=clay, SC=sandy clay, SiC=silty clay, SL=sandy loam, fSL=fine sandy loam, S=sand, LS=loamy sand.

3. Results and Discussion

3.1. Locations of the Studied Fields in the Study Area

Locations of the studied fields (Figure 2) were between latitudes 01° 12' and 02° 24' S, and between longitudes 031° 46' and 031° 50' E, with altitude ranging from 1226 - 1345 meters above sea level (masl) in Bukoba District. In Missenyi District, the studied fields were between latitudes 01° 06' and 01° 11' S and between longitudes 031° 23' and 031° 27' E, with altitude ranging from 1140 - 1240 masl. In Biharamulo

District, the studied fields were between latitudes 02° 38' and 02° 40' S and between longitudes 031° 18' and 031° 23' E, with altitude ranging from 1251 - 1480 masl (Table 3).

Table 2. Classes and values of soil fertility index.

Class	Soil fertility index	Description
S1	>80	Good fertility
S2	80-51	Moderate fertility
S3	50-20	Marginal fertility
N	<20	Poor fertility

Source: [38, 39, 37].

Table 3. Geographical locations of the studied fields in Bukoba, Missenyi and Biharamulo Districts, Tanzania.

District	Village	Silo sampling site	Geographical location		
			Latitude (S)	Longitude (E)	Altitude (masl)
Bukoba	Butairuka	Rushabirwa farm	01° 24' 20.4"	031° 46' 43.9"	1345
		Mpanju farm	01° 24' 21.1"	031° 47' 18.8"	1330
		Kahigi farm	01° 24' 31.1"	031° 47' 36.7"	1305
		Bana farm	01° 24' 53.8"	031° 49' 53.9"	1331
	Kiilima	Kyabitara farm	01° 15' 17.5"	031° 47' 20.1"	1360
		Degratias farm	01° 12' 57.4"	031° 50' 56.8"	1226
		Ifunya farm	01° 13' 40.0"	031° 50' 19.4"	1229
		Baguma farm	01° 12' 50.7"	031° 49' 27.1"	1250
		Respicius farm	01° 14' 30.5"	031° 49' 53.9"	1258
		Godwin farm	01° 15' 17.5"	031° 50' 05.1"	1263
Missenyi	Igayaza	TARI- Maruku Centre	01° 25' 01.7"	031° 46' 39.4"	1350
		Farmers Extension Centre	01° 07' 29.2"	031° 23' 35.0"	1240
	Mabuye	Masood farm	01° 08' 48.8"	031° 24' 52.0"	1159
		Kaloli farm	01° 09' 09.4"	031° 23' 17.9"	1193
		Rubega farm	01° 08' 13.2"	031° 23' 33.3"	1217
		Tautus farm	01° 06' 48.8"	031° 23' 59.3"	1208
		Mhonge farm	01° 09' 30.1"	031° 27' 17.9"	1140
		Maida farm	01° 10' 28.2"	031° 26' 42.1"	1142
		Mabuye society	01° 11' 00.2"	031° 27' 17.1"	1153
		Pascal farm	01° 10' 40.3"	031° 25' 24.9"	1153
Gervas farm	01° 11' 46.8"	031° 25' 48.6"	1149		

District	Village	Silo sampling site	Geographical location		
			Latitude (S)	Longitude (E)	Altitude (masl)
Biharamulo	Rukirwengama	Mabuye Primary School	01° 11' 38.1"	031° 26' 00.8"	1159
		Edmund farm	02° 39' 51.1"	031° 21' 06.0"	1424
		Benjamin farm	02° 39' 06.5"	031° 23' 15.5"	1460
		Chubwa farm	02° 38' 47.1"	031° 23' 51.8"	1449
		Wilson farm	02° 38' 01.5"	031° 22' 43.9"	1445
	Rukaragata	Mtanzania farm	02° 38' 58.6"	031° 22' 10.9"	1251
		Yustina farm	02° 39' 17.2"	031° 18' 17.3"	1434
		Chinga farm	02° 40' 19.1"	031° 18' 07.8"	1480
		Mkanirwa farm	02° 39' 51.5"	031° 18' 33.8"	1444
		Village office	02° 40' 03.6"	031° 19' 03.0"	1427
		Mutalemwa farm	02° 39' 19.3"	031° 19' 03.0"	1427
		Farmers Extension Centre	02° 38' 52.1"	031° 18' 49.3"	1427

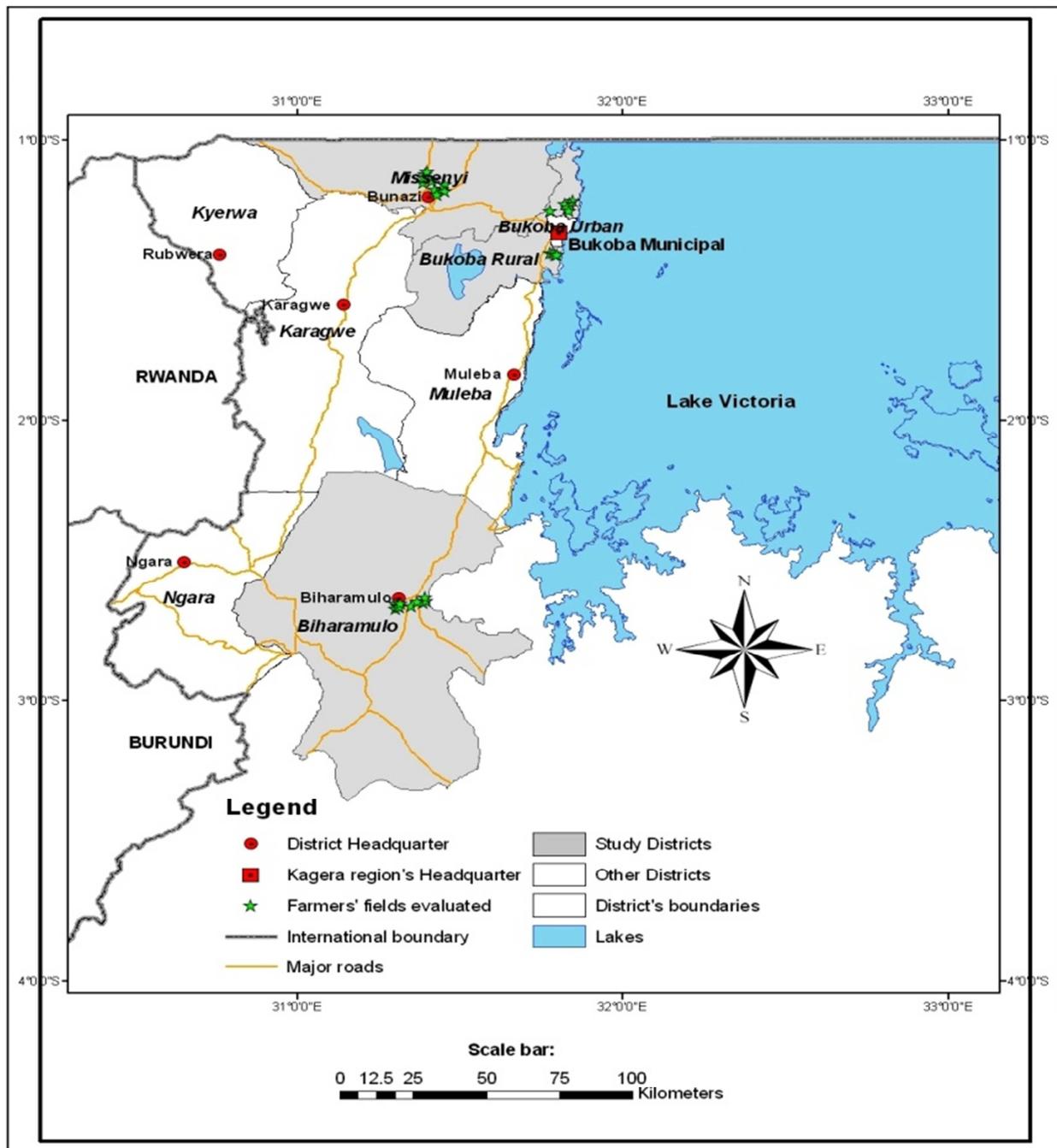


Figure 2. The map of Kagera Region, Tanzania showing fields evaluated in the study area.

3.2. Some Physical Properties of the Soils of the Studied Fields

Soil textural classes of the studied fields ranged from sandy clay to sandy clay loam in Bukoba District, from sandy to clay and sandy clay loam in Missenyi District and from sandy loam to sandy clay loam in Biharamulo District (Table 4). In Bukoba District about, 64% and 36% of the studied fields had sandy clay loam and sandy clay soil texture, respectively. In Missenyi and Biharamulo Districts, the studied fields had diverse soil texture. In Missenyi District, about 37%, 18%, 18%, 18% and 9% of the studied fields had sandy clay loam, sandy clay, clay loam, clay, and sandy soil texture, respectively. In Biharamulo District, about 46%, 36%, 9% and 9% of the studied fields had sandy clay loam, sandy clay, sandy loam and clay soil texture, respectively.

Nevertheless, the soil textures of many (86.7%) fields are favourable for crop production since they allow root proliferation, aeration, water infiltration and holding capacity, soil nutrients retention and drainage [17, 37] as compared to few

(13.3%) fields, which had clay and sandy soil texture. Clay texture has poor water infiltration, poor aeration, poor drainage and to some extent low root proliferation which can affect the performance of some crops like root crops. Sandy soil texture has poor water holding capacity, poor nutrient holding capacity and high water infiltration [17]. Therefore, incorporation of organic matter such as manure, compost, cover crops and crop residues in those soils is of great importance to improve soil particle aggregation, tilth, OM content, drainage, water holding capacity and soil nutrients retention capacity.

The silt: clay ratio is one of the soil parameters that signify the age of the soils as the lower the ratio the more weathered the soils are [40]. The silt: clay ratio of the soils of studied fields ranged from 0.13 - 0.49 in Bukoba District, from 0.12 - 0.76 in Missenyi District and from 0.07 - 0.59 in Biharamulo District. Therefore, based on the values of silty: clay ratio of the studied fields, the soils of many farms in Bukoba District were comparatively more weathered than those in Biharamulo District and the least weathered were those in Missenyi District.

Table 4. Particle size distribution of the studied soils in Bukoba, Missenyi, and Biharamulo Districts, Tanzania.

District	Village	Soil sampling site	Particle size (%)			Textural class	Silt: Clay ratio
			Sand	Silt	Clay		
Bukoba	Butairuka	Rushabirwa farm	51.80	9.92	38.38	SC	0.26
		Mpanju farm	48.80	8.92	44.28	SC	0.20
		Kahigi farm	57.80	6.92	35.28	SC	0.20
		Bana farm	51.80	7.02	41.18	SC	0.17
		Kyabitara farm	52.80	11.92	35.28	SC	0.34
	Kiilima	TARI Maruku Centre	54.80	14.30	30.80	SCL	0.46
		Degratias farm	60.80	6.92	32.28	SCL	0.21
		Ifunya farm	62.80	5.92	31.28	SCL	0.19
		Baguma farm	51.80	15.92	32.28	SCL	0.49
		Respicius farm	62.80	7.92	29.28	SCL	0.27
Missenyi	Igayaza	Godwin farm	56.80	4.92	38.28	SC	0.13
		Farmers Extension Centre	44.80	20.02	34.28	CL	0.58
		Masood farm	33.80	34.92	31.28	CL	1.12
		Kaloli farm	53.80	19.92	26.28	SCL	0.76
		Rubega farm	48.80	14.92	36.28	SC	0.41
	Mabuye	Tautus farm	40.80	16.92	42.28	C	0.40
		Mhonge farm	28.80	24.92	46.28	C	0.54
		Maida farm	52.80	15.92	21.28	SCL	0.75
		Mabuye society	72.80	5.92	21.28	SCL	0.28
		Pascal farm	58.80	7.92	33.28	SCL	0.24
Biharamulo	Rukirwengama	Gervas farm	90.80	1.92	7.28	S	0.26
		Mabuye Primary School	74.80	7.28	17.92	SL	0.41
		Edmund farm	61.80	8.92	29.28	SCL	0.30
		Benjamin farm	71.80	1.92	26.28	SCL	0.07
		Chubwa farm	77.80	2.92	19.28	SL	0.15
	Rukaragata	Wilson farm	73.80	1.92	24.28	SCL	0.08
		Mtanzania farm	67.80	8.92	28.28	SCL	0.32
		Yustina farm	54.80	9.92	35.28	SC	0.28
		Chinga farm	35.80	8.92	55.28	C	0.16
		Mkanirwa farm	51.80	17.92	30.28	SCL	0.59
	Village Office	51.80	12.92	35.28	SC	0.37	
	Mutalemwa farm	47.80	11.92	40.28	SC	0.30	
	Farmers Extension Centre	50.80	5.28	43.92	SC	0.12	

Soil textural class: SC=Sandy clay; SCL=Sandy clay loam; CL=Clay loam; C=Clay; S=Sand; SL=Sandy loam.

3.3. Soil Chemical Properties

3.3.1. Soil pH and Electrical Conductivity

The pH in water of the studied fields ranged from strongly

acid (5.1) to medium acid (5.7) in Bukoba District, from strongly acid (5.2) to slightly acid (6.1) in Missenyi District and from strongly acid (5.1) to slightly acid (6.5) in

Biharamulo District [36, 41-44] (Table 5). In Bukoba District, about 91% and 9% of the fields had strongly acid and moderately acid soil pH, respectively. In Missenyi District, about 36% of the fields had strongly acid soil pH, 55% had moderately acid soil pH and 9% had slightly acid soil pH. In Biharamulo District, about 55% of the studied fields had strongly acid soil pH, 27% had moderately acid soil pH and 18% had slightly acid soil pH.

The low soil pH observed in many studied fields in Bukoba District as compared to Missenyi and Biharamulo Districts was due to the high rainfall (> 2500 mm) experienced in Bukoba District [22, 9, 20]. Bukoba District is characterized as a high rainfall area [13, 22]. High rainfall lead to leaching which removes the basic cations from the surface soil to the subsurface, leaving more H⁺ in topsoil, hence low soil pH (more acidic condition) in topsoil [17]. Acid soils with low pH (< 5.5) have a great potential for Mn, Al and Fe toxicity, deficiencies of some essential nutrients and retardation of microbial activity. Poor microbial activity

affects the decomposition of soil organic matter [36, 17]. The soils with pH < 5.5 can also cause the dissolution of Al and Fe minerals, which precipitates with P, leading to P fixation [36, 17, 45]. Therefore, for optimum and sustainable crop production, application of liming materials such as calcium carbonate (CaCO₃) calcium hydroxide (Ca(OH)₂) magnesium carbonate (MgCO₃) or magnesium hydroxide (Mg(OH)₂) in farmers' fields with soil pH of < 5.5 is desirable to increase the current low soil pH [46, 17].

The electrical conductivity (EC) of the studied fields in Bukoba, Missenyi and Biharamulo Districts (Table 5) was very low (0.03 - 0.17 dS m⁻¹) [36, 43, 44, 47]. However, [36, 44] reported that the soils with EC value of < 1.7 dS m⁻¹ are favourable for crop growth and development as they cannot cause crop yield reduction while those with EC at the range from 5.9 - 10 dS m⁻¹ can cause crop yield reduction up to 100%. Therefore, according to [36, 44], the EC of soils of the fields were favourable for crop growth and development.

Table 5. Levels of some chemical properties and their ratings for the studied soils in Bukoba, Missenyi and Biharamulo Districts, Tanzania.

District	Village	Soil sampling site	Soil pH _w (1:2.5)	EC (dS m ⁻¹)	OC (%)	OM (%)	TN (%)	C:N ratio	Bray-1 P (mg kg ⁻¹)	SO ₄ -S (mg kg ⁻¹)		
Bukoba	Butairuka	Rushabirwa farm	5.1 sta	0.04 vl	2.93 h	5.04 h	0.24 m	12 gq	6.31 l	5.21 m		
		Mpanju farm	5.1 sta	0.03 vl	3.16 h	5.44 h	0.26 m	12 gq	7.42 m	10.42 m		
		Kahigi farm	5.2 sta	0.04 vl	2.54 h	4.37 h	0.23 m	11 gq	8.04 m	8.33 m		
		Bana farm	5.4 sta	0.04 vl	2.93 h	5.04 h	0.22 m	13 gq	11.51 m	10.07 m		
		Kyabitara farm	5.4 sta	0.08 vl	3.90 vh	6.71 vh	0.28 m	14 mq	5.10 l	9.03 m		
		TARI Maruku Centre	5.1 sta	0.05 vl	3.10 h	5.33 h	0.41 m	8 gq	1.38 l	7.88 m		
	Kiilima	Degratias farm	5.1 sta	0.07 vl	3.00 h	5.16 h	0.28 m	11 gq	12.18 m	4.51 l		
		Ifunya farm	5.1 sta	0.05 vl	4.10 vh	7.05 vh	0.29 m	14 mq	2.55 l	7.54 m		
		Baguma farm	5.1 sta	0.03 vl	5.61 vh	9.65 vh	0.41 m	14 mq	2.56 l	3.47 l		
		Respicius farm	5.1 sta	0.05 vl	3.90 vh	6.71 vh	0.29 m	13 gq	3.17 l	5.68 m		
		Godwin farm	5.7 ma	0.05 vl	2.92 h	5.02 h	0.28 m	10 gq	19.67 m	9.54 m		
		Missenyi	Igayaza	Farmers Extension Centre	5.4 sta	0.05 vl	2.15 m	3.70 m	0.13 l	17 mq	75.44 h	12.14 m
				Masood farm	5.3 sta	0.04 vl	2.06 m	3.54 m	0.13 l	16 mq	29.49 h	11.14 m
Kaloli farm	5.6 ma			0.12 vl	2.73 h	4.70 h	0.16 l	17 mq	34.75 h	11.07 m		
Rubega farm	5.8 ma			0.06 vl	2.23 m	3.84 m	0.18 l	12 gq	86.44 h	6.43 m		
Mabuye	Tautus farm		5.2 sta	0.03 vl	2.01 m	3.46 m	0.12 l	17 mq	30.61 h	7.07 m		
	Mhonge farm		5.6 ma	0.17 vl	1.76 m	3.03 m	0.16 l	11 gq	21.91 h	3.99 l		
	Maida farm		5.7 ma	0.07 vl	1.95 m	3.35 m	0.19 l	10 gq	29.74 h	2.86 l		
Biharamulo	Rukirwengama	Mabuye society	5.6 ma	0.05 vl	1.32 m	2.27 m	0.15 l	9 gq	37.26 h	2.71 l		
		Pascal farm	5.8 ma	0.07 vl	1.91 m	3.29 m	0.18 l	11 gq	26.96 h	4.17 l		
		Gervas farm	6.1 sa	0.07 vl	1.26 m	2.17 m	0.11 l	11 gq	51.85 h	3.62 l		
		Mabuye Primary School	6.0 m	0.06	1.30 m	2.24 m	0.13 l	8 gq	35.32 h	3.21 l		
		Edmund farm	5.9 ma	0.04 vl	0.98 l	1.69 l	0.05 vl	20 mq	3.41 l	3.93 l		
		Benjamin farm	5.1 sta	0.03 vl	0.72 l	1.24 l	0.04 vl	18 mq	1.39 l	8.93 m		
		Chubwa farm	5.5 sta	0.03 vl	0.65 l	1.12 l	0.04 vl	16 mq	1.97 l	3.93 l		
		Wilson farm	6.1 sa	0.03 vl	0.73 l	1.26 l	0.05 vl	15 mq	6.04 l	6.67 m		
		Mtanzania farm	5.2 sta	0.04 vl	0.96 l	1.65 l	0.06 vl	16 mq	1.67 l	9.57 m		
		Rukaragata	Yustina farm	5.3 sta	0.03 vl	1.37 m	2.36 m	0.08 vl	17 mq	4.56 l	6.93 m	
Rukaragata	Chinga farm	5.6 ma	0.03 vl	1.72 m	2.96 m	0.07 vl	25 pq	0.44 l	8.21 m			
	Mkanirwa farm	6.5 sa	0.06 vl	1.27 m	2.18 m	0.08 vl	16 mq	1.52 l	3.71 l			
	Village Office	5.4 sta	0.03 vl	1.33 m	2.29 m	0.08 vl	17 mq	1.39 l	3.93 l			
	Mutalemwa farm	5.7 ma	0.03 vl	1.76 m	3.03 m	0.08 vl	22 pq	1.10 l	6.76 m			
	Farmers Extension Centre	5.4 sta	0.03 vl	1.20 l	2.06 l	0.18 l	7 gq	4.96 l	6.32 m			

Chemical property: EC=electric conductivity; OC=organic carbon; TN=total nitrogen; C:N=carbon: nitrogen ratio; Bray-1 P=Bray-1 phosphorus; SO₄-S=sulphate-sulphur.

Rating: sta=strongly acid; ma=moderate acid; sa=slightly acid; l=low; vl=very low; h=high; vh=very high; m=medium; gq=good quality; mq=moderate quality; pq=poor quality.

3.3.2. Organic Carbon, Total Nitrogen and Carbon-Nitrogen Ratio

The soil organic carbon of the studied fields in Bukoba District ranged from high (2.54%) to very high (5.61%) (Table 5). In Missenyi District, it ranged from low (1.01%) to high (2.73%) while in Biharamulo District it ranged from low (0.65%) to medium (1.76%) [36, 41-44]. In Bukoba District, about 55% and 45% of the studied fields had very high and high OC, respectively, while in Missenyi District, about 91% and 9% of the studied fields had medium and high OC, respectively. In Biharamulo District, about 45% of the fields had medium OC and 55% had low OC (Table 3). The low OC in some fields in Biharamulo District may be due to poor management of organic matter caused by poor farming practices deployed by farmers, such as crop residues removal after harvesting and bush burning during land preparation [22, 3].

Total nitrogen (TN) of the studied fields was medium (0.22 - 0.41%) in Bukoba District, low (0.11 - 0.19%) in Missenyi District and very low (0.04%) to low (0.18%) in Biharamulo District [36, 41-44]. The low to very low levels of TN in Missenyi and Biharamulo Districts may be due to the medium and low levels of OC in those fields (Table 5). Other researchers [48] reported that soil organic matter (SOM) is a primary source of nitrogen in the soil. However, [47] reported that SOM content is not a quantitative indicator of the capacity of soil to supply nitrogen for plant growth; even though the soils may have high SOM content but the time and amount of nitrogen released from the soil organic matter depend on soil temperature, moisture, microbial activity and many other soil management factors.

The carbon-nitrogen ratio (C:N ratio) of the soil is an indication of the quality of organic matter present in the soil [44]. The C:N ratio of the studied farmers' fields in Bukoba District ranged from good quality (8) to medium quality (14). In Missenyi District, it ranged from good quality (8) to medium quality (17) while in Biharamulo District it ranged from good quality (7) to poor quality (25) [42, 36, 44, 49]. In Bukoba District, about 73% and 27% of the studied fields had good quality and medium quality C:N ratios, respectively, while in Missenyi District, about 64% and 56% of the studied fields had good quality and medium C:N ratios, respectively. Moreover, in Biharamulo District, about 9%, 73% and 18% of the studied fields had good, medium and poor quality C:N ratios, respectively (Table 5). Good quality C:N ratios of some fields in the study area was an indication of the presence of good quality organic matter, leading to high decomposition rate by soil microbes thereby leading to nutrient release into the soils [50, 17] and the opposite occurs due to the presence of poor quality organic matter. Therefore, planting of legume cover crops such *Mucuna pruriens*, *Tephrosia vogelii* and Lablab [22] and green manure crops such as *Leucaena spp*, *Tithonia diversifolia*, alfalfa and pea (*Pisum sativum*) followed by incorporation into the soil [3] in those fields with poor quality organic matter is desirable for improving the C:N ratio of the soils.

3.3.3. Extractable Phosphorus and Sulphur

The extractable phosphorus (P) of the studied fields in Bukoba District ranged from low (1.38 mg kg⁻¹) to medium (19.67 mg kg⁻¹). In Missenyi and Biharamulo Districts Extractable P was high (21.91 - 75.44 mg kg⁻¹) and low (0.44 - 6.04 mg kg⁻¹), respectively [42-44, 47, 49] (Table 5). The low to medium levels of extractable P in the fields in Bukoba and Biharamulo Districts may be attributed to the low inherent P in the parent materials developed mainly on basement rocks of granite, quartzite and shale [51, 13, 45]. It may also be due to low soil pH that normally favours reaction with iron (Fe) and aluminium (Al) to inhibit the availability of P into the soil for plant uptake due to P fixation [36, 52, 17, 45, 53]. According to [36], plant response to applied P could be expected when soil available P is less than 15 mg kg⁻¹ soil. Therefore, the use of inorganic P fertilizers such TSP, SSP and DAP and organic fertilizers such manure, compost and incorporation of green manure crops and crop residues [3] into those soils with low available P is desirable, to improve soil P levels. Appropriate uses of organic resources also improve soil pH levels hence, enhancing the availability of fixed P in the soils [17].

The sulphate sulphur (SO₄-S) levels of the studied fields ranged from low levels of 3.47, 2.71 and 3.71 mg kg⁻¹ in Bukoba, Missenyi and Biharamulo Districts, respectively to medium levels of 10.07, 12.14 and 9.57 mg kg⁻¹ in Bukoba, Missenyi and Biharamulo Districts, respectively [47] (Table 5). In Bukoba District, about 18% and 82% of the studied fields had low and medium SO₄-S, respectively. In Missenyi District, about 54% and 46% of the studied fields had low and medium levels of extractable SO₄-S. In Biharamulo District about, 46 and 54% of the fields had low and medium levels extractable SO₄-S. However, [36] reported that in most tropical soils a sulphur content of 6 mg kg⁻¹ is the critical level, below which response of most tropical crops is expected. Therefore, according to [36], about 36.4% of the studied fields in the study area had inadequate levels of sulphur, hence sulphur-containing fertilizers such as magnesium sulphate (MgSO₄), potassium sulphate (K₂SO₄) or ammonium sulphate ((NH₄)₂SO₄) are desirable in those fields at the recommended rate for optimal and sustainable crop yields.

3.3.4. Exchangeable Bases

Exchangeable calcium (Ca²⁺) of the studied fields (Table 6) in Bukoba District ranged from low (2.30 cmol(+) kg⁻¹) to medium (3.80 cmol(+) kg⁻¹) and from low (2.30 cmol(+) kg⁻¹) to high (10.80 cmol(+) kg⁻¹) in Missenyi District. In Biharamulo District, it ranged from medium (2.80 cmol(+) kg⁻¹) to high (6.80 cmol(+) kg⁻¹) [41-44, 47, 49]. In Bukoba District, about 28% and 72% of the fields had low and medium exchangeable Ca, respectively while in Missenyi District, about 27% and 73% of the fields had low and high exchangeable Ca, respectively. In Biharamulo District, about 73% and 27% of the fields had medium and high exchangeable Ca, respectively.

Exchangeable magnesium (Mg^{2+}) of the studied fields in Bukoba District ranged from low ($0.44 \text{ cmol}(+) \text{ kg}^{-1}$) to medium ($1.07 \text{ cmol}(+) \text{ kg}^{-1}$) and from medium ($1.40 \text{ cmol}(+) \text{ kg}^{-1}$) to very high ($4.35 \text{ cmol}(+) \text{ kg}^{-1}$) in Missenyi District. In Biharamulo District, it ranged from medium ($1.33 \text{ cmol}(+) \text{ kg}^{-1}$) to very high ($3.98 \text{ cmol}(+) \text{ kg}^{-1}$) [41-44, 47, 49]. In Bukoba District, about 64% and 36% of the fields had low and medium exchangeable Mg, respectively, while in Missenyi District, about 9%, 64% and 27% of the fields had medium, high and very high exchangeable Mg, respectively. In Biharamulo District, about 36%, 18% and 46% of the fields had medium, high and very high exchangeable Mg, respectively.

Exchangeable potassium (K^+) of the studied fields in Bukoba District ranged from very low ($0.08 \text{ cmol}(+) \text{ kg}^{-1}$) to low ($0.18 \text{ cmol}(+) \text{ kg}^{-1}$) and from low ($0.24 \text{ cmol}(+) \text{ kg}^{-1}$) to medium ($0.98 \text{ cmol}(+) \text{ kg}^{-1}$) in Missenyi District. In Biharamulo District, it ranged from very low ($0.09 \text{ cmol}(+) \text{ kg}^{-1}$) to medium ($0.42 \text{ cmol}(+) \text{ kg}^{-1}$) [41-44, 47, 49] (Table 6).

In Bukoba District, about 64% and 36% of the fields had very low and low exchangeable K, respectively, while in Missenyi District, about 18% and 82% of the fields had low and medium exchangeable K, respectively. In Biharamulo District, about 36%, 55% and 9% of the fields had very low, low and medium exchangeable K, respectively.

Exchangeable sodium (Na^+) of the studied fields in Bukoba District was very low ($0.04 - 0.09 \text{ cmol}(+) \text{ kg}^{-1}$) and ranged from very low ($0.05 \text{ cmol}(+) \text{ kg}^{-1}$) to low ($0.18 \text{ cmol}(+) \text{ kg}^{-1}$) in Missenyi District. In Biharamulo District, it ranged from very low ($0.04 \text{ cmol}(+) \text{ kg}^{-1}$) to low ($0.14 \text{ cmol}(+) \text{ kg}^{-1}$) [43, 44, 47, 49] (Table 6). In Bukoba District, all (100%) studied fields had very low exchangeable Na while in Missenyi District, about 45.5%, 45.5% and 9%, of the fields had very low, low and medium exchangeable Na, respectively. In Biharamulo District, about 82% and 18% of the fields had very low and low exchangeable Na, respectively, which signify no sodicity problem in the studied fields [36, 45].

Table 6. Exchangeable bases and cation exchange capacity levels and ratings of the studied soils in Bukoba, Missenyi and Biharamulo Districts, Tanzania

District	Village	Soil sampling site	Ca	Mg	K	Na	CEC	ESP	BS
			$\text{Cmol}(+) \text{ kg}^{-1}$					%	
Bukoba	Butairuka	Rushabirwa farm	3.80 m	1.07 m	0.08 vl	0.05 vl	5.80 vl	0.86 nsd	86.21 h
		Mpanju farm	3.30 m	1.04 m	0.09 vl	0.08 vl	7.60 l	1.05 nsd	59.34 m
		Kahigi farm	3.80 m	0.72 l	0.12 vl	0.06 vl	7.40 l	0.81 nsd	63.51 h
		Bana farm	3.80 m	0.68 l	0.09 vl	0.05 vl	6.20 l	0.81 nsd	74.52 h
		Kyabitaru farm	3.30 m	0.53 l	0.13 l	0.07 vl	7.00 l	1.00 nsd	57.57 m
	Kiilima	TARI Maruku	2.90 m	0.44 l	0.15 l	0.09 vl	20.60 m	0.44 nsd	12.82 l
		Degratias farm	2.30 l	0.64 l	0.18 l	0.05 vl	13.00 m	0.38 nsd	24.38 m
		Ifunya farm	2.80 m	0.75 l	0.12 vl	0.08 vl	15.20 m	0.53 nsd	24.67 m
		Baguma farm	2.30 l	0.72 l	0.14 l	0.09 vl	16.80 m	0.54 nsd	19.35 l
		Respicus farm	2.80 m	1.06 m	0.11 vl	0.09 vl	11.29 l	0.80 nsd	35.96 m
Missenyi	Igayaza	Godwin farm	2.30 l	0.95 m	0.09 vl	0.04 vl	11.00 l	0.36 nsd	30.73 m
		Extension Centre	2.30 l	2.34 h	0.24 l	0.08 vl	13.20 m	0.61 nsd	37.58 m
		Masood farm	2.80 m	2.28 h	0.25 l	0.10 vl	16.80 m	0.60 nsd	32.32 m
		Kaloli farm	2.30 l	4.35 vh	0.60 m	0.09 l	17.20 m	0.52 nsd	42.67 m
		Rubega farm	2.80 m	3.13 vh	0.36 m	0.11 l	17.20 m	0.64 nsd	37.21 m
	Mabuye	Tautus farm	2.30 l	2.69 h	0.30 m	0.07 vl	14.40 m	0.49 nsd	37.22 m
		Mhonge farm	7.80 h	2.75 h	0.98 m	0.11 l	23.00 m	0.48 nsd	50.61 m
		Maida farm	7.80 h	3.11 vh	0.47 m	0.13 l	18.00 m	0.72 nsd	63.94 h
		Mabuye society	6.30 h	2.26 h	0.37 m	0.07 vl	13.20 m	0.53 nsd	68.18 h
		Pascal farm	10.8 h	2.01 h	0.67 m	0.18 l	19.80 m	0.91 nsd	68.99 h
Biharamulo	Rukirwengama	Gervas farm	9.80 h	2.15 h	0.59 m	0.05 vl	16.12 m	0.31 nsd	78.10 h
		Mabuye Primary	5.80 h	1.40 m	0.51 m	0.58 m	7.60 l	7.63 slsd	109.08 h
		Edmund farm	4.80 m	2.76 h	0.16 l	0.14 l	8.00 l	1.75 nsd	98.25 h
		Benjamin farm	2.80 m	1.33 m	0.10 vl	0.10 l	5.20 vl	1.92 nsd	83.27 h
		Chubwa farm	3.30 m	1.41 m	0.09 vl	0.06 vl	6.60 l	0.91 nsd	73.64 h
	Rukaragata	Wilson farm	3.30 m	1.49 m	0.10 vl	0.04 vl	6.20 l	0.65 nsd	79.52 h
		Mtanzania farm	2.80 m	2.46 h	0.10 vl	0.05 vl	8.00 l	0.63 nsd	67.63 h
		Yustina farm	7.30 h	3.60 vh	0.42 m	0.06 vl	14.60 m	0.41 nsd	77.95 h
		Chinga farm	6.30 h	3.98 vh	0.20 l	0.07 vl	15.20 m	0.46 nsd	69.41 h
		Mkanirwa farm	6.80 m	3.13 vh	0.33 l	0.05 vl	11.80 l	0.42 nsd	87.37 h
	Village Office	5.20 m	3.01 vh	0.20 l	0.06 vl	12.00 l	0.50 nsd	70.58 h	
	Mutalemwa farm	6.80 h	3.44 vh	0.20 l	0.04 vl	15.00 m	0.27 nsd	69.87 h	
	Extension Centre	4.75 m	1.57 m	0.16 l	0.07 vl	15.40 m	0.45 nsd	42.53 m	

Chemical property: Ca=calcium, Mg=magnesium, K=potassium, Na=sodium CEC=cation exchange capacity, ESP=exchangeable sodium percentage, BS=base saturation.

Rating: l=low; vl=very low; h=high; vh=very high; m=medium, gq; nsd=non sodic.

The low levels of exchangeable bases in some studied fields in the study area were attributed to low soil pH. Other researchers [47] reported that calcium deficiency usually

occurs on very acidic soils with low organic matter. Another reason may be the nature of parent materials being dominated by shales and quartzite, which are aluminous, siliceous and

ferruginous with low levels of soluble bases [51, 13]. In addition, leaching of soluble bases such as K and Mg occurs due to high rainfall [22, 17] predominantly in Bukoba and Missenyi, which receive annual rainfall ranging from 1100 mm to > 2500 mm [19, 20].

The soil with low exchangeable bases may lead to plant nutrient imbalances, unavailability and nutrient induced deficiencies [54, 45]. However, this study indicated that in all studied fields, exchangeable K was more limiting nutrients than other exchangeable bases, as 70% of the studied fields had low to very low levels of exchangeable K. The low levels of exchangeable K in soils affect crop growth and development. Potassium plays a major cationic role in the plants and is therefore, regarded as an essential element to plant life [55]. Plants cannot survive without its presence due to its importance in controlling many physiological processes, such as photosynthesis, enzyme activation, transportation of metabolites and water protein synthesis as well as improving plant growth, development and yields [56]. Adequate level of exchangeable K in soil for plant uptake, also help to minimize the risk of drought stress in plants as it control the process of opening and closing of stomata in [57]. Therefore, use K-containing fertilizers such as muriate of potash (KCl) sulphate of potash (K_2SO_4), potassium nitrate (KNO_3) or potassium meta-phosphate (KPO_3) together with manure or/and compost, is desirable in those fields with low levels of exchangeable K for improving K levels in the soils.

3.3.5. Cation Exchange Capacity, Percent Base Saturation and Exchangeable Sodium Percentage

The fertility status of the soil is reflected by its cation exchange capacity (CEC), and higher CEC values reflect higher soil fertility [58]. The CEC of the studied fields in Bukoba District ranged from very low ($5.80 \text{ cmol}(+) \text{ kg}^{-1}$) to medium ($16.80 \text{ cmol}(+) \text{ kg}^{-1}$) and from low ($7.60 \text{ cmol}(+) \text{ kg}^{-1}$) to medium ($23.00 \text{ cmol}(+) \text{ kg}^{-1}$) in Missenyi District. In Biharamulo District, it ranged from very low ($5.20 \text{ cmol}(+) \text{ kg}^{-1}$) to medium ($15.40 \text{ cmol}(+) \text{ kg}^{-1}$) [44, 47, 49] (Table 6). In Bukoba District, about 9%, 55% and 36% of the fields had very low, low and medium CEC, respectively, while in Missenyi District, all the studied fields had medium CEC. In Biharamulo District, about 9%, 55% and 36% of the fields had very low, low and medium CEC. The low levels of CEC in some fields in the study area may be due to low organic matter content in the soils.

The percentage base saturation (BS) of the studied fields in Bukoba District ranged from low (12.86%) to high (86.21%) and it ranged from medium (32.32%) to high (109.08%) in Missenyi District. In Biharamulo District, BS was high (42.53 - 98.25%) in all studied fields [36]. In Bukoba District, about 18%, 55% and 27% of the fields had low, medium and high BS, respectively, while in Missenyi District about 60% and 40% of the studied fields had medium and high BS, respectively. In Biharamulo District, all studied fields had

high BS (Table 6). The low level of BS in some fields in Bukoba District may be attributed to high rainfall (>2500 mm) received annually [22, 20], which leads to leaching of soluble bases. However, [59] reported that BS value of >50% is high and favourable for crop production whereas BS value of <50% is low and less favourable for crop production. Low base saturation levels may result in very acid soils and may favour toxicity of cations like aluminium, iron and manganese [36, 60]. Therefore, according to [59]; 55%, 46% and 9% of studied fields in Bukoba Missenyi and Biharamulo Districts, respectively were less favourable for crop growth and development. Hence, application of fertilizers containing soluble bases e.g. CAN, MOP or sulphate of potash is desirable to improve the levels of exchangeable bases in those soils. Exchangeable sodium percentage (ESP) of the studied fields ranged from 0.36 to 1.92%, which according to [36, 43, 44]; the soils of the studied fields were non-sodic, hence favourable for crop growth and development.

3.3.6. Extractable Micronutrients

Extractable zinc (Zn) of the studied fields (Table 7) in Bukoba District ranged from medium (0.85 mg kg^{-1}) to high (6.95 mg kg^{-1}) and was high ($4.89 - 18.41 \text{ mg kg}^{-1}$) in Missenyi District. In Biharamulo District, extractable Zn ranged from medium (1.93 mg kg^{-1}) to high (3.69 mg kg^{-1}) in the studied fields [61-63]. In Bukoba District, about 55% and 45% of the fields had medium and high extractable Zn, respectively while in Missenyi District, about 9% and 91% of the fields had medium and high extractable Zn, respectively. In Biharamulo District, about 18% and 82% of the fields had medium and high extractable Zn, respectively. About 70% of the studied fields in the study area had high level of extractable Zn. Therefore, proper management of Zn in those farmers' fields with high level of Zn is desirable, for example, proper or limited use of Zn-based fungicide [64].

Extractable iron (Fe) of the studied fields was high, ranging from $19.50 - 444.64 \text{ mg kg}^{-1}$, $33.73 - 473.21 \text{ mg kg}^{-1}$ and $13.86 - 105.79 \text{ mg kg}^{-1}$ in Bukoba, Missenyi and Biharamulo Districts, respectively [65, 61, 63]. Thus, all the studied fields had high levels of extractable Fe (Table 7). The high levels of extractable Fe in those fields were attributed to the nature of parent materials, being quartzite and shale, which are aluminous, siliceous and ferruginous with low magnesium and potassium content [51, 13]. However, [66] reported that Ferrous Fe concentrations of > 400 mg kg^{-1} in the soil during most of the season are associated with toxicity; therefore, management of Fe in those fields with Fe levels >400 mg kg^{-1} is desired. For example, through combined use of organic fertilizers (farmyard manure, compost and/or crop residues) and inorganic fertilizers (P and K fertilizers) to decrease Fe levels. Moreover, use of liming materials such as $CaCO_3$ and $MgCO_3$ to increase the pH of the soils in those fields with strongly acid soils.

Table 7. Some micronutrients levels with their ratings of the studied fields in Bukoba, Missenyi and Biharamulo Districts, Tanzania.

District	Village	Soil sampling site	Zn	Fe	Mn	Cu
			mg kg ⁻¹			
Bukoba	Butairuka	Rushabirwa farm	1.98 m	326.79 h	3.45 m	2.34 h
		Mpanju farm	1.05 m	396.43 h	3.64 m	2.66 h
		Kahigi farm	0.91 m	356.93 h	2.41 m	1.88 m
		Bana farm	0.85 m	444.64 h	3.97 m	1.86 m
		Kyabitara farm	1.48 m	337.50 h	2.93 m	2.81 h
	Kiilima	Degratias farm	2.84 h	441.07 h	3.53 m	1.09 m
		Ifunya farm	3.98 h	414.29 h	2.24 m	1.58 m
		Baguma farm	6.95 h	241.97 h	2.54 m	2.34 h
		Respicius farm	3.96 h	233.93 h	2.24 m	1.72 m
		Godwin farm	5.51 h	336.71 h	4.22 m	3.44 h
Missenyi	Igayaza	TARI Maruku Centre	0.89 m	19.50 h	9.03 h	0.87 m
		Farmers Extension Centre	4.89 h	437.50 h	16.10 m	3.28 h
		Masood farm	6.99 h	446.43 h	48.62 m	2.66 h
		Kaloli farm	7.67 h	271.43 h	37.07 m	1.72 m
		Rubega farm	9.80 h	337.50 h	22.41 m	2.19 h
	Mabuye	Tautus farm	4.20 h	473.21 h	18.97 m	3.44 h
		Mhonge farm	18.41 h	467.86 h	29.28 m	4.22 h
		Maida farm	15.32 h	426.76 h	70.34 m	2.50 h
		Mabuye society	9.66 h	160.71 h	52.59 m	0.94 m
		Pascal farm	6.11 h	137.50 h	60.34 m	1.88 m
Biharamulo	Rukirwengama	Gervas farm	10.89 h	105.29 h	37.93 m	0.78 m
		Mabuye Primary School	0.83 m	33.73 h	1.48 m	0.59 m
		Edmund farm	2.76 h	89.29 h	28.45 m	1.25 m
		Benjamin farm	1.93 m	41.07 h	29.31 m	0.47 m
		Chubwa farm	2.22 h	94.29 h	25.66 m	0.47 m
	Rukaragata	Wilson farm	2.05 h	46.43 h	21.25 m	1.09 m
		Mtanzania farm	2.27 h	37.50 h	37.07 m	1.25 m
		Yustina farm	3.24 h	44.04 h	37.07 m	2.50 h
		Chinga farm	3.01 h	83.93 h	41.55 m	1.25 m
		Mkanirwa farm	3.18 h	87.50 h	33.62 m	2.19 h
	Village Office	Village Office	3.69 h	105.79 h	33.62 m	2.34 h
		Mutalemwa farm	3.13 h	64.29 h	50.00 m	2.34 h
		Farmers Extension Centre	1.38 m	13.86 h	26.19 h	3.34 h

Micronutrient: Zn=zinc, Fe=iron, Mn=manganese, Cu=copper.

Rating: l=low, m=medium, h=high.

Extractable manganese (Mn) of the studied fields was medium, with the values ranging from 2.24 - 0.03 mg kg⁻¹, 1.48 - 70.34 mg kg⁻¹ and 21.25 - 50.00 mg kg⁻¹ in Bukoba, Missenyi and Biharamulo Districts, respectively [67, 62, 63]. This signified favourable levels of extractable Mn in all studied pedons. Extractable copper (Cu) of the studied fields ranged from medium level of 0.87, 0.59 and 0.47 mg kg⁻¹ in Bukoba, Missenyi and Biharamulo, respectively, to high level of 3.44, 4.22 and 3.34 mg kg⁻¹ in Bukoba, Missenyi and Biharamulo, respectively [62, 63]. In Bukoba District, about 55% and 45% of the studied fields had medium and high exchangeable Cu, respectively, while in Missenyi District, about 46% and 54% of the studied fields had medium and high extractable Cu, respectively. In Biharamulo District, about 55% and 45% of the studied fields had medium and high extractable Cu, respectively. Proper management of Cu in those fields with high levels of Cu is desirable, for example, proper or limited use of Cu-based fungicides [64].

3.3.7. Nutrient Balances in the Soils of the Study Area

The balance of nutrients in the soil is very important as it influences the availability and uptake of nutrients by the plants. The abundance or deficit of one nutrient in the soil

may affect the availability of other nutrients by inducing deficiencies of nutrients present in good quantities [68, 60]. In this study, therefore, nutrient balances were determined using the ratios of Ca: Mg, Ca: TEB, Mg: K and (K: TEB)%.

The Ca: Mg ratios of the studied fields ranged from favourable, with values of 2.42, 1.20 and 2.34 for some soils of Bukoba, Missenyi and Biharamulo Districts, respectively, to unfavourable, with the value of 6.23, 5.37 and 1.14 for some soils of Bukoba, Missenyi and Biharamulo Districts, respectively (Table 8). Other researchers [36, 60] reported that the ratios between 1.2 and 5.2 are favourable for crop growth and development. In Bukoba District, about 73% and 27% of the fields had favourable and unfavourable Ca: Mg ratios, respectively while, in Missenyi about 55% and 45% of the fields had favourable and unfavourable Ca: Mg ratios, respectively. In Biharamulo, about 91% and 9% of the fields had favourable and unfavourable Ca: Mg ratios, respectively. Notably, However, [69] reported that presence of more calcium than magnesium in the soils signifies good conditions for crop growth, in terms of improved gas exchange, good clay aggregation and soil structure stability. The soils with unfavourable Ca: Mg ratios can lead to nutrient imbalance in the soils, which limit the uptake of both

Ca and Mg by plants [68, 60].

Table 8. Nutrient balance levels and ratings of the studied soils in Bukoba, Missenyi and Biharamulo Districts, Tanzania.

District	Village	Soil sampling site	Ca: Mg	Ca: TEB	Mg: K	% (K: TEB)
Bukoba	Butairuka	Rushabirwa farm	3.55 f	0.76 uf	13.38 uf	1.60 uf
		Mpanju farm	3.17 f	0.73 uf	11.56 uf	2.00 uf
		Kahigi farm	5.28 uf	0.81 uf	6.00 uf	2.55 f
		Bana farm	5.59 uf	0.8 uf	7.50 uf	1.95 uf
		Kyabitara farm	6.23 uf	0.82 uf	4.08 uf	3.23 f
	Kiilima	Degratias farm	3.59 f	0.73 uf	3.56 f	5.68 f
		Ifunya farm	3.73 f	0.75 uf	6.25 uf	3.20 f
		Baguma farm	3.19 f	0.71 uf	5.14 uf	4.31 f
		Respicius farm	2.64 f	0.69 uf	9.64 uf	2.71 f
		Kodwin farm	2.42 f	0.68 uf	10.56 uf	2.66 f
Missenyi	Igayaza	TARI Maruku Centre	4.45 f	0.74 uf	2.93 f	5.68 f
		Farmers Extension Centre	0.98 uf	0.46 f	9.75 uf	4.84 f
		Masood farm	1.20 f	0.52 uf	9.12 uf	4.60 f
		Kaloli farm	0.53 uf	0.31 f	7.25 uf	8.17 f
		Rubega farm	0.89 uf	0.44 f	8.69 uf	5.63 f
	Mabuye	Tautus farm	0.86 uf	0.43 f	8.97 uf	5.60 f
		Mhonge farm	2.84 f	0.67 uf	2.81 f	8.42 f
		Maida farm	2.51 f	0.68 uf	6.62 uf	4.08 f
		Mabuye society	2.79 f	0.70 uf	6.11 uf	4.11 f
		Pascal farm	5.37 uf	0.79 uf	3.00 f	4.90 f
Biharamulo	Rukirwengama	Gervas farm	4.56 f	0.78 uf	3.64 f	4.69 f
		Mabuye Primary School	4.14 f	0.70 uf	2.75 f	6.15 f
		Edmund farm	1.74 f	0.61 uf	17.25 uf	2.00 uf
		Benjamin farm	2.11 f	0.65 uf	13.30 uf	2.31 f
		Chubwa farm	2.34 f	0.68 uf	15.67 uf	1.85 uf
	Rukaragata	Wilson farm	2.21 f	0.67 uf	14.90 uf	2.00 uf
		Mtanzania farm	1.14 uf	0.52 uf	24.60 uf	1.85 uf
		Yustina farm	2.10 f	0.64 uf	3.57 f	3.69 f
		Chinga farm	1.58 f	0.60 uf	19.90 uf	1.90 uf
		Mkanirwa farm	2.17 f	0.66 uf	9.48 uf	3.20 f
		Village Office	1.73 f	0.61 uf	15.05 uf	2.36 f
		Mutalemwa farm	1.98 f	0.65 uf	17.20 uf	1.91 uf
		Farmers Extension Centre	3.03 f	0.73 uf	9.81 uf	2.44 f

Chemical property: Ca=calcium, Mg=magnesium, K=potassium, TEB=total exchangeable bases.

Rating: f=favourable, uf=unfavourable.

The Ca: TEB ratios of the studied fields was unfavourable, with values ranging from 0.68 - 0.82 and from 0.52 - 0.73 in Bukoba and Biharamulo Districts, respectively. In Missenyi District, it ranged from favourable (0.31) to unfavourable (0.78). The Ca: TEB values above 0.5 are unfavourable and affect the uptake of other exchangeable bases, particularly K and Mg [36]. In Bukoba and Biharamulo Districts, all studied fields had unfavourable Ca: TEB ratios while in Missenyi District, about 36% and 64% of the studied fields had favourable and unfavourable Ca: TEB ratio, respectively.

The Mg: K ratios of the studied fields ranged from favourable, with values ranging from 2.93 - 3.56, 2.75 - 3.64 to unfavourable with values ranging from 4.1 - 13.38, 6.11 - 9.75 in Bukoba and Missenyi Districts, respectively. In Biharamulo Districts, it ranged from favourable (3.57) to unfavourable with values ranging from 9.48 - 24.60 (Table 8). The Mg: K ratios ranging from 1 - 4 are favourable for crop growth and development [36, 44]. In Bukoba District, about 18% and 82% of the studied fields had favourable and unfavourable Mg: K ratios, respectively, while in Missenyi District, about 36% and 64% of the studied fields had favourable and unfavourable Mg: K ratios, respectively. In Biharamulo, about 9% and 91% of the studied fields had

favourable and unfavourable Mg: K ratios, respectively. This study revealed that about 83.3% of the studied fields in the study area had unfavourable Mg: K ratios caused by low amount of K in the soils. Therefore, use of K-containing fertilizers such as muriate of potash (MOP), sulphate of potash, Potassium nitrate, or potassium meta-phosphate in those fields is desirable for sustainable crop production and optimum yields.

3.3.8. Summary of Some Soil Chemical Properties of the Studied Fields in Bukoba, Missenyi and Biharamulo Districts, Tanzania

The mean values and ranges of some soil chemical properties in the studied fields in Bukoba, Missenyi and Biharamulo Districts are presented in Table 9. The soil pH of the studied fields ranged from 5.1 - 5.7, 5.2 - 6.1 and 5.1 - 6.5, with the mean value of 5.23 ± 0.21 , 5.61 ± 0.26 and 5.63 ± 0.43 (Table 9), which are strongly acid, medium acid and medium acid in Bukoba, Missenyi and Biharamulo Districts, respectively [36, 44]. The EC of the studied fields ranged from 0.03 - 0.08, 0.03- 0.17 and 0.03 - 0.04 dS m^{-1} , with the mean values of 0.05 ± 0.02 , 0.07 ± 0.04 and 0.04 ± 0.01 dS m^{-1} , which are all low in all districts [43, 44].

Chemical Property	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
5. C:N ratio	-0.35	0.04	0.74*	0.42	-													
6. P	0.74*	0.12	-0.63	-0.37	-0.81**	-												
7. SO ₄ -S	0.58	-0.01	-0.50	-0.60	-0.18	0.40	-											
8. Ca	-0.07	-0.22	-0.50	-0.73*	0.06	-0.16	0.43	-										
9. Mg	-0.15	-0.52	-0.19	-0.13	-0.31	0.03	-0.01	0.05	-									
10. K	-0.31	0.52	0.33	0.44	0.10	-0.15	-0.54	-0.54	-0.65*	-								
11. Na	-0.58	-0.22	0.75*	0.59	0.70*	-0.84**	-0.26	-0.19	0.08	0.16	-							
12. CEC	-0.26	-0.02	0.71*	0.82**	0.25	-0.23	-0.57	-0.85**	-0.15	0.57	0.45	-						
13. ESP	-0.19	-0.13	-0.15	-0.40	0.31	-0.42	0.40	0.77**	0.16	-0.44	0.28	-0.72*	-					
14. BS	0.06	-0.19	-0.57	-0.73*	-0.09	0.03	0.40	0.94**	0.18	-0.61	-0.36	-0.94**	0.74*	-				
15. Zn	0.07	-0.12	0.67*	0.84**	0.11	-0.03	-0.53	-0.83**	0.10	0.23	0.28	0.84**	-0.70*	-0.79**	-			
16. Fe	0.10	0.18	-0.56	-0.58	-0.23	0.39	0.46	0.24	-0.35	0.08	-0.50	-0.25	-0.06	0.21	-0.56	-		
17. Mn	0.58	-0.01	-0.53	-0.38	-0.55	0.82**	0.42	0.04	0.14	-0.34	-0.74*	-0.41	-0.10	0.30	-0.19	0.46	-	
18. Cu	0.43	-0.19	-0.00	-0.07	0.07	0.06	0.52	0.39	0.12	-0.57	-0.02	-0.53	0.59	0.50	-0.20	-0.23	0.29	-

Pearson’s correlation at 95% confidence level, * significant at $P \leq 0.05$, ** significant at $P \leq 0.01$; where P is the probability. Chemical property: EC=electrical conductivity, OC=organic carbon, TN=total nitrogen, C:N=carbon: nitrogen ratio, P=phosphorus, SO₄-S=sulphate- sulphur, Ca=calcium, Mg=magnesium, K=potassium, Na=sodium, CEC=cation exchange capacity, ESP=exchangeable sodium percent, BS=base saturation, Zn=zinc, Fe=iron, Mn=manganese, Cu=copper.

ii. Correlation in Missenyi District

Pearson’s correlations among some chemical properties of the soils of the studied fields in Missenyi District are presented in Table 11. The results revealed that pH of the soils correlated negatively at $r=0.67$, $r=0.73$ and $r=0.72$ and significantly ($p \leq 0.05$) with C:N ratio, Fe and Cu, respectively. This signified that the soil pH had a negative effect on C:N ratio, Fe and Cu since as pH increases, the C:N ratio, Fe and Cu decrease, and vice-versa. Extractable Cu and Fe are readily available in acid soil up to toxic level when soil pH is <4 and decreases when the soil pH increases [36]. The increase in pH, lead to precipitation of extractable Fe as insoluble Fe hydroxides, thus reducing the concentrations of

Fe in the soil solution [70]. However, [74] reported positive and significant correlations between soil pH and Fe due to high content of OM in the soil. They concluded that soil pH correlates positively with Fe content in the form of power function and not in linear relationship because Fe content in the soil is also influenced by the soil conditions such as, soil compaction, poor soil aeration, presence of other nutrients, leaching and soil erosion. The results also revealed that the pH correlated positively at $r=0.70$ and $r=0.74$ and significantly ($p \leq 0.05$) with Ca and BS, respectively, which signified that as soil pH increases, Ca and BS also increase. Other researchers [36, 17, 53] reported similar results of increased Ca in the soil when soil pH increased.

Table 11. Correlations among some chemical properties of the soils of studied fields in Missenyi District, Tanzania.

Chemical Property	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. pH	-																	
2. EC	0.27	-																
3. OC	-0.39	0.13	-															
4. TN	0.27	0.32	0.31	-														
5. C:N ratio	-0.67*	-0.20	0.69*	-0.46	-													
6. P	0.21	-0.31	0.14	-0.07	0.13	-												
7. SO ₄ -S	-0.57	-0.16	0.72*	-0.33	0.92**	0.29	-											
8. Ca	0.70*	0.28	-0.65*	0.24	-9.79**	-0.37	-0.79**	-										
9. Mg	-0.05	0.43	0.73*	0.37	0.31	0.01	0.29	-0.45	-									
10. K	0.47	0.90**	-0.15	0.32	-0.43	-0.45	-0.46	0.63	0.14	-								
11. Na	0.14	0.19	0.26	0.78**	-0.28	-0.26	-0.20	0.39	-0.03	0.33	-							
12. CEC	0.30	0.77**	0.09	0.52	-0.33	-0.43	-0.31	0.48	0.15	0.84**	0.63	-						
13. ESP	-0.05	-0.17	0.32	0.71*	-0.13	-0.07	-0.02	0.17	-0.10	-0.07	0.90**	0.23	-					
14. BS	0.74*	0.11	-0.72*	0.13	-0.79**	-0.26	-0.80**	0.90**	-0.35	0.43	0.11	0.13	-0.01	-				
15. Zn	0.41	0.69*	-0.31	0.41	-0.65*	-0.25	-0.59	0.47	0.15	0.66*	0.13	0.65*	-0.18	0.36	-			
16. Fe	-0.73*	0.05	0.43	-0.02	0.48	-0.04	0.41	-0.57	0.21	-0.20	-0.01	0.10	0.01	-0.75*	0.11	-		
17. Mn	0.30	-0.03	-0.25	0.48	-0.57	-0.55	-0.48	0.60	-0.12	0.16	0.51	0.23	0.47	0.60	0.28	-0.36	-	
18. Cu	-0.72*	0.15	0.29	-0.15	0.48	-0.09	0.35	-0.42	0.03	-0.02	-0.02	0.14	-0.03	-0.64*	0.05	0.91**	-0.51	-

Pearson’s correlation at 95% confidence level, * significant at $P \leq 0.05$, ** significant at $P \leq 0.01$; where P is the probability. Chemical property: EC=electrical conductivity, OC=organic carbon, TN=total nitrogen, C:N=carbon: nitrogen ratio, P=phosphorus, SO₄-S=sulphate- sulphur, Ca=calcium, Mg=magnesium, K=potassium, Na=sodium, CEC=cation exchange capacity, ESP=exchangeable sodium percent, BS=base saturation, Zn=zinc, Fe=iron, Mn=manganese, Cu=copper.

The OC of the soils correlated positively at $r=0.69$, $r=0.72$ and $r=0.73$ and significantly ($p \leq 0.05$) with C:N ratio, SO₄-S and Mg, respectively. This signified that OC had an influence

on the C:N ratio, SO₄-S and Mg, which means that as OC increases, the C:N ratio, SO₄-S and Mg also increase and vice-versa. The OC is a reflection of soil organic matter;

increase of OM in the soil creates a soil nutrient pool for plant nutrients since the decomposition of OM releases some soil nutrients [3].

The BS of the soils of the studied fields correlated negatively at $r=-0.75$ and $r=-0.65$ and highly significantly ($p\leq 0.01$) with extractable Fe and Cu respectively. This signified that the BS had negative effects on the availability of extractable Fe and Cu in the soil since the increase of BS, caused the decrease of Fe and Cu, and vice-versa. The BS is a measure of exchangeable bases in the soils and high BS reflects the basic cations in the soil [36, 17], which are readily available when soil pH is high (alkaline) as opposed to Fe and Cu which are readily available when the soil pH is low (acid). This substantiates the negative and significant correlation between BS and micronutrients (Fe and Cu) observed in the soils of the studied fields in Missenyi District.

iii. Correlation in Biharamulo District

Pearson's correlations among some chemical properties of the soils of the studied fields in Biharamulo District are presented in Table 12. The results revealed that the pH of the soils correlated positively ($r=0.64$) and significantly ($p\leq 0.05$) with EC, which signified that the soil pH had an influence on EC, since as pH increases, the EC also increases, and vice-versa. Soil electrical conductivity relates directly to salinity, which refers the presence of soluble salts in the soils. Soil pH is not directly affects soil EC but might affects solubility of salts and soil moisture content, as more alkaline soils, have

less amount amounts of soluble salts, hence; they reported negative correlation between soil pH and soil EC [74]. The results of this study therefore, were not similar to that reported by [74]. This was attributed to the very low EC, exchangeable Na and ESP observed in the soils of the studied fields (Tables 5 and 6).

The OC of the soils correlated positively ($r=0.70$) and significantly ($p\leq 0.05$) with C:N ratio. The OC also correlated positively at $r=0.85$, $r=0.85$ $r=0.93$ $r=0.97$ $r=0.79$ $r=0.88$ and $r=0.89$ and highly significantly ($p\leq 0.01$) with TN, Ca, Mg, K, CEC, Zn, Mn and Cu, respectively. This signified that OC had a positive effect on the C:N ratio, TN, Ca, Mg, K, CEC, Zn, Mn and Cu. Therefore, as OC increases, C:N ratio, TN, Ca, Mg, K, CEC, Zn, Mn and Cu also increase, and vice-versa. The OC is a reflection of soil organic matter given that the soil with high OC content reflects high organic matter in the soil [17]. The increase of OM in the soil creates a soil nutrient pool for plant nutrients as the decomposition of OM releases some soil nutrients like N, S, Mg and micronutrients [3, 72, 17]. Exchangeable Ca of the soils of the studied fields correlated positively at $r=0.88$, $r=0.88$ $r=0.98$ $r=0.84$ and $r=0.92$ and highly significantly ($p\leq 0.01$) with Mg, K, CEC, Zn and Cu, respectively. This signified that exchangeable Ca had a positive effect on Mg, K, CEC, Zn and Cu, in the soils since as Ca increases, Mg, K, CEC, Zn and Cu, also increase, and vice-versa. Similar results were reported by [53] working on the soils of southeastern Tanzania.

Table 12. Correlations among some chemical properties of the soils of studied fields in Biharamulo District, Tanzania.

Chemical Property	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1. pH	-																	
2. EC	0.64*	-																
3. OC	0.09	0.00	-															
4. TN	0.20	0.24	0.85**	-														
5. C:N ratio	-0.07	-0.25	.70*	0.23	-													
6. P	0.23	-0.14	-0.41	-0.21	-0.49	-												
7. SO ₄ -S	-0.56	-0.34	0.06	-0.12	0.23	-0.10	-											
8. Ca	0.33	0.21	0.85**	0.85**	0.44	-0.13	-0.26	-										
9. Mg	0.12	0.16	0.93**	0.86**	0.61	-0.29	-0.02	0.88**	-									
10. K	0.24	0.34	0.59	0.78**	0.07	0.08	-0.23	0.88**	0.72*	-								
11. Na	-0.13	0.02	-0.25	-0.45	0.27	-0.01	-0.14	-0.17	-0.10	-0.16	-							
12. CEC	0.09	0.00	0.97**	0.89**	0.57	-0.30	-0.02	0.92**	0.95**	0.73*	-0.31	-						
13. ESP	-0.23	-0.06	-0.62	-0.77**	-0.03	0.06	0.03	-0.56	-0.57	-0.47	0.85**	-0.70*	-					
14. BS	0.47	0.46	-0.35	-0.30	-0.14	0.37	-0.43	0.01	-0.18	0.13	0.71*	-0.35	0.64*	-				
15. Zn	0.17	0.16	0.79**	0.89**	0.30	-0.25	-0.42	0.84**	0.83**	0.73*	-0.14	0.84**	-0.55	-0.12	-			
16. Fe	0.35	0.10	0.22	0.19	0.21	-0.37	-0.81**	0.28	0.25	0.09	0.18	0.22	-0.09	0.12	0.53	-		
17. Mn	-0.17	-0.03	.882**	0.70*	0.64*	-0.57	0.31	0.64*	0.77**	0.40	-0.27	0.82**	-0.51	-0.48	0.56	-0.03	-	
18. Cu	0.14	0.10	0.89**	0.97**	0.35	-0.22	-0.16	0.92**	0.89**	0.82**	-0.35	0.95**	-0.71*	-0.28	0.93**	0.26	0.71*	-

Pearson's correlation at 95% confidence level, * significant at $P\leq 0.05$, ** significant at $P\leq 0.01$; where P is the probability.

Chemical property: EC=electrical conductivity, OC=organic carbon, TN=total nitrogen, C:N=carbon: nitrogen ratio, P=phosphorus, SO₄-S=sulphate- sulphur, Ca=calcium, Mg=magnesium, K=potassium, Na=sodium, CEC=cation exchange capacity, ESP=exchangeable sodium percent, BS=base saturation, Zn=zinc, Fe=iron, Mn=manganese, Cu=copper.

3.3.10. Soil Fertility Status of the Studied Fields in Bukoba, Missenyi and Biharamulo Districts, Tanzania

Based on soil fertility index, which integrate all soil parameter analyzed indexes [37-39]; the soil fertility statuses of the fields in Bukoba District ranged from poor fertility to moderate fertility. In Missenyi District, they ranged from

poor to good fertility. In Biharamulo District, the soil fertility statuses of the fields ranged from poor fertility to marginal fertility (Table 13). In Bukoba District, about 55% 27% and 18% of the fields had poor fertility, marginal fertility and moderate fertility, respectively while in Missenyi District, about 9% and 91% the fields had poor and good fertility, respectively. In Biharamulo District, about 55% and 45% of

the fields had poor fertility and marginal fertility, respectively (Table 14). The results summed over the total number of the studied fields revealed that about 66.7% of the studied fields had poor, marginal and moderate fertility status and 33.3% had good fertility status; hence, soil fertility management practices are desirable in those fields with poor to moderate fertility status. For example, use of inorganic fertilizers such CAN, NPK, TSP, DAP, MOP, Minjingu Mazao and/or YaraMila fertilizers (Winner, Cereal, Complex, Java) is desirable to improve N, P, K, S and micronutrient contents in

those fields with inadequate levels of these nutrients. The use of organic fertilizers such as farmyard manure, compost and incorporation of green manure and crop residues in the soils is desired to improve nutrient holding capacity of the soils, soil moisture conservation, soil particle aggregation, tilth, C:N ratio and addition of nutrients in the soils [17]. Moreover, use of liming materials such CaCO₃, MgCO₃, Ca(OH)₂ and Mg(OH)₂ is desirable to increase the pH of the soils [3] since about 56.3% of the studied fields had strongly acid soil pH, at the range of 5.1 - 5.5 (Table 5).

Table 13. Soil fertility status of the studied fields based on soil fertility index in Bukoba, Missenyi and Biharamulo Districts, Tanzania.

District	Village	Soil sampling site	Soil fertility index	Soil fertility status
Bukoba	Butairuka	Rushabirwa farm	15	Poor fertility
		Mpanju farm	15	Poor fertility
		Kahigi farm	13	Poor fertility
		Bana farm	26	Marginal fertility
		Kyabitara farm	30	Marginal fertility
	Kiilima	Degratias farm	51	Moderate fertility
		Ifunya farm	14	Poor fertility
		Baguma farm	25	Marginal fertility
		Respicius farm	9	Poor fertility
		Godwin farm	64	Moderate fertility
		TARI Maruku Centre	3	Poor fertility
Missenyi	Igayaza	Farmers Extension Centre	255	Good fertility
		Masood farm	253	Good fertility
		Kaloli farm	361	Good fertility
		Rubega farm	351	Good fertility
		Tautus farm	355	Good fertility
	Mabuye	Mhonge farm	230	Good fertility
		Maida farm	329	Good fertility
		Mabuye society	117	Good fertility
		Pascal farm	316	Good fertility
		Gervas farm	97	Good fertility
		Mabuye Primary school	15	Poor fertility
Biharamulo	Rukirwengama	Edmund farm	24	Marginal fertility
		Benjamin farm	2	Poor fertility
		Chubwa farm	4	Poor fertility
		Wilson farm	8	Poor fertility
		Mtanzania farm	4	Poor fertility
	Rukaragata	Yustina farm	29	Marginal fertility
		Chinga farm	39	Marginal fertility
		Mkanirwa farm	41	Marginal fertility
		Village Office	16	Poor fertility
		Mutalemwa farm	29	Marginal fertility
		Farmers Extension Centre	7	Poor fertility

Table 14. Soil fertility status of the studied fields and their percentage in Bukoba, Missenyi and Biharamulo Districts, Tanzania.

District	Number of field	Soil fertility status	Percentage (%)
Bukoba	6	Poor fertility	55
	3	Marginal fertility	27
	2	Moderate fertility	18
Missenyi	1	Poor fertility	9
	10	Good fertility	91
Biharamulo	5	Poor fertility	55
	6	Marginal fertility	45
Overall	20	Poor, marginal and moderate fertility	66.7
	10	Good fertility	33.3

However, the calculated soil fertility indices gave the general ratings of the soil fertility status of each studied field since the factor ratings are based on the ranges of rating values (Table 1). Therefore, the limiting nutrients for each studied field were identified to understand the specific

nutrients that may limit crop growth and development. The identified limiting nutrients were P, K, Mg Ca and S in Bukoba District, N, S, and Ca in Missenyi District and N, P, K, OC and S in Biharamulo District (Table 15). In Bukoba District, K was a limiting nutrient in all 11 fields followed by

Mg in seven fields, P in six fields, Ca in three fields and S in two fields. In Missenyi District, N was a limiting nutrient in all 11 fields followed by S, in six fields and Ca in three fields. In Biharamulo District, N and P were the limiting nutrients in all eleven fields followed by K in 10 fields, OC in six fields and S in four fields. Therefore, the most limiting nutrients were K and P in Bukoba District, N and S in Missenyi District and N, P, K in Biharamulo District. However, the

results of percentage limitation of each limiting nutrients across all studied fields indicated that N and K were the most limiting elements (67%) followed by P (52%), S (32%), Mg and OC (18%) and the least was Ca (15%) (Table 15). Other researchers [20] working on these soils of the study area reported N, P, K and OC to be the limiting nutrients in those soils.

Table 15. Limiting nutrients in the studied fields in Bukoba, Missenyi and Biharamulo Districts, Tanzania.

District	Village	Soil sampling site	Limiting nutrients		
Bukoba	Butairuka	Rushabirwa farm	P and K		
		Mpanju farm	K		
		Kahigi farm	K and Mg		
		Bana farm	K and Mg		
		Kyabitara farm	P, K and Mg,		
	Kiilima	Degratias farm	K, Mg, Ca and S		
		Ifunya farm	P, K and Mg,		
		Baguma farm	P, K, Mg, Ca and S		
		Respicius farm	P and K		
		Godwin farm	K and Ca		
		TARI Maruku Centre	P, K, and Mg		
Missenyi	Igayaza	Farmers Extension Centre	N and Ca		
		Masood farm	N		
		Kaloli farm	N and Ca		
		Rubega farm	N		
	Mabuye	Tautus farm	N and Ca		
		Mhonge farm	N and S		
		Maida farm	N and S		
		Mabuye society	N and S		
		Pascal farm	N and S		
		Gervas farm	N and S		
		Mabuye Primary School	N and S		
Biharamulo	Rukirwengama	Edmund farm	N, P, K, OC and S		
		Benjamin farm	N, P, K and OC		
		Chubwa farm	N, P, K, OC and S		
		Wilson farm	N, P, K and OC		
		Mtanzania farm	N, P, K and OC		
	Rukaragata	Yustina farm	N and P		
		Chinga farm	N, P and K		
		Mkanirwa farm	N, P, K and S		
		Village Office	N, P, K and S		
		Mutalemwa farm	N, P and K		
		Farmers Extension Centre	N, P, K and OC		
		Limiting nutrient	Frequency of occurrence	Limitation percent (%)	
		Nitrogen (N)	22	67	
		Potassium (K)	22	67	
Phosphorus (P)	17	52			
Sulphur (S)	12	36			
Magnesium (Mg)	6	18			
Organic carbon (OC)	6	18			
Calcium	5	15			

Based on limiting nutrients, about 15 soil fertility groups (Table 16) identified in the study area. Group 1 comprised two nutrients (N and S), which both found to be the limiting nutrients in six fields. Group 2 comprised four nutrients (N, P, K and OC), which were all found to be the limiting nutrients in four fields. Group 3 comprised three nutrients (P, K and Mg), which were all found to be the limiting nutrients in three fields. Group 4 comprised two nutrients (N and Ca), which both found to be the limiting nutrients in three fields.

Group 5 comprised five nutrients (N, P, K, S and OC), which were all found to be the limiting nutrients in two fields. Group 6 comprised four nutrients (N, P, K and S), which were all found to be the limiting nutrients in two fields. Group 7 comprised four nutrients (N, P and K), which were all found to be the limiting nutrients in two fields. Group 8 comprised two nutrients (P and K), which both found to be the limiting nutrients in two fields. Group 9 comprised two nutrients (K and Mg), which both found to be the limiting

nutrients in two fields. Group 10 comprised one nutrient (N), which found to be the limiting nutrient in two fields.

Other groups comprised one (K), two (N and P) and (K and Ca), four (K, Mg, Ca and S) and five (P, K, Mg, Ca and S) nutrient (s), which were all found to be the limiting nutrients in one field (Table 16). The identified groups are useful for developing specific fertilizer recommendations for deploying specific soil fertility management strategies based on the limiting nutrients. Therefore, for improving the fertility status of studied fields, farmers should be advised based on the limiting nutrients in their farms.

Table 16. Soil fertility groups and their frequencies of occurrence based on the limiting nutrients in the studied fields in Bukoba, Missenyi and Biharamulo Districts, Tanzania

Soil fertility group	Frequency of occurrence in the fields	Limiting nutrients
Group 1	6	N and S
Group 2	4	N, P, K and OC
Group 3	3	P, K and Mg
Group 4	3	N and Ca
Group 5	2	N, P, K, S and OC
Group 6	2	N, P, K and S
Group 7	2	N, P and K
Group 8	2	P and K
Group 9	2	K and Mg
Group 10	2	N
Group 11	1	K
Group 12	1	N and P
Group 13	1	K and Ca
Group 14	1	K, Mg, Ca and S
Group 15	1	P, K, Mg, Ca and S

4. Conclusions and Recommendations

4.1. Conclusions

The results of this study indicated that soil texture of the studied many fields are favourable for growth and development of most of the crops; except few fields in Missenyi District, which had clay and sandy soil texture. The soil pH of the studied fields ranged from medium to strongly acid while EC was low and favourable for crop growth and development. However, the soil pH levels of the studied fields in Bukoba District may lead to readily availability of Fe, deficiency of some essential nutrients, poor microbial activities and P fixation, hence affect the growth and development of most of the crops.

The results indicated correlation variations among the soil chemical properties due to variations in the levels of soil chemical properties. For example, in Bukoba District, soil pH correlated positively and significantly with exchangeable P, implying that exchangeable P may be unavailable for plant uptake in the high acid soil (low pH) due to P fixation, and vice versa. In Missenyi District, soil pH correlated negatively and significantly with C:N ratio, Fe and Cu and thus implies that Cu and Fe are readily available in soil with low pH (acid soil) and decreases when the soil pH increases (alkaline soil).

Based on the soil fertility index (SFI), the studied fields were rated as good fertility, moderate fertility, marginal

fertility and poor fertility while based on the limiting nutrients; about 15 soil fertility groups were identified. This therefore, calls for farm/site specific fertilizer recommendations.

The results of the limiting nutrients across the studied fields indicated generally that N and K were the most limiting nutrients followed by P, S, Mg and OC and the least was Ca. Specifically, N and P were the most limiting nutrients in Bukoba District, N and S in Missenyi District and N, P and K in Biharamulo District.

4.2. Recommendations

As a consequence of the results obtained in this study, the following are recommended:

1. To improve soil fertility status of those fields with poor to marginal soil fertility status based on limiting nutrients, specific soil fertility management practices are desirable in those fields. For example, use of appropriate combinations of inorganic fertilizers such as; calcium ammonium nitrate (CAN), compound NPK, triple superphosphate (TSP), di-ammoniumphosphate (DAP), muriate of potash (MOP), sulphate of potash, potassium nitrate, potassium meta-phosphate, Minjingu Mazao, Minjingu Nafaka, Yara-Mila formulations (WINNER, CEREAL, COMPLEX, UNIK 17, JAVA) or/and Yara-Vera AMIDAS at the recommended rates can alleviate the nutrient limitations. Specific use of these fertilizers will improve N, P, K, Ca, Mg and S levels in the soils of the studied fields. Fertilizers should be applied by considering the 4R nutrient stewardship, which focuses on applying the right fertilizer source at the right rate, at the right time and the right place [3, 75].
2. Concurrently, increased use of organic fertilizers such as farmyard manure, compost, cover crops and incorporation of green manure and crop residues in the soils is recommended to improve nutrient holding capacity of the soils, soil moisture conservation, soil particle aggregation, soil tilth, C:N ratio and nutrient contents in the soils [17]. It is worth to note, for example, that farmyard manure is generated in the *Kibanja* (*Bibanja* in plural) areas (home gardens) in the study area.
3. Use of liming materials such CaCO_3 , MgCO_3 , Ca(OH)_2 , CaO and M(gOH)_2 is recommended to increase the pH of the soils in those fields with strongly acid soils and reduce high levels ($> 400 \text{ mg Fe kg}^{-1}$) of extractable Fe
4. Moreover, we recommend management of extractable Fe in those fields with Fe levels of $> 400 \text{ mg kg}^{-1}$ to decrease the current Fe toxicity potential. This can be done through application of P-containing fertilizers such as TSP, Minjingu Nafaka/Mazao and/or DAP and K-containing fertilizers such as muriate of potash, potassium meta-phosphate and/or potassium nitrate and organic fertilizer such farmyard manure, compost and/or crop residues to reduce the high levels of Fe in those soils.

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