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RESEARCH AND DEVELOPMENT SUBDIVISION

RESEARCH REPORT

AN ANALYSIS OF SOIL FERTILITY IN THE LAKE LIAMBEZI WHITE MAIZE FARMING AREA, ZAMBEZI REGION, NAMIBIA

2024

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LIST OF ACRONYMS

AEZ	-	Agro-Ecological Zones of Namibia
SOM	-	Soil Organic Matter
pH	-	Measure of the relative amount of free hydrogen and hydroxyl ions in the soil / A measure of how acidic/basic the soil solution is.
Ppm	-	Part per million, concentration of the number of parts of a solute dissolved in one million parts of a solution in the soil
N	-	Nitrogen
P	-	Phosphorus
K	-	Potassium
Ca	-	Calcium
Mg	-	Magnesium
Na	-	Sodium
EC	-	Electrical Conductivity
CEC	-	Cation Exchange Capacity
IPNI	-	International Plant Nutrition Institute
Cluster 1	-	Sample sites (farms) grouped in numbering order from sites 1 to 11
Cluster 2	-	Sample sites (farms) grouped in numbering order from sites 12 to 21
uS/cm	-	Microsiemens per centimetre, the electrical conductivity SI measurement unit

1. INTRODUCTION

The declining trend in farm soil productivity, soil fertility, and nutrient availability for crop uptake has been a significant concern for crop producers worldwide (Erenstein et al., 2022). Sustainable agronomic activities and soil fertilisation have become essential and preliminary measures for ensuring a resilient food production system. These practices aim to meet current and future food demands without compromising the functionality and productivity of farm soils. Maize production and traditional cultivation practices are associated with nutrient absorption from the soil and adverse physico-chemical changes, which may contribute to soil degradation. This degradation can lead to reduced soil total nitrogen, changes in soil pH, and the loss of other essential nutrients required for maize growth. These practices may contribute to a larger problem: a gradual decline in soil fertility and reduced maize yields (Hepute & Abah, 2017). Therefore, sustainable maize production is a critical element for maintaining and improving maize field productivity.

Sustainable agriculture utilises and maintains the capacity of agricultural natural resources and ecosystem productivity, and their usefulness to society, over the long run. Maize production primarily depends on sustainable agronomic practices, such as the effective and efficient application of fertilisers to promote balanced soil nutrient levels and enhance soil fertility. Adequate soil fertilisation, proper water management, and weed and pest control contribute to increased maize yield (Hepute & Abah, 2017). Sustainable maize cultivation and appropriate soil fertilisation are essential in the Lake Liambezi maize farming region. This significance extends beyond the cultivation of staple food crops in the Lake Liambezi area, encompassing broader objectives such as national food security, poverty alleviation, and socio-economic development of rural areas. Maize (*Zea mays* L.), wheat, and rice are the world's leading staple cereals. Maize, together with wheat and rice, constitutes a significant component of the human diet, accounting for an estimated 42 percent of the world's food calories and 37 percent of protein intake (Erenstein et al., *2022*). White maize is exclusively produced in Namibia for human consumption and is recognised as one of Namibia's staple food crops and a controlled commodity. Maize production occupies approximately 17,360 ha annually, based on an average over 17 years (2005/2006 – 2021/2022). Maize recorded an annual average domestic marketed tonnage of 55,062, imported tonnage of 94,920, and a total annual average consumption of 149,982 tonnes. Namibia is a net importer of maize, accounting for 63% per annum (NAB, 2022). At Lake Liambezi, farmers cultivate maize without fertiliser application, assuming the soil is naturally fertile. This practice might threaten sustainable maize production and deplete soil nutrients.

Henceforth, the soil fertility status and crop nutrient availability levels at the Lake Liambezi maize farming area need to be determined in relation to maize crop nutrient requirements and the estimated potential yield (productivity) attainable when using recommended fertilisation programmes. This study's outcome, therefore, provides baseline information for farmers and future studies.

1.1. Hypothesis

Null hypothesis (H_o) – The available soil nutrient levels at the Lake Liambezi maize farming area are within optimum levels and adequate for optimum maize growth and productivity.

Alternate hypothesis (H_1) – The available soil nutrient levels at the Lake Liambezi maize farming area are not within optimum levels and adequate for optimum maize growth and productivity.

Statistical hypothesis test results indicate a significant difference in average soil nutrient levels at the Lake Liambezi maize farming area (p-value = 0.05), supporting the alternate hypothesis that available soil nutrients differ from the required nutrients for optimal maize growth. Thus, the statistical results support the alternate hypothesis. Therefore, there is a need for a soil fertility management programme at the Lake Liambezi maize farming area.

1.2. Problem statement

The Lake Liambezi area in the Zambezi Region has a high potential for white maize farming. The area has high potential for white maize production; currently, many small-scale farmers cultivate maize there. However, local farmers perceive that soil nutrients are sufficiently available for crop uptake; thus, it is alleged that no fertiliser application is needed. This practice might have severe negative implications for soil fertility and threaten crop productivity in the Lake Liambezi farming area if not well informed. Thus, this required a scientific approach, including statistical analysis, to enable proper soil fertility management through appropriate fertilisation programmes recommended for sustainable crop production (Subedi & Ma, 2009).

Therefore, there is a need to determine soil fertility levels and crop nutrient availability at the Lake Liambezi maize farming area, in correlation with maize crop nutrient requirements, and to estimate the potential yield (productivity) attainable with recommended fertilisation programmes (Power & Prasad, 1997). This study's outcome, therefore, provides baseline information for local farmers and future studies.

1.3. Objectives of the study

1. To define the current soil fertility status at Lake Liambezi maize farming area in the Zambezi Region of Namibia.
2. To establish a site-specific fertiliser application rate for sustainable fertility management at Lake Liambezi.
3. To promote a sustainable maize farming system at Lake Liambezi.

1.4. Significance of the study

The cultivation of maize crops without fertiliser application and other unsustainable practices may adversely affect soil capability and, hence, lead to a loss of soil productivity. Furthermore, despite the potential long-term threat posed by some of these agronomic activities to both maize production and soil productivity, there is currently no documented study tracking the effects of ongoing practices on soil health in the Lake Liambezi maize farming area.

Therefore, this study assessed the current soil fertility levels in the maize farming area of Lake Liambezi relative to maize crop growth requirements, the nutrients required to sustain and enhance maize soil productivity, and recommended appropriate soil fertilisation programs.

2. MATERIALS AND METHODS

2.1. Study area

Lake Liambezi area comprises about 300 km^2, of which 100 km^2 is open water when the Lake is full. The Lake is located between the Linyanti and Chobe rivers, about 60km south of Katima Mulilo in the Zambezi Region, at a latitude of 17.9110°S, and a longitude of 24.3728°E (Simasiku, 2014). The area receives up to 600 mm per annum. Despite the fishery and aquatic activities dominating livelihood activities for the people of Lake Liambezi, the Lake is surrounded by several maize crop fields visible in the centre of the Lake depression.

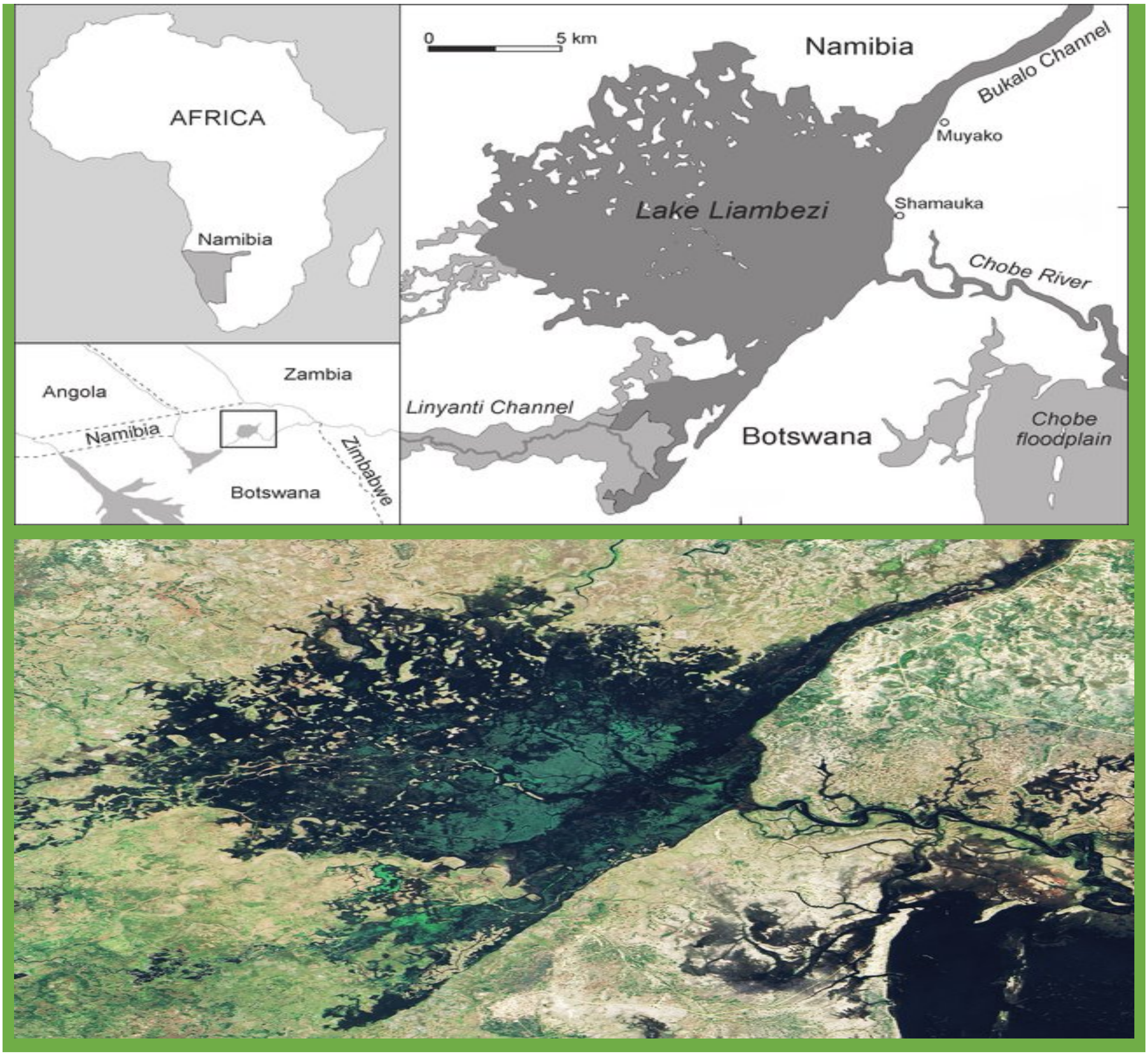

Figure 1: *Lake Liambezi Map (Source: Simasiku, 2014)*

2.2. Soil sample collection

A total of 21 maize producers from the surrounding areas of Lake Liambezi were randomly selected to participate in this study, whereby at least an area of 1 ha was marked from each maize crop field per farmer as representative and divided into two sampling grids (0.5 ha each) (segments 1 & 2 per farm). According to Hepute and Abah (2017), a sampling grid/segment minimises field selection bias and provides systematic, structured samples with proper field representation. Then, two soil samples of different soil depths (consisting of 1 sample within topsoil [0-15 cm] and another 1 sample within subsoil [16-30 cm]) were randomly collected from each sampling segment. Thus, a total of eighty-four (84) soil samples were collected for laboratory analysis.

Table 1: Soil sample size

Production Zones	Regions	Sample size			Total
		Farms	Segments	Soil samples: 2 Depths	
Zambezi	Zambezi – Lake Liambezi	21	2	2	84

2.3. Soil Samples preparation and analysis

The soil samples were dried at room temperature. Subsequently, each sample was crushed and sieved through a 2 mm sieve. Laboratory analyses of the soil parameters were then carried out on the soil fraction less than 2 mm using standard laboratory procedures. Soil particles were determined using the hydrometer method. The following soil parameters were analysed: soil pH, organic matter content, phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), electrical conductivity (EC), Sodium (Na), and Nitrogen (N).

2.4. Data analysis

Data derived from two replicate analyses of the soil parameters were calculated as the mean of the parameter. Furthermore, a two-tailed t-test (paired sample mean, $p < 0.05$) was used to determine the significance of differences in mean data between the standard maize crop growth nutrient requirements and soil properties. Descriptive analysis was performed in Microsoft Excel and Word to analyse the field-collected data, with figures and tables tabulated and presented in the results and discussion section below.

3. RESULTS

The results of the present study and the means for various areas are discussed in this section. The total sample comprised 21 sites (farms), divided into Cluster 1 and Cluster 2. Cluster 1 constitutes sample sites 1 (Farm 1) through 11, corresponding to Farms 1 to 11. While Cluster 2 constitutes sample site 12 (Farm 12), it extends through sample site 21 (Farm 21). This study presents analysis data results on the following soil parameters from the Lake Liambezi farming area, **encompassing** both topsoil and subsoil layers: soil pH, organic matter content, phosphorus (P), calcium (Ca), magnesium (Mg), potassium (K), electrical conductivity (EC), sodium (Na), and nitrogen (N) for Cluster 1 and Cluster 2.

3.1. Soil nutrient requirements for the maize crop

According to du Plessis (2003), fertilising maize crops is of utmost importance for enhancing yield performance. Therefore, this requires a precise application rate. The proper management of nutrients and sustainable soil fertility in relation to site-specific available nutrients is critical for maize crop performance. Table 2 shows recommended standard nutrient application rates and required optimum levels.

Table 2: *Maize recommended standards, nutrient application rate, and required optimum levels*

Nutrients	***Low rate {kg/ha} / {%}***	***High rate {kg/ha} / {%}***
Soil pH	5.5	6.0
Soil texture	clay-loam soils - <10% sandy soil and > 30% clay soil content.	
Soil organic matter	2%	5%
Phosphorus	20 - 40 kg/ha	90 kg/ha
Calcium	<100kg/ha	
Magnesium	<125kg/ha	
Potassium	30 kg/ha	70 kg/ha
Nitrogen	50 -80 kg/ha	150 – 200 kg

(Source: Cropnuts, 2020 & du Plessis, 2003)

A recommended standard rate for NPK application is the balance of 60-120 kg N, 40-60kg P, and 40 kg K/ha. However, the available quantity (20 t/ha, or 20 kg on an area of 10 m2, such as a patch 2 m wide and 5 m long) of kraal manure should be incorporated into the field before sowing (Miles & Manson, 1998). A combination of organic manure and chemical fertilisers is known to give better yields and improve soil fertility than chemical fertilisers alone (Agri-Update, 1998). For effective and efficient fertiliser application, one-fourth of the nitrogen and the total quantity of phosphorus and potash should be applied before sowing. The remaining nitrogen should be applied in two equal doses. Half of the total nitrogen (60 kg N/ha) should be top-dressed at the knee-high stage, while the rest of the nitrogen should be applied with the emergence of the flag leaf. Nitrogen in the form of urea should be carefully applied, 15-20 cm away from the plants to avoid any leaf injury. The best response from nitrogen is obtained when the top-dressed fertiliser is covered with light soil after application (Laker, 2005; Muthaura, 2017).

3.2. Soil texture

Soil texture is one of the important physical properties of farm soil, and it plays a key role in maize cultivation. These properties specify the proportions of sand, silt, and clay minerals separated within a particular soil sample. Soil texture classification is for sustainable agriculture as it indirectly influences soil fertility management (Aarthi & Sivakumar, 2020). Other key crop-cultivating properties, such as soil water-holding capacity, plant growth, and crop choice, are influenced by soil texture and, in turn, indirectly affect maize productivity and yield. For example, chlorophyll content in leaves was lower in sandy loam than in silty clay soil (Barman & Choudhury, 2020).

Although soil texture remains relatively stable, conducting a soil texture analysis at least once helps you better understand your soil and select suitable crop cultivars for each soil type. In addition to soil testing for nutrients, soil texture is key to determining soil suitability and to applying an appropriate management approach (Cropnuts, 2020). Soil texture influences how well the soil retains water and nutrients, depending on particle size. Sand has larger soil particles, which hold less water and nutrients because nutrients are more easily leached than in clay-rich soil textures. Thus, this influences the water and fertiliser management approach to be applied at that specific farm (Cropnuts, 2020).

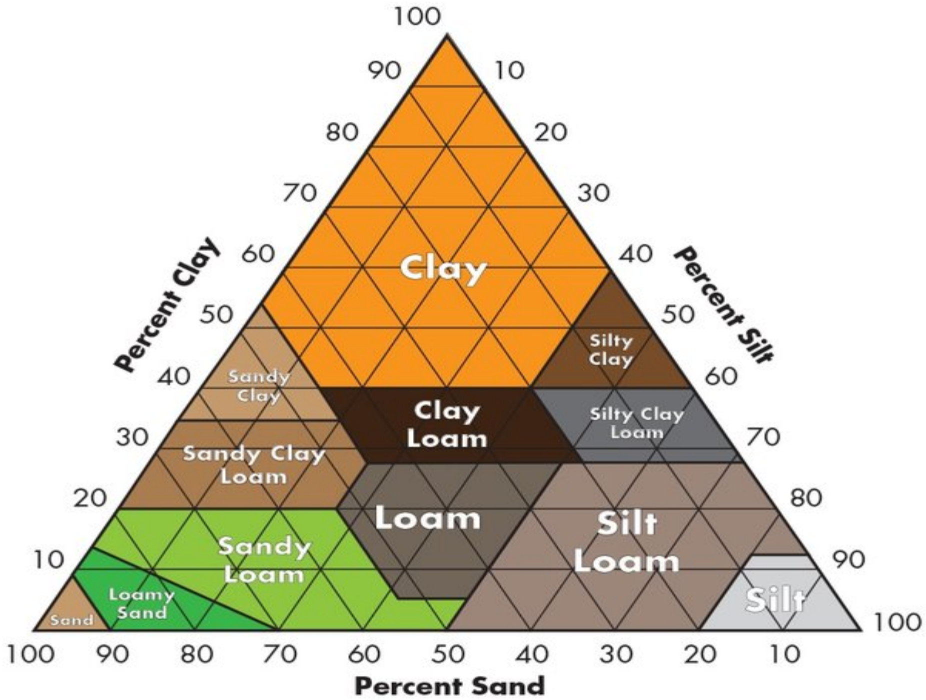

Figure 2: *Soil texture triangle classification (Source: USDA, 2018) | doi:10.1371/journal.pone.0131299.g005*

This study used the USDA (United States Department of Agriculture) soil texture triangle classification (Figure 2) to classify soil texture. According to Barman and Choudhury (2020), the USDA soil texture triangle classification is the best basic tool in soil classification. Laboratory analysis showed heterogamous topsoil with loamy sand, sandy loam, and loamy textural classes at both farm Clusters 1 and 2 (Tables 3 & 4). These possess predominantly excellent drainage and good nutrient retention abilities. Therefore, with appropriate tillage practices, proper fertilisation, and the incorporation of organic matter through mulching and cover crops, the soils of Lake Liambezi maize farm can be sustained for long-term productivity.

Table 3: *Cluster 1 - Soil texture classification per site*

Site	***Identification*** Segment	***Textural Class*** Segment	***Sand*** %	***Silt*** %	***Clay*** %	***Textural Class*** Site	***Sand*** %	***Silt*** %	***Clay*** %	***Textural Class*** Cluster 1	***Sand*** %	***Silt*** %	***Clay*** %
Site 1	A_1	*Loamy Sand*	84.1	10.4	5.5	*Sandy Loam*	75.4	17.1	7.5				
	A_2	*Sandy Loam*	66.7	23.8	9.4								
Site 2	A_1	*Loamy Sand*	44.1	35.0	20.8	*Clay Loam*	40.0	20.5	39.6				
	A_2	*Clay*	35.8	5.9	58.3								
Site 3	A_1	*Loamy Sand*	79.7	15.2	6.0	*Sandy Loam*	73.3	18.6	8.7				
	A_2	*Sandy Loam*	66.8	22.0	11.3								
Site 4	A_1	*Sandy Clay Loam*	48.9	27.5	23.6	*Loam*	49.5	30.4	20.2				
	A_2	*Loam*	50.1	33.2	16.7								
Site 5	A_1	*Sandy Clay*	52.2	4.3	43.5	*Sandy Clay*	53.8	3.7	42.6				
	A_2	*Sandy Clay*	55.3	3.1	41.6								
Site 6	A_1	*Loam*	42.5	43.5	14.0	*Loam*	44.2	40.1	15.8	***Sandy Clay Loam***	***55.9***	***23.3***	***20.8***
	A_2	*Loam*	45.9	36.6	17.5								
Site 7	A_1	*Clay Loam*	29.6	42.9	27.5	*Clay Loam*	38.8	22.8	38.0				
	A_2	*Clay Loam*	48.0	2.6	48.5								
Site 8	A_1	*Loamy sand*	75.3	16.5	8.2	*Sandy Loam*	77.6	14.9	7.6				
	A_2	*Loamy Sand*	79.9	13.3	6.9								
Site 9	A_1	*Loamy Sand*	81.6	6.3	12.2	*Loamy Sand*	84.5	7.7	7.9				
	A_2	*Sand*	87.4	9.1	3.5								
Site 10	A_1	*Sandy Loam*	51.7	29.5	18.8	*Loam*	46.0	34.0	20.1				
	A_2	*Loam*	40.3	38.4	21.3								
Site 11	A_1	*Silty Loam*	28.4	50.4	21.2	*Loam*	32.3	46.6	21.2				
	A_2	*Loam*	36.2	42.7	21.1								

A Topsoil (0-15cm), **$_1$ Segment 1, *$_2$ Segment 2*

Soil samples from Cluster 1 (sites 1 - 11) on both segments 1 and 2 of topsoil (0-15cm) overall recorded high sand content of 56% with low clay content of 21%; with continuous maximum tillage, the soil texture physical properties might be low on water holding capacity and nutrients retention. Thus, there is a need to add organic matter through mulching and cover crops to sustain and enhance the clay content in the soil of the Lake Liambezi maize farming area. The final soil texture class at Cluster 1 is Sandy Clay Loam soil.

Table 4: *Cluster 2 - Soil texture classification per site*

Site	Identification	Texture Class	Sand	Silt	Clay	Texture Class	Sand	Silt	Clay	Texture Class	Sand	Silt	Clay
	Segment	Segment	%	%	%	Site	%	%	%	Cluster 2	%	%	%
Site 12	A_1	*Loam*	39.9	37.0	23.1	*Loam*	38.5	35.8	25.8				
	A_2	*Clay loam*	37.0	34.6	28.4								
Site 13	A_1	*Clay loam*	31.5	35.2	33.3	*Clay Loam*	37.2	34.2	28.6				
	A_2	*Loam*	42.9	33.2	23.8								
Site 14	A_1	*Sandy loam*	61.9	24.6	13.5	*Sandy Loam*	61.7	22.2	16.2				
	A_2	*Sandy loam*	61.4	19.8	18.8								
Site 15	A_1	*Sandy loam*	65.3	23.4	11.3	*Sandy Loam*	74.4	16.3	9.4				
	A_2	*Loamy sand*	83.5	9.1	7.4								
Site 16	A_1	*Loamy sand*	82.1	12.3	5.6	*Loam Sand*	79.4	15.1	5.6				
	A_2	*Loamy sand*	76.6	17.9	5.5					***Loam***	***47.8***	***31.4***	***20.7***
Site 17	A_1	*Silty loam*	25.0	60.2	14.8	*Silt Loam*	29.4	57.4	13.2				
	A_2	*Silty loam*	33.8	54.6	11.6								
Site 18	A_1	*Clay loam*	21.8	48.4	29.8	*Silt Loam*	20.8	52.3	27.0				
	A_2	*Silty loam*	19.8	56.1	24.1								
Site 19	A_1	*Loam*	42.4	36.9	20.7	*Sandy Loam*	56.0	27.8	16.3				
	A_2	*Sandy loam*	69.6	18.6	11.8								
Site 20	A_1	*Loam*	35.8	1.2	63.0	*Clay Loam*	36.2	25.7	38.2				
	A_2	*Silty loam*	36.6	50.1	13.3								
Site 21	A_1	*Loam*	44.8	43.1	12.1	*Clay Loam*	45.0	27.8	27.3				
	A_2	*Sandy clay*	45.1	12.5	42.4								

A Topsoil (0-15cm), **$_1$ Segment 1, *$_2$ Segment 2*

The present results indicate that sandy clay loam and loam are the dominant soil textures in both clusters 1 and 2 of the Lake Liambezi maize farming area. This is a medium-sized particle soil texture that is optimal to high suitability for maize cultivation. The maize crop requires clay-loam soils with excellent water retention and adequate drainage to facilitate root penetration. According to the study by du Plessis (2003), it is recommended that maize soil texture comprise less than 10% sand and more than 30% clay. The overall results indicate that sand content exceeds 10% and clay content is below 30%, indicating the need for sustainable soil tillage management. The final soil texture class in Cluster 2 is Loam.

3.3. Soil PH

Soil pH is critical because it measures the soil's acidity and alkalinity. Soil pH is the most important parameter influencing chemical, biological, and physiological processes in the soil, as well as the nutrients available for plant uptake. At very high or very low pH levels, nutrients become unavailable for crop uptake, increasing wastage and environmental contamination due to volatility (Cropnuts, 2020). Table 5 shows the soil pH levels for Cluster 1 (sites 1–11).

Table 5: *Cluster 1 soil pH level per site*

Site	Identification: Segment	pHw	Average pH per site	Average pH of Cluster 1
Site 1	A_1	6.66	6.98	**7.46**
	A_2	7.30		
Site 2	A_1	6.23	5.82	
	A_2	5.40		
Site 3	A_1	6.73	7.39	
	A_2	8.04		
Site 4	A_1	7.49	7.60	
	A_2	7.70		
Site 5	A_1	7.75	7.73	
	A_2	7.71		
Site 6	A_1	7.67	7.29	
	A_2	6.91		
Site 7	A_1	7.23	7.38	
	A_2	7.53		

Site 8	A_1	8.79	8.57	
	A_2	8.34		
Site 9	A_1	8.39	8.35	
	A_2	8.31		
Site 10	A_1	7.71	7.82	
	A_2	7.93		
Site 11	A_1	7.38	7.18	
	A_2	6.97		

Table 6 shows the soil pH levels for cluster 2 (sites 12–21).

Table 6: *Cluster 2 soil pH level per site*

Site	Identification	pHw	Average pH per site	Average pH of Cluster 2
	Segment			
Site 12	A1	7.38	7.46	**7.01**
	A2	7.54		
Site 13	A1	7.16	7.55	
	A2	7.93		
Site 14	A1	8.16	8.29	
	A2	8.41		
Site 15	A1	8.19	8.30	
	A2	8.41		
Site 16	A1	8.03	7.74	
	A2	7.44		
Site 17	A1	5.10	5.45	
	A2	5.80		
Site 18	A1	6.34	6.45	
	A2	6.56		
Site 19	A1	7.05	7.20	

	A2	7.34		
Site 20	A1	4.69	4.56	
	A2	4.43		
Site 21	A1	6.87	7.14	
	A2	7.41		

On average, soil sample results recorded slightly neutral pH levels across all sites within both Clusters 1 and 2 (Tables 4 and 5), with Cluster 1 recording a pH range of 5.4 to 8.7, averaging 7.5 in the topsoil. In cluster 2, a pH range of 4.4 to 8.4, averaging 7.0, was recorded in the topsoil. Maize requires a soil pH of 5.8 to 6.0; therefore, for optimum maize production, clusters with a lower pH need to be increased to 6.0, whereas pH exceeding 6.0 needs to be lowered. Soil microbial activity is optimised at pH levels around 6.0, thereby increasing nutrient cycling and biological activity. When soil pH drops below 5.5, the availability of Mg, calcium, K, and molybdenum decreases. There can also be reduced herbicide effectiveness at soil pH below 5.5 and below 5.0; toxicity from certain trace elements can affect plant health (Cropnuts, 2020).

Therefore, it is recommended to neutralise the soil in the Lake Liambezi maize farming area to achieve soil pH values between 5.8 and 6.0, optimise maize crop production, sustainably enhance soil microbial activity, increase soil organic matter, and avoid trace nutrient imbalances (Subedi, 2009).

3.4. Soil organic matter

Soil Organic Matter (SOM) is the most crucial factor in soil fertility and overall soil function. An optimum SOM of 5% in the soil is strongly recommended and beneficial to various soil and crop performance factors (Du et al., 2024). Healthy soil should contain organic matter comprising living organisms (microbes and macrobes), continuous addition of fresh crop residues, active organic matter (decomposers), and stable organic matter (humus) to regularly replenish nutrients removed or taken up (Power, 1997). This enhances the beneficial physical, chemical, and biological activities in soil (Cropnuts, 2020).

According to Biernbaum (2012), the amount of organic matter in mineral soils (sand, loam, or clay) ranging from 1% and below are at minimal, and are very low levels for optimum crop production and sustainable soil productiveness. While organic matter content at 2% to 4% are at moderate to an optimum level and at 5% and greater are high. The consensus is that the more soil organic matter, the better. Figure 3 shows soil organic matter (%) values of soil samples from Cluster 1.

As shown in Figure 3 below, the average soil organic matter (SOM) content in Cluster 1 samples is slightly low, with 1.7% in the topsoil and 1.5% in the subsoil. Within Cluster 1, sites 2, 10, and 5 recorded moderate topsoil SOM levels at 2.2%, 2.1%, and 2.0%, respectively, while sites 8 and 9 recorded the lowest values at 1.2% each.

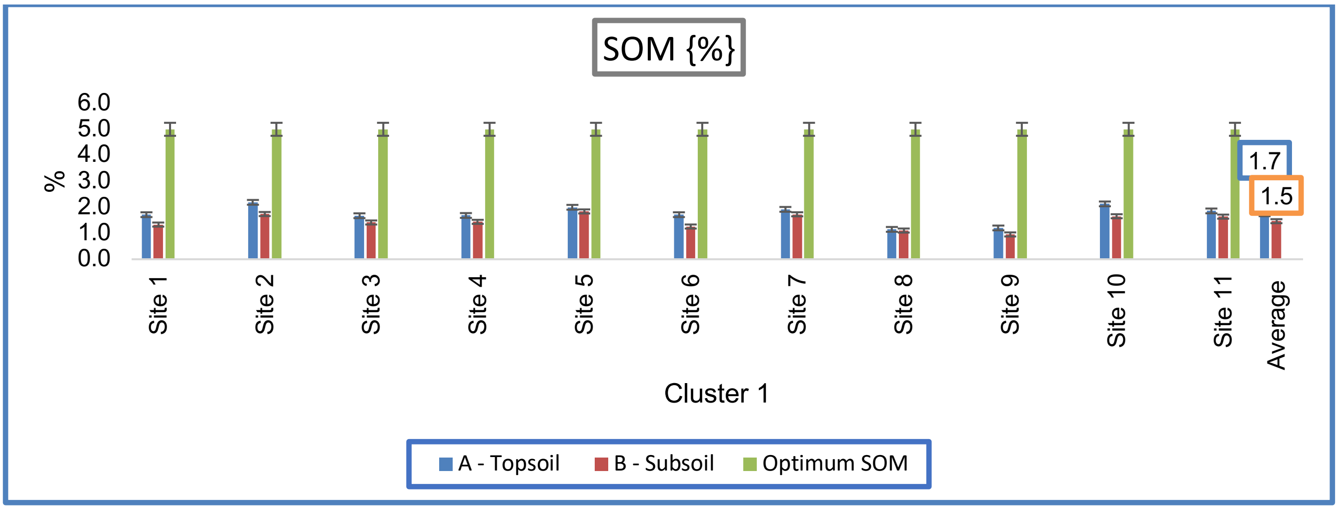

Figure 3: *Soil organic matter % within Cluster 1 soil samples*

Figure 4 shows soil organic matter (%) values of samples from cluster 2. Results for cluster 2, comprising sample sites 12 (farm 12) to 21 (farm 21), show again a slightly low level of soil organic matter, with an average of 1.8% in the topsoil and 1.4% in the subsoil. Among cluster 2 samples, sites 20, 17, and 21 showed moderate soil organic matter (SOM) levels in the topsoil: 2.5%, 2.3%, and 2.2%, respectively. Sites 15 and 16 recorded the lowest soil organic matter levels, 1.1% and 1.4%, respectively.

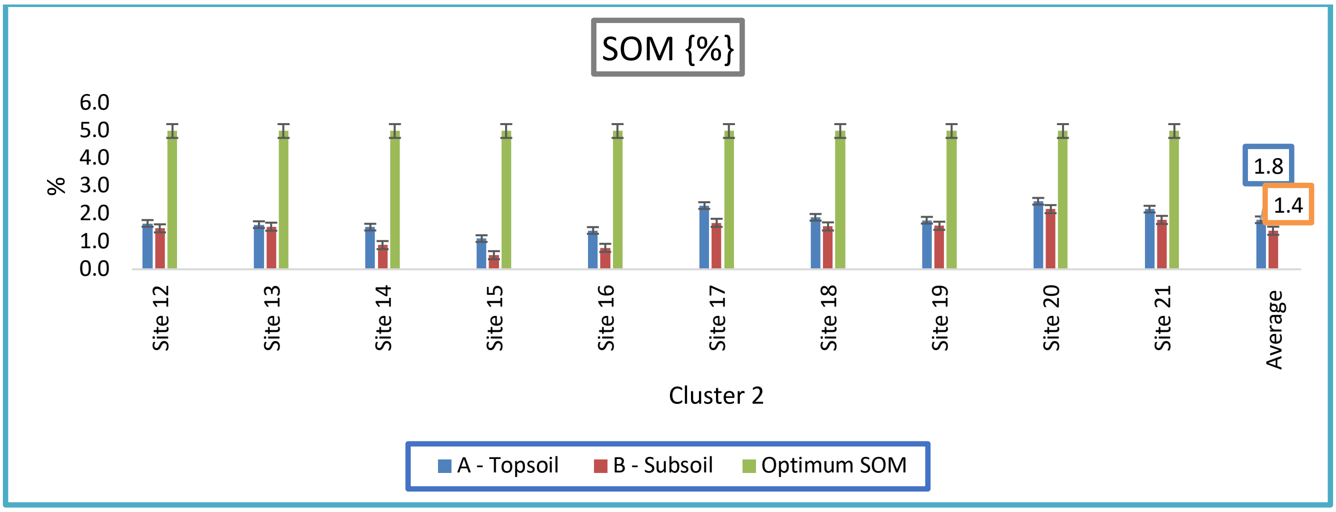

Figure 4: *Soil organic matter % within cluster 2 soil samples*

Overall, the SOM content across all sites in Clusters 1 and 2, as presented in Figures 3 and 4, remains below the optimum level required for maize production (5%). This indicates the need for deliberate interventions to increase soil organic matter in both clusters to reach the desired levels.

The application of compost and mulching materials such as leaves, straw, hay, bark, and wood shavings will provide significant benefits by enriching the soil with organic matter, conserving soil moisture, and suppressing weed growth. These practices will, in turn, enhance soil fertility and contribute to sustainable maize production in the Lake Liambezi farming area (Erenstein, 2022).

In addition, the introduction of cover crops or green manure can supply organic inputs that serve as food for soil microorganisms, thereby improving microbial activity and accelerating the build-up of soil organic matter. Furthermore, incorporating animal manure provides another reliable source of organic matter, which can improve soil structure and nutrient availability, ultimately supporting higher maize yields in the Lake Liambezi maize-producing area (Kucerik et al., 2024).

3.5. Phosphorus

Phosphorus (P) is important in maize production for crop growth, plant structure, reproduction, fruiting, maturity, and the rooting system (Goswami et al., 1990). The optimal phosphorus levels in the soil for sustainable maize crop production range from 25 to 70 ppm (Warncke et al., 2009).

Figure 5 shows soil phosphorus (P) values of soil samples from Cluster 1 of the Lake Liambezi maize farming area. The present phosphorus content in Cluster 1 soil samples showed extremely low averages of 7 ppm in the topsoil and 15.7 ppm in the subsoil. Among the Cluster 1 samples, site 4 showed moderate phosphorus levels in the topsoil and subsoil, at 39 ppm and 26 ppm, respectively. Sites 1, 3, and 6-11 recorded the lowest phosphorus values. However, within the subsoil, site 2 recorded the highest value of phosphorus of 74.5 ppm, exceeding the threshold level of phosphorus (70 ppm). Figure 6 shows soil phosphorus values from Cluster 2 soil samples.

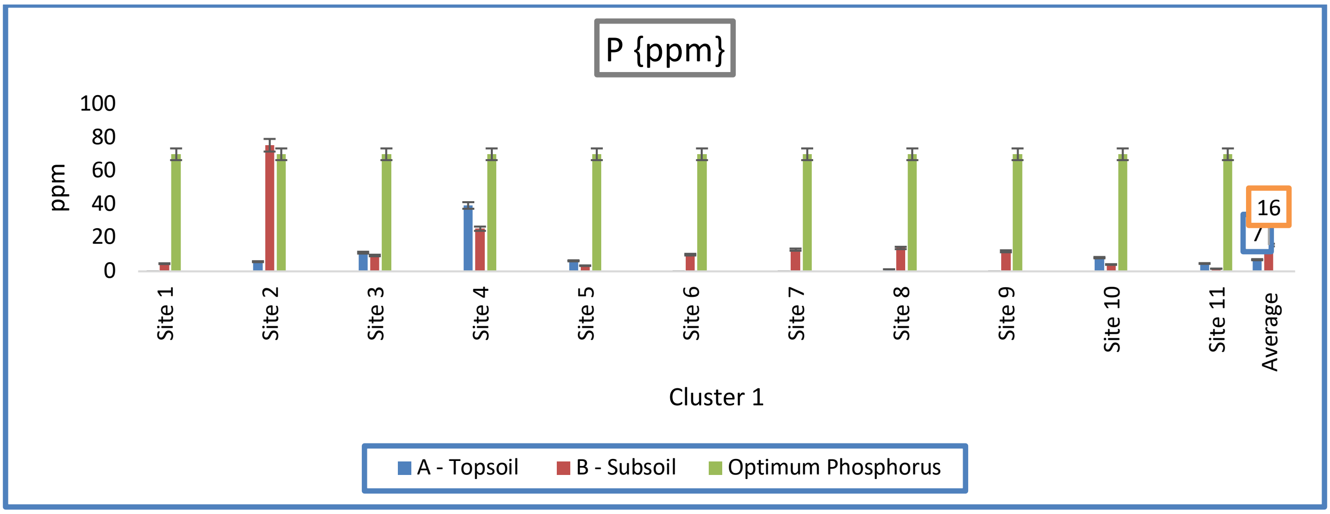

***Figure 5:** Soil phosphorus values within Cluster 1 soil samples*

Furthermore, the phosphorus content in Cluster 1 soil samples showed very low averages of 7 ppm in the topsoil and 16 ppm in the subsoil. Within Cluster 1, site 4 had moderate phosphorus levels of 39 ppm in the topsoil and 26 ppm in the subsoil. Conversely, sites 1, 3, and 6-11 exhibited the lowest phosphorus levels. Significantly, in the subsoil, site 2 recorded the highest phosphorus level of 74.5 ppm, exceeding the recommended threshold of 70 ppm (Figure 5).

Figure 6 displays the phosphorus content results from Cluster 2 soils. Phosphorus values within Cluster 2 soil samples recorded slightly low averages of 4 ppm in the topsoil and below-zero values in the subsoil. Among the Cluster 2 samples for both topsoil and subsoil, all sites show critically low phosphorus levels, ranging from 0 ppm to 12.8 ppm (Figure 6). These values are significantly below the optimum range of 25-70 ppm required for maize production. As such, current phosphorus levels are insufficient to sustainably support optimal maize yields in the long term (Bai et al., 2013; Syngenta, 2018).

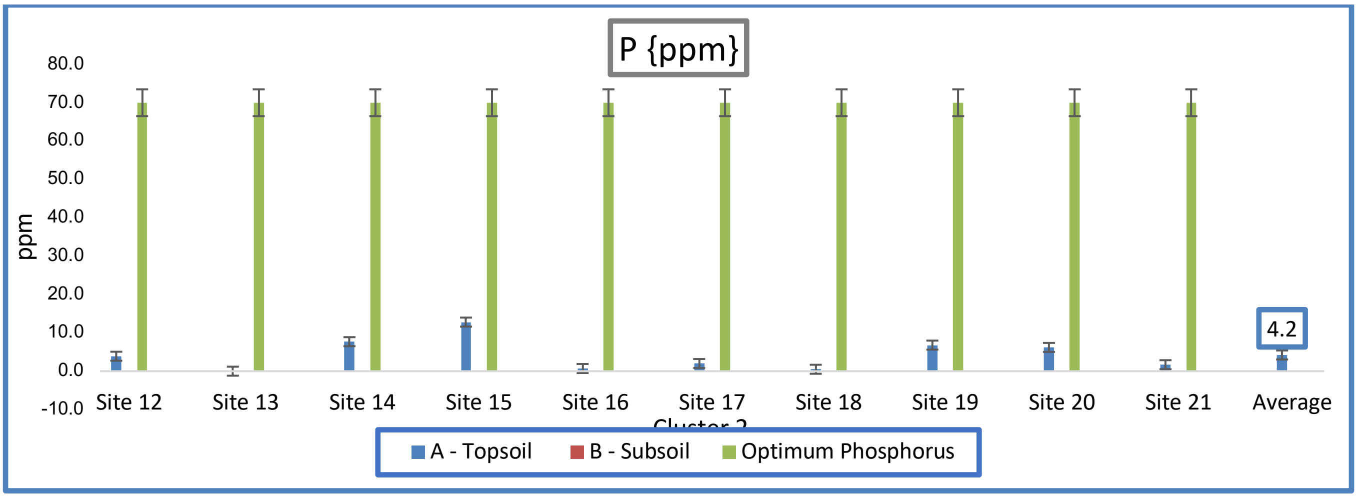

***Figure 6:** Soil phosphorus values within Cluster 2 soil samples*

To attain optimal phosphorus levels in the topsoil of the Lake Liambezi maize farming area, current average values of 4-7 ppm must be increased by approximately 21-46 ppm to reach the desired range of 25-70 ppm. This can be achieved through the implementation of phosphorus fertilisation programmes. However, the precise quantity of phosphorus required (kg/ha) will depend on several factors, including the crop variety, target grain yield, economic considerations, and the type and form of fertiliser used.

The statistical findings of the current study indicate that there are no statistically significant differences both within and between the sample groups. Consequently, a standard phosphorus application rate of 40-100 kg/ha is recommended for optimal maize growth in the Lake Liambezi region. This conversion is based on the soil weight determinant factor of 2.24, applied to convert ppm values to kilograms per hectare (ResearchGate, 2019). Nonetheless, the actual application rate should be adjusted based on prevailing conditions, including climate, yield targets, and specific production practices for each cropping season.

Other studies have shown that adopting appropriate fertilizer management in combination with suitable tillage practices can enhance soil fertility and improve maize production. This is because soil physicochemical properties are strongly influenced by tillage methods, seasonal crop uptake, and fertiliser application strategies (Nwodom & Nweze, 2020).

3.6. Potassium

Potassium (K) is an essential macronutrient required in large amounts for optimal maize growth. It plays a vital role in enzyme activation, numerous physiological processes within plant tissues, and the synthesis of starch and protein in maize crops (Nwodom & Nweze, 2020). In addition, potassium enhances maize's drought tolerance, thereby improving resilience under water-limited conditions (Syngenta, 2018). For sustainable maize production, optimal soil potassium levels should range from 40 to 120 ppm (Muthaura, 2017).

Figure 7 presents the potassium values of soil samples collected from Cluster 1 in the Lake Limabezi maize farming area, Zambezi Region, Namibia. The results show potassium content values in Cluster 1 soil samples, with high averages of 694 ppm in the topsoil and 307 ppm in the subsoil. Among Cluster 1 samples, sites 10, 6, and 5 recorded the highest potassium levels in the topsoil at 1514 ppm, 817 ppm, and 797 ppm, respectively. Sites 9, 8, and 1 recorded the lowest potassium values in the topsoil layer at 146 ppm, 445 ppm, and 485 ppm, respectively. However, at subsoil sites, 9, 8, and 4 recorded the lowest potassium levels of 48 ppm, 138 ppm, and 157 ppm, respectively.

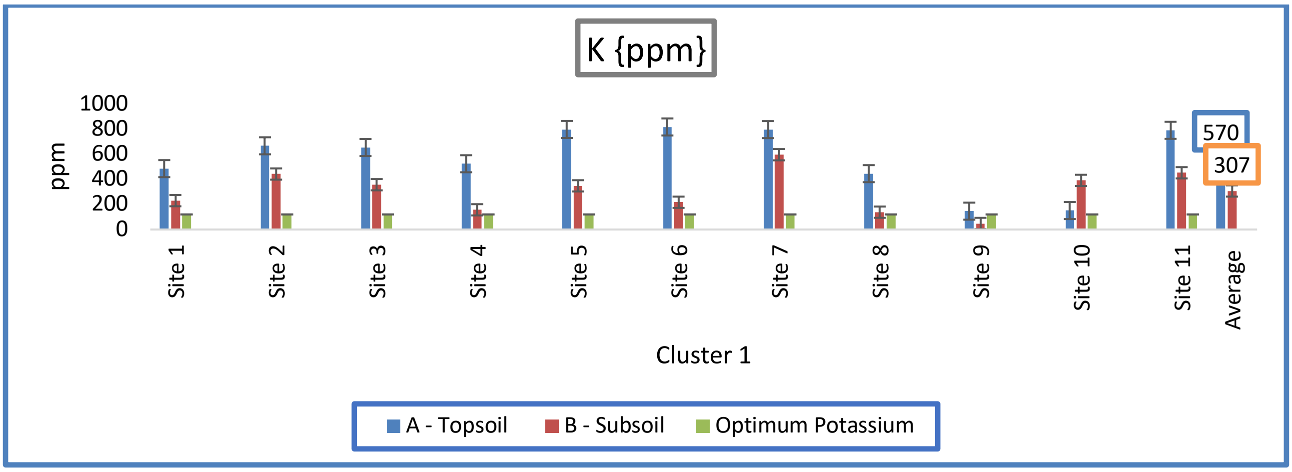

Figure 7: *Soil potassium values within Cluster 1 soil samples*

Figure 8 shows the soil potassium (K) values of soil samples from cluster 2. Within Cluster 2, potassium (K) levels averaged 563 ppm in the topsoil and 427 ppm in the subsoil. These values are considerably higher than the optimum potassium range required for maize production. The highest topsoil potassium levels were recorded at sites 13, 12, and 17, with 739 ppm, 696 ppm, and 638 ppm, respectively. Conversely, the lowest subsoil potassium values were recorded at sites 15, 16, and 14, with 85 ppm, 95 ppm, and 143 ppm, respectively. Notably, only sites 15 and 16 fall within the recommended optimum potassium range for maize production.

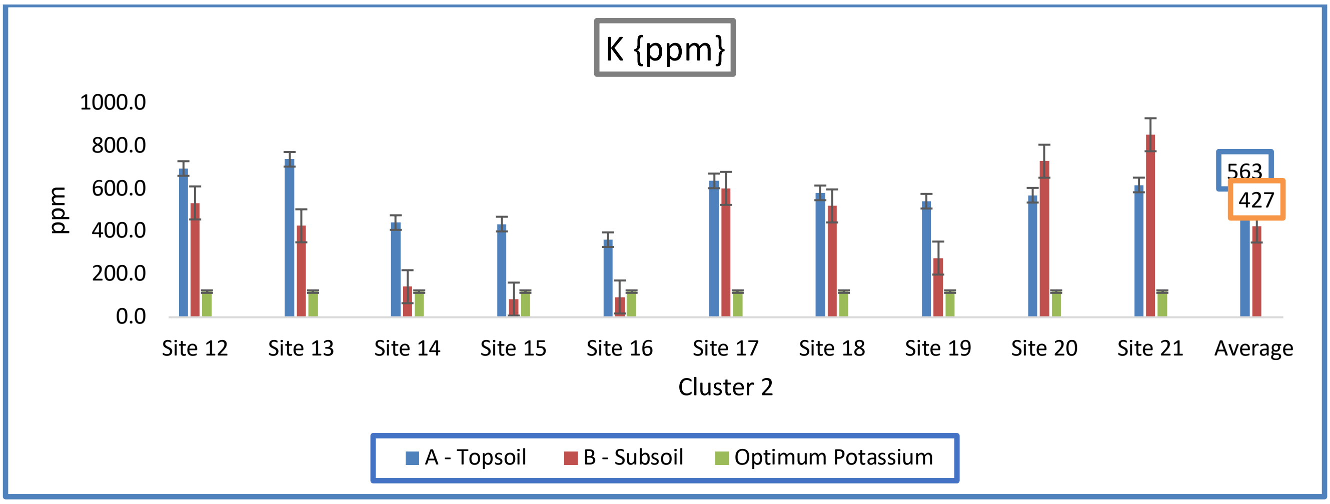

Figure 8: *Soil potassium values within Cluster 2 soil samples*

Overall, the results indicate that average potassium levels in the soils of Clusters 1 and 2 in the Lake Liambezi maize farming area range from 563 to 694 ppm (Figures 7 and 8). These values are significantly above the optimum range (120 ppm), raising concerns about potential nutrient imbalances that may limit the availability of other essential trace elements for plant uptake. Excessive potassium levels can also lead to toxicity in maize crops (Bai et al., 2013; Syngenta, 2018).

To address this, it is imperative to develop an efficient potassium fertiliser management strategy that incorporates regular monitoring of soil nutrient levels in both clusters. The use of organic amendments such as organic matter, mulching, and pH control, during peak nutrient demand periods, could help regulate and neutralise excess potassium. Furthermore, the statistical analysis of this study revealed no significant differences within and between sample groups, suggesting that a standard potassium fertilisation programme, tailored to local climatic conditions, yield targets, and production practices, would be appropriate for the Lake Liambezi maize farming area (Nwodom & Nweze, 2020).

3.7. Calcium

Calcium (Ca) is an essential plant nutrient that supports the metabolic uptake of other nutrients, proper cell development, and enhances crop resistance against diseases (ResearchGate, 2019). For sustainable maize production, optimal soil calcium levels range from 100 to 400 ppm.

Figure 9 presents the calcium (Ca) values of soil samples from Cluster 1. Calcium (Ca) values within Cluster 1 soil samples were notably high, with averages of 323 ppm in the topsoil and 345 ppm in the subsoil. Within the topsoil, the highest calcium concentrations were recorded at sites 10, 7, and 1, with values of 504 ppm, 458 ppm, and 367 ppm, respectively. In the subsoil, sites 7, 2, and 1 recorded the highest levels, at 404 ppm, 403 ppm, and 400 ppm, respectively. Overall, sites 2, 7, and 10 exceeded the optimum calcium threshold by 3 ppm, 4 ppm, and 104 ppm, respectively, while the remaining sites in Cluster 1 are within the recommended range.

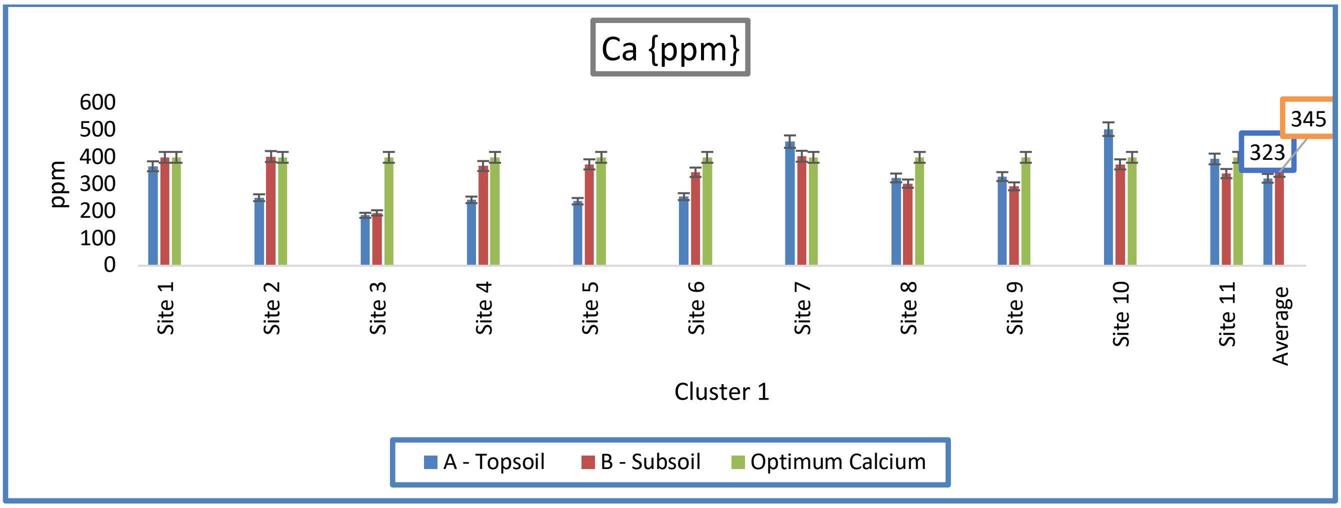

Figure 9: *Soil calcium values within Cluster 1 soil samples*

Figure 10 below presents the calcium (Ca) values of soil samples from Cluster 2. Calcium (Ca) values within Cluster 2 soil samples were exceptionally high, averaging 3,885 ppm in the topsoil and 3,168 ppm in the subsoil. Among the topsoil samples, the highest calcium concentrations were recorded at sites 12, 17, and 13, with values of 4,639 ppm, 4,624 ppm, and 4,468 ppm, respectively. In the subsoil, sites 21, 17, and 12 recorded the highest calcium levels at 4,443 ppm, 4,286 ppm, and 3,943 ppm, respectively.

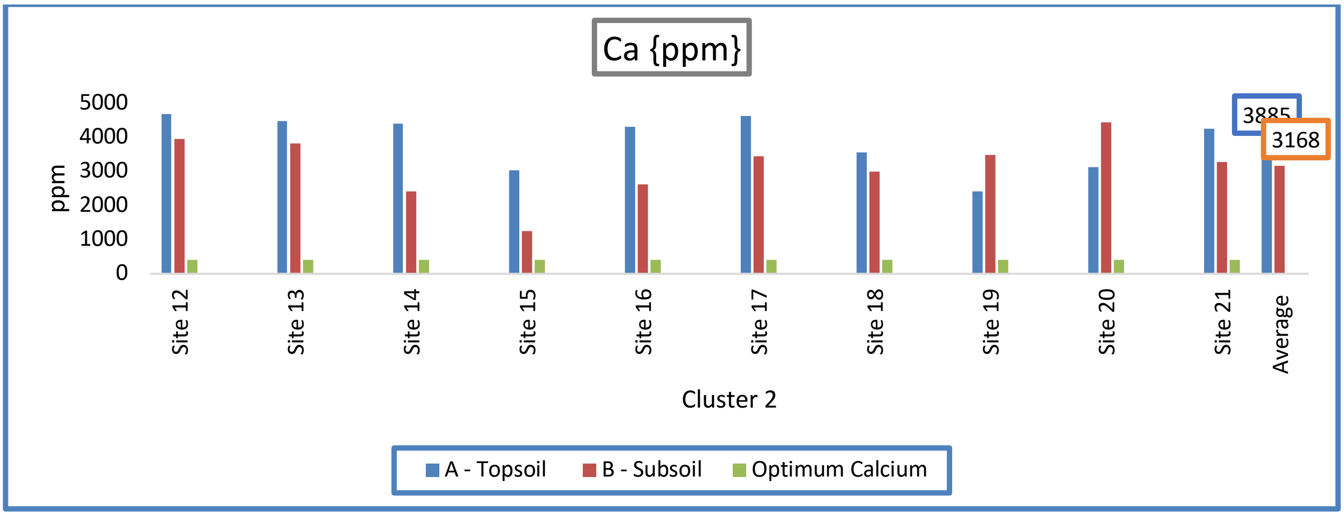

Figure 10: *Soil calcium values within cluster 2 soil samples*

Although calcium is required in relatively small amounts for maize growth, its deficiency (<100 ppm) significantly reduces root system development. Calcium-deficient maize plants typically display shorter, dark brown roots and initial chlorosis on young leaves, which eventually progresses to necrosis and leaf tip burn (do Moraes Gatti et al., 2023). However, the current results show average calcium levels of 3,233–3,880 ppm in the soils of Clusters 1 and 2 in the Lake Liambezi maize farming area (Figures 8 and 9), which are far above the optimum range. Such excessively high concentrations may cause nutrient imbalances, reduce the availability of other essential elements, and potentially lead to calcium toxicity in maize.

Therefore, continuous monitoring of soil calcium levels in both clusters at Lake Liambezi is imperative (Bai et al., 2013; Syngenta, 2018). Excess calcium levels can be managed by incorporating organic amendments, avoiding acidic fertilisers, and applying mulch to improve soil balance. Furthermore, statistical analysis from this study indicated no significant differences within or between sample groups, suggesting that a standard calcium fertilisation programme adapted to climate conditions, yield targets, and production practices would be appropriate for the Lake Liambezi maize farming area (Nwodom & Nweze, 2020).

3.8. Magnesium

Magnesium (Mg) is an essential nutrient for maize, primarily required for chlorophyll synthesis and several physiological and biochemical processes (do Moraes Gatti et al., 2023). The optimal magnesium concentration in soils for sustainable maize production ranges from 25 to 45 ppm (do Moraes Gatti et al., 2023).

Data from Cluster 1 (Figure 11) indicate that magnesium levels were high, averaging 189 ppm in the topsoil and 237 ppm in the subsoil. Within the topsoil, the highest concentrations were observed at sites 6, 11, and 10, with 257 ppm, 254 ppm, and 248 ppm, respectively. In the subsoil, sites 7, 2, and 11 recorded the highest values, at 361 ppm, 254 ppm, and 253 ppm, respectively.

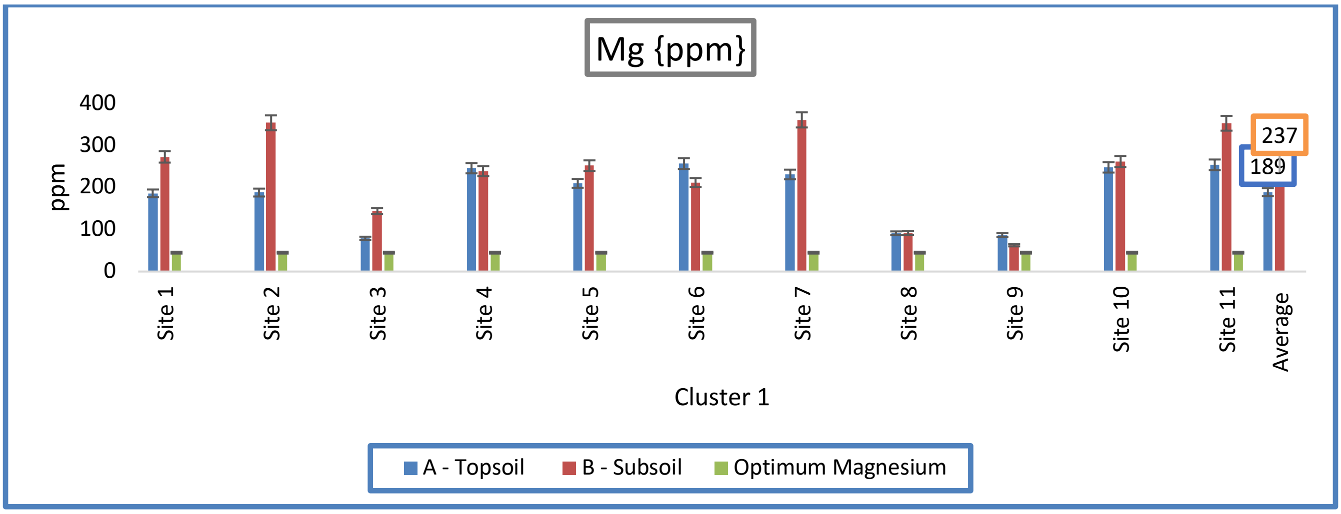

Figure 11: *Soil magnesium values within Cluster 1 soil samples*

Figure 12 shows soil magnesium (Mg) values of soil samples from Cluster 2. Cluster 2 exhibited elevated magnesium levels, averaging 230 ppm in the topsoil and 237 ppm in the subsoil. The highest topsoil concentrations were recorded at sites 18, 21, and 12, with values of 307 ppm, 305 ppm, and 253 ppm, respectively. In the subsoil, the highest values were observed at sites 13, 18, and 17, with 395 ppm, 392 ppm, and 383 ppm, respectively.

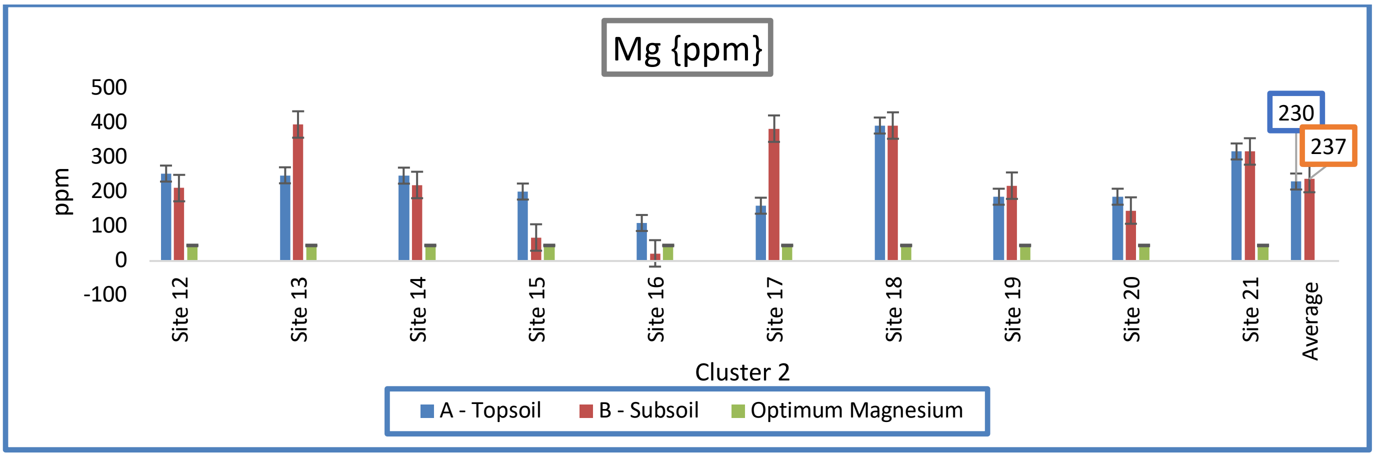

Figure 12: Soil magnesium values within Cluster 2 soil samples

Overall, magnesium concentrations in both clusters far exceed the optimum range of 25-45 ppm required for maize cultivation. Such excessive levels may contribute to nutrient imbalances by limiting the availability of other essential elements, thereby potentially constraining crop growth. An exception was noted at site 16 in Cluster 2, where the subsoil magnesium content was below the recommended range. Given these findings, continuous monitoring of soil magnesium levels in both clusters at Lake Liambezi is strongly recommended (Bai et al., 2013; Syngenta, 2018).

To address excessive magnesium, soil management practices such as incorporating organic matter, applying mulches, and using organic fertilisers are recommended, as these can help buffer the soil and restore nutrient balance. Statistical analysis from this study revealed no significant differences within or between sample groups, suggesting that a standard magnesium fertilisation programme, tailored to prevailing climate conditions, yield targets, and production practices, would be suitable for the Lake Liambezi maize farming area (Bai et al., 2013; Nwodom & Nweze, 2020; Syngenta, 2018).

3.9. Sodium

Measuring soil sodium (Na) levels is essential for assessing salinity status and guiding the application of appropriate management practices, such as leaching, to flush excess salts from the soil profile and away from the root zone (Rhoades et al., 1999).

Figure 13 presents the sodium (Na) concentrations of soil samples from Cluster 1. Results indicate that sodium concentrations in Cluster 1 soils were generally low, with 189 ppm in the topsoil and 281 ppm in the subsoil. Nonetheless, some sites exhibited markedly elevated levels. In the topsoil, the highest sodium concentrations were recorded at sites 6, 8, and 9, with values of 530 ppm, 320 ppm, and 238 ppm, respectively. Similarly, in the subsoil, the highest values were observed at sites 1, 5, and 2, with values of 531 ppm, 480 ppm, and 459 ppm, respectively. All these values exceed the ideal sodium threshold of 40 ppm required for balanced soil conditions, highlighting potential risks of sodium accumulation, which may lead to soil structural degradation, reduced water infiltration, and impaired nutrient uptake.

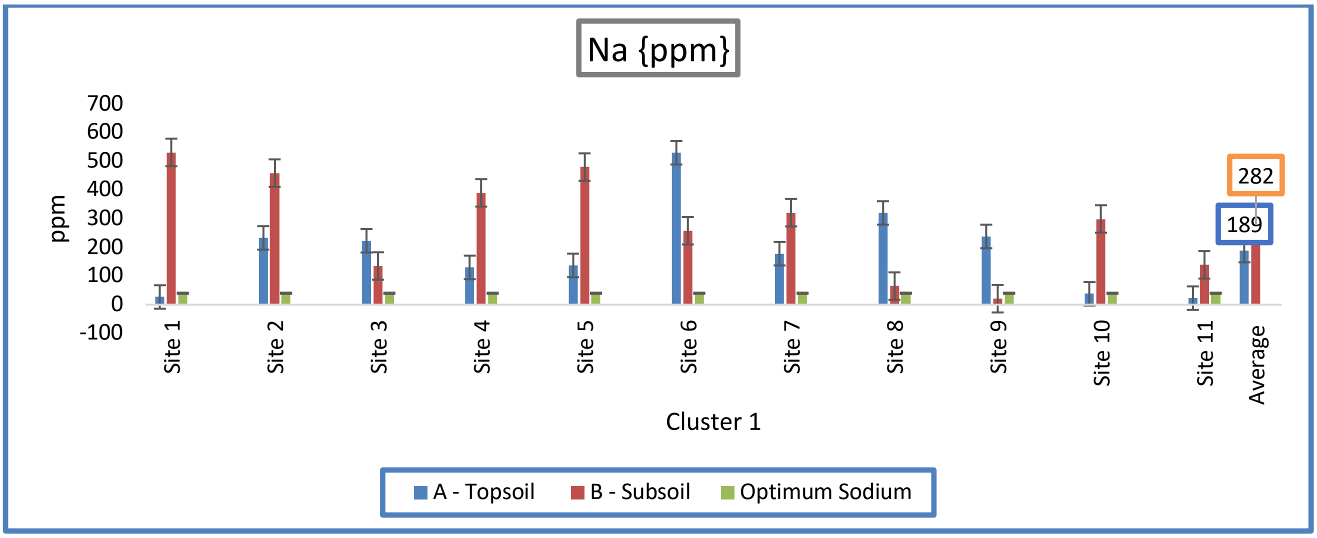

Figure 13: *Soil sodium values within Cluster 1 soil samples*

Figure 14 shows sodium content values (Na ppm) of soil samples from Cluster 2. The results show that sodium values are high, with average values of 89 ppm in topsoil and 174 ppm in subsoil. Cluster 2 soil sample results show that the highest sodium values were recorded in the topsoil at sites 20, 21, and 19, with 415 ppm, 202 ppm, and 140 ppm, respectively. Subsoil samples from sites 20, 17, and 13 recorded the highest sodium levels of 502 ppm, 322 ppm, and 266 ppm, respectively.

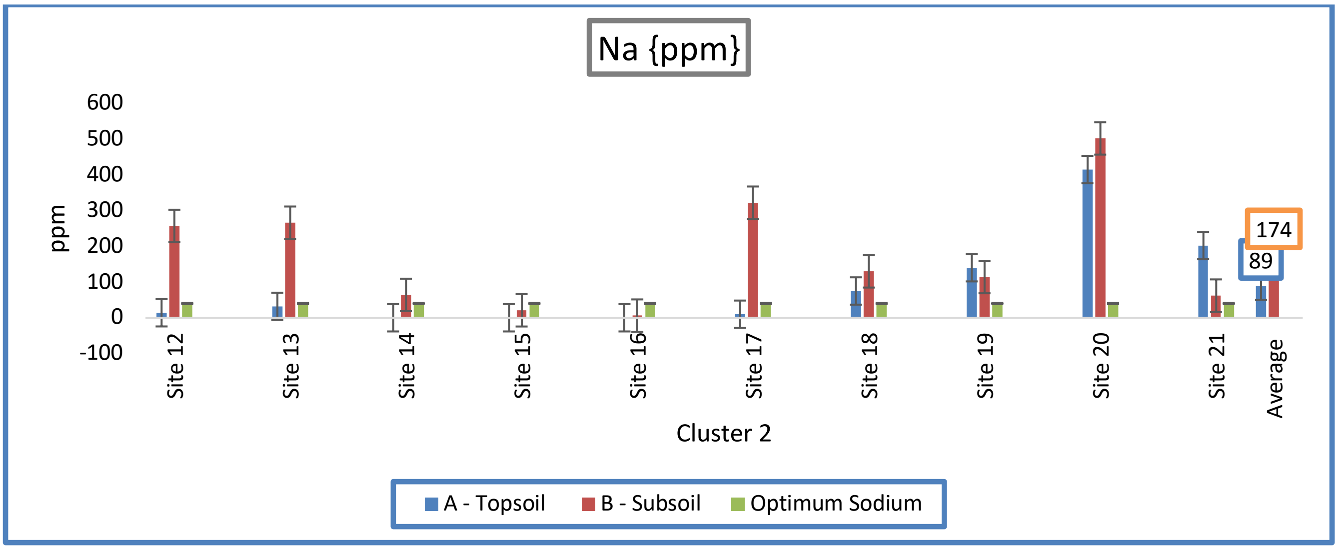

Figure 14: *Soil sodium values within Cluster 2 soil samples*

Sodium is not considered a plant nutrient; therefore, high levels can cause problems with soil salinity, soil structure disturbance, and poor uptake of other nutrients by plants. An ideal soil sodium level should not exceed 40 ppm (Moraes Gatti et al., 2023). Therefore, recorded sodium values in Clusters 1 and 2 are high and require remedial measures to lower them to the optimal soil range for sustainable maize crop production, as this may severely affect crop performance. As per the statistical results of this study, the sodium levels within the same groups and between sample groups are not statistically significantly different; therefore, a standard sodium fertilisation programme with appropriate consideration of climate, yield targets, and production practices at Lake Liambezi farming area is recommended (Nwodom & Nweze, 2020).

3.10. Nitrogen

Nitrogen is a vital nutrient in maize production, significantly influencing plant growth and development. A sufficient nitrogen supply supports robust vegetative growth, leading to sturdy stalks and dense foliage, which are crucial for enhancing the plant's ability to capture sunlight and optimise photosynthesis (Kafle et al., 2023). Figures 15 and 16 below illustrate soil samples' nitrogen (N) content from Clusters 1 and 2 within the Lake Liambezi maize farming area. The recorded nitrogen concentrations were initially measured in grams per kilogram (g/kg) and converted to parts per million (ppm) using the standard conversion factor: 1 g/kg = 1000 ppm. This conversion facilitates a more precise assessment of nitrogen levels relative to recommended thresholds for maize farming.

Results presented in Figure 15 below indicate that soil samples from Cluster 1 revealed elevated nitrogen concentrations in the topsoil at sites 4, 5, 7, and 2, with values of 6,250 ppm, 5,700 ppm, 5,700 ppm, and 4,850 ppm, respectively. The average subsoil nitrogen content was 1,968 ppm, with site 2 recording the highest concentration (3,950 ppm), followed by site 7 (3,700 ppm). In contrast, sites 8 and 9 showed the lowest nitrogen levels, with site 8 registering only 850 ppm. Considering that the recommended nitrogen level is 2,000 ppm, the topsoil for sites 2, 4, 5, 6, 7, 10, and 11 exceeds the optimal threshold, including the subsoil for sites 1, 2, 5, and 7. In contrast, other sites remained below the requirement, except the subsoil in site 10, which is 2,000 ppm.

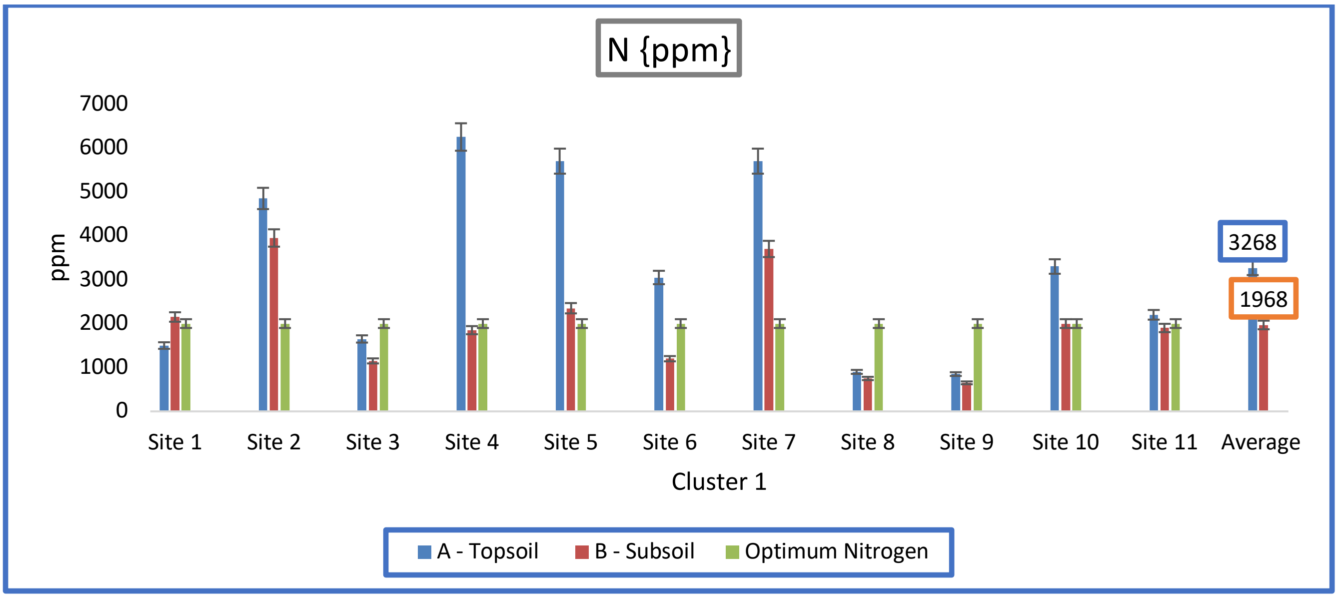

Figure 15*: Soil nitrogen values within Cluster 1 soil samples*

In Figure 16, the recorded average nitrogen concentrations in the topsoil and subsoil were 2,860 ppm and 2,780 ppm, respectively, indicating excessively high nitrogen content. Such elevated levels can cause nutrient imbalances, delay crop maturation, and increase the risk of lodging, all of which may negatively impact maize growth (Dahiya et al., 2018). Notably, sites 12, 14, 15, 16, and 19 recorded nitrogen levels below the recommended threshold (2,000 ppm).

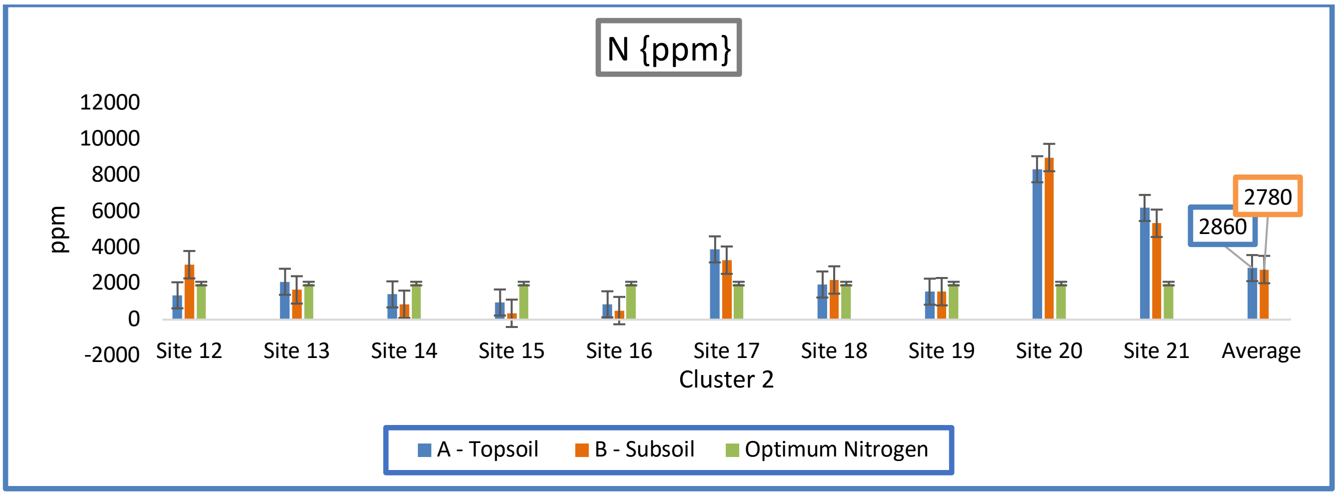

Figure 16: Soil nitrogen values within cluster 2 soil samples

3.11. Electrical conductivity

Electrical Conductivity (EC) affects crop yield and the availability of other nutrients in the soil. Thus, EC is a stronger indicator of soil fertility and is also used to determine soil salinity (Cropnuts, 2020). The optimal EC level, ranging from 800 – 2500 µS/cm, should be present in the soil and maintained accordingly (do Moraes Gatti et al., 2023).

Figure 17 shows the soil Electrical Conductivity (EC) values of soil samples from cluster 1. The results show Electrical Conductivity (EC) levels within cluster 1 soil samples. The data indicate that EC values are extremely low, with average values of 561 µS/cm in the topsoil and 420 µS/cm in the subsoil. Cluster 1 soil sample results show that EC values were recorded at sites 6, 2, and 4 in the topsoil at 1211 µS/cm, 1075 µS/cm, and 862 µS/cm, respectively, within the required EC range. Within subsoil sites 1 and 3-11, the lowest EC values were recorded, which are below the threshold.

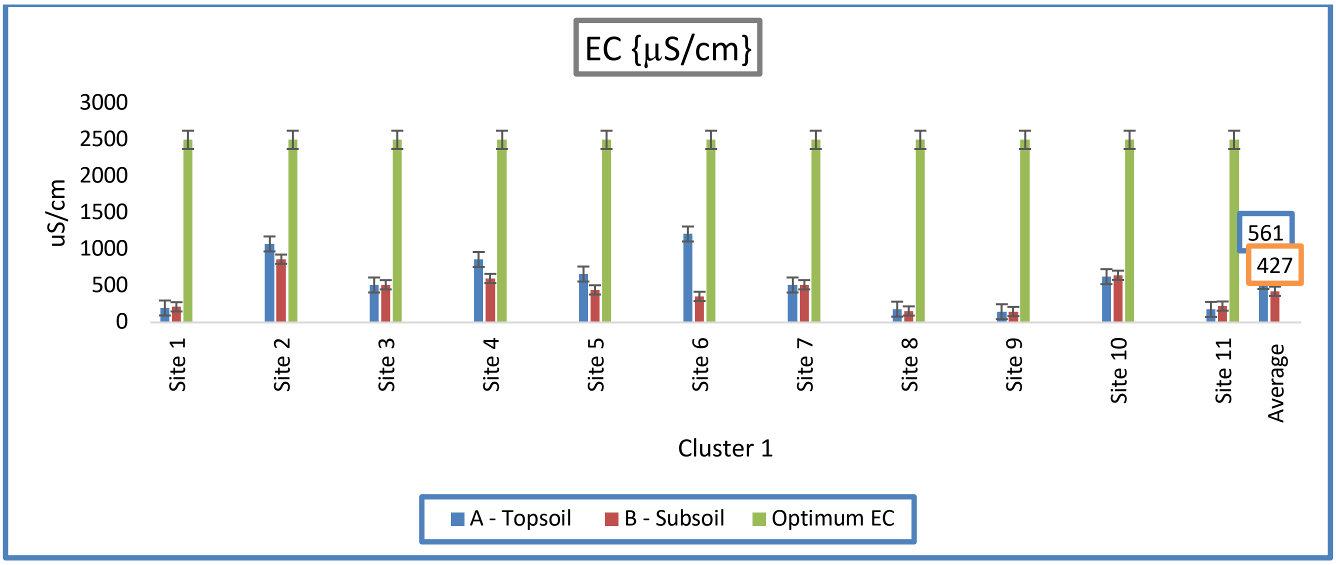

Figure 17: *Soil Electrical Conductivity values within Cluster 1 soil samples*

Figure 18 shows the electrical conductivity (EC) values for soil samples from Cluster 2. The results presented show electrical conductivity (EC) levels within Cluster 2 soil samples. Overall, EC values were low, averaging 513 µS/cm in the topsoil and 498 µS/cm in the subsoil. In the topsoil, the highest EC values were recorded at sites 20, 17, and 21, with 1,464, 1,371, and 538 µS/cm, respectively. In the subsoil, sites 20, 17, and 21 also recorded the highest EC values, at 1,418 µS/cm, 1,385 µS/cm, and 554 µS/cm, respectively. Sites 17 and 20 in both the topsoil and subsoil fall within the recommended EC threshold, while site 21 remains below the optimum range.

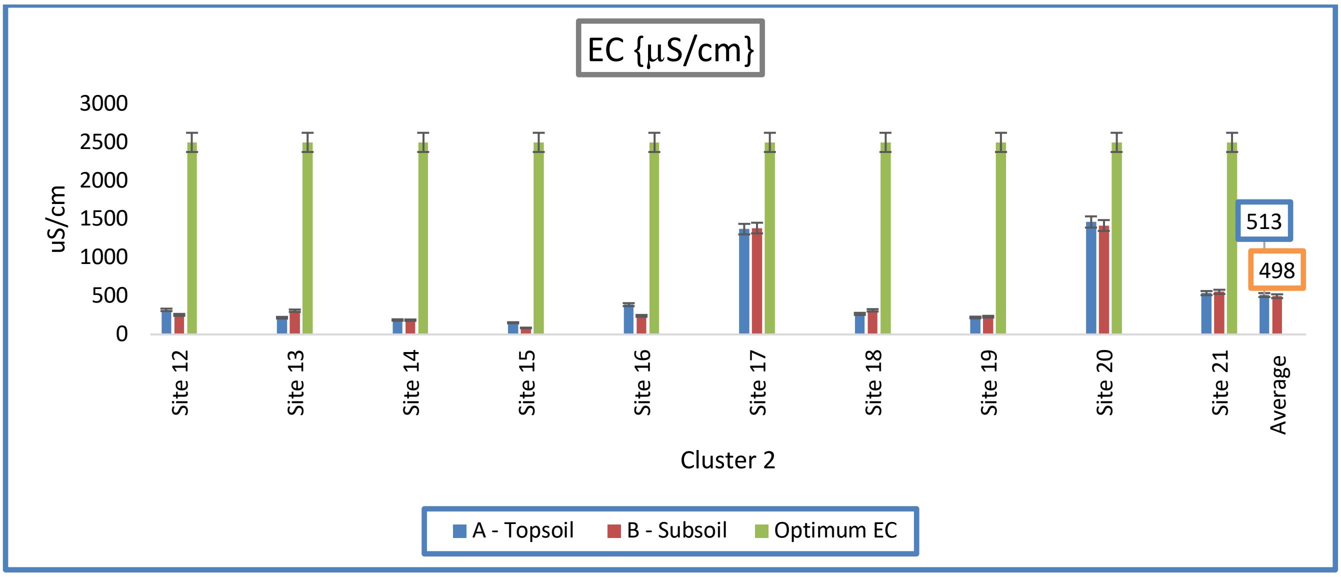

Figure 18: *Soil Electrical Conductivity values within Cluster 2 soil samples*

Electrical conductivity reflects the availability of nutrients for crop uptake. It correlates positively with essential plant nutrients such as nitrogen, phosphorus, potassium, calcium, magnesium, and cation exchange capacity (CEC), which also indicates soil salinity levels (Kitchen et al., 1999). Accurate EC measurement in the Lake Liambezi maize farming area is therefore critical for implementing efficient agricultural practices and maintaining long-term soil functionality.

However, excessively high EC can hinder nutrient absorption and increase osmotic pressure, while low EC levels, as recorded in this study (average 513–516 µS/cm), may severely limit plant health and reduce crop yield. To improve soil fertility and support sustainable maize production, it is necessary to implement practices that increase EC to the optimum range. Based on the study results, the following soil properties require targeted amendments: soil organic matter (SOM), phosphorus, potassium, calcium, magnesium, electrical conductivity, and sodium (Table 7).

Table 7: *Soil physiochemical properties and corrective action required to meet the maize plant nutrient requirements in the Lake Liambezi farming area*

Soil property	***Soil property status***	***Action***
pH	*Optimum pH value*	Continuous pH balancing
Soil texture	*Good soil texture for optimum crop growth*	Maintain and enhance soil texture and structure – minimal tillage
Soil Organic Matter {SOM}	*At a minimum critical level*	Apply organic content fertiliser, green cover crop, mulch, and minimal tillage
Phosphorus {P}	*Below critical level*	Increase the soil pH by applying a phosphorus-containing fertiliser

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Potasium {K}	*Above the critical level*	Reduce and control K values in the soil by adding organic matter, avoid nutrient imbalances, and monitor pH, soil moisture, and EC level
Calcium {Ca}	*Above the critical level*	Reduce and control Ca levels in the soil by adding organic matter, avoiding nutrient imbalances, and monitoring pH and EC.
Magnesium {Mg}	*Above the critical level*	Reduce and control K levels in the soil by adding organic matter, avoiding nutrient imbalances, monitoring pH, and increasing EC levels.
Electrical Conductivity {EC}	*Below critical level*	Increase the EC level in the soil by applying organic content fertiliser
Sodium {Na}	*Above critical level*	Reduce and control Na values in the soil, apply gypsum, avoid nutrient imbalances, and monitor pH and EC levels.
Nitrogen {N}	*Below critical level*	Increase soil N by applying nitrogen fertilisers (urea and ammonium nitrate).

(Samarakoon et al., 2006; Power & Prasad, 1997). *Value status: Low / Optimum / High*

Results on soil pH levels and soil texture type at the Lake Liambezi maize farming area indicate promising suitability for maize production, with soil pH levels and soil texture types recording optimal and good status, respectively. However, Soil Organic Matter, phosphorus and electrical conductivity values are below critical minimal level posing a massive threat to sustainable maize production with possible depletion of nutrients foreseen through seasonal nutrients uptake or removal from the soil on every harvest (Samarakoon et al*.,* 2006; Power & Prasad, 1997), thus, there is need to introduce a soil fertility management programme and increase these nutrients levels to the optimum amount in the soil. Furthermore, results depict that potassium, calcium, magnesium and sodium values in the soil are extremely high, above the critical level, this implies possible nutrient imbalances and excessive amounts which might be detrimental to the crop's performance and the soil health, thus, there is need for control amendments practices to reduce these elements levels in the soil to avoid nutrients toxicity (Samarakoon et al., 2006; Power & Prasad, 1997).

As per the statistical results of the present study, the sodium levels within the same groups and between sample groups are not statistically significantly different; therefore, a standard sodium fertilisation programme with appropriate consideration of climate, yield targets, and production practices at Lake Liambezi farming area is recommended (Nwodom & Nweze, 2020).

Africa is the continent with the lowest fertilizer use per hectare, despite possessing geologically old, infertile, and degraded soils. There are a variety of soil types in the five major AgroEcological Zones (AEZ) of Africa. Sixty-five percent of Africa's agricultural land is degraded. Soil fertility depletion, a manifestation of soil degradation, is currently a serious threat to food security among smallholder farmers, and Namibia is no exception. Because of this state of affairs, there is a strong case for enhanced fertiliser use (Muthaura, 2017). Maize yield has reportedly increased over the control use of NPK fertiliser application in various AEZ. When soils are amended with lime and manure, yield response has been even higher, thus making fertilizer investment worthwhile (Laker, 2005). Therefore, this research discussed the issues of soil fertility, productivity, and sustainability associated with effective and efficient fertiliser use in the Lake Liambezi maize farming area of Namibia's Zambezi Region.

3.12. Statistical data analysis results

In overall, statistical results on all analysed parameters at P>0.05, namely, pH, Soil Organic Matter (SOM), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), electrical conductivity (EC), sodium (Na), and nitrogen (N) using Anova single factor statistical analysis method were used to establish average, variance, standard deviation, p-value and significant difference among nutrients between groups and within groups. The results indicate that the average and variance of the available nutrient levels in Lake Liambezi maize soil differ significantly from the required nutrient levels, indicating a need for a soil fertility management programme through sustainable agricultural practices. Results further indicate that all parameters analysed, both between and within groups, are not statistically significantly different at P>0.05. Thus, for soil fertility amendments and fertilisation programmes, a standard, optimum fertiliser application rate for all sites shall be established and recommended based on the optimum required amount of each nutrient in the soil for maize production at Lake Liambezi across all sampled sites in Clusters 1 and 2.

***Table 8:** Summary of statistical analysis results on pH and SOM*

Anova: Single Factor **_pH_**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	22	160.82	7.31	0.590648
Column 2	22	163.95	7.452273	0.597647

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.222657	1	0.222657	0.37475	0.543726	4.072654

Within Groups	24.95419	42	0.594147
Total	25.17684	43	

Statistically not significant, P > 0.05

Anova: Single Factor ***SOM***

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	22	266.71	12.12318	2456.011
Column 2	22	35.67	1.621364	0.139289

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	1213.17	1	1213.17	0.987863	0.325957	4.072654
Within Groups	51579.16	42	1228.075			
Total	52792.33	43				

Statistically not significant, P > 0.05

Table 9: *Summary of statistical analysis results on P and K*

Anova: Single Factor **_P_**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	22	304.9	13.85909	858.0225
Column 2	22	193.8	8.809091	106.3104

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	280.5275	1	280.5275	0.581806	0.449868	4.072654
Within Groups	20250.99	42	482.1665			
Total	20531.52	43				

Statistically not significant, P > 0.05

Anova: Single Factor **_K_**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	22	9420	428.1818	65728.25
Column 2	22	12587	572.1364	210790.2

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	227952	1	227952	1.648729	0.20617	4.072654
Within Groups	5806888	42	138259.2			
Total	6034840	43				

Statistically not significant, P > 0.05

Table 10: *Summary of statistical analysis results on Ca and Mg*

Anova: Single Factor **Ca**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	22	78563	3571.045	1096558
Column 2	22	68626	3119.364	2325634

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2244181	1	2244181	1.311546	0.258599	4.072654
Within Groups	71866032	42	1711096			
Total	74110213	43				

Statistically not significant, P > 0.05

Anova: Single Factor **Mg**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	22	4872	221.4545	11211.97
Column 2	22	4480	203.6364	10133.67

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3492.364	1	3492.364	0.32722	0.57035	4.072654
Within Groups	448258.5	42	10672.82			
Total	451750.9	43				

Statistically not significant, P > 0.05

Table 11: *Summary of statistical analysis results on EC and Na*

Anova: Single Factor **EC**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	22	10757.2	488.9636	147467.2
Column 2	22	10819.1	491.7773	111341.6

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	87.08205	1	87.08205	0.000673	0.979427	4.072654
Within Groups	5434985	42	129404.4			
Total	5435072	43				

Statistically not significant, P > 0.05

Anova: Single Factor **Na**

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	22	5573	253.3182	49259.27
Column 2	22	4765	216.5909	39814.73

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	14837.82	1	14837.82	0.333157	0.566887	4.072654
Within Groups	1870554	42	44537			
Total	1885392	43				

Statistically not significant, P > 0.05

Table 12: Summary of statistical analysis results on N

Anova: Single Factor ***N***

SUMMARY

Groups	Count	Sum	Average	Variance
Column 1	21	64550	3073.81	5004154.2
Column 2	21	49450	2354.72	3932476.9

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5428809.52	1	5428810	1.214956	0.276940	4.084746
Within Groups	178732619	40	4468315			
Total	184161428.6	41				

Statistically not significant, P >0.05

4. CONCLUSION

The study highlights significant nutrient imbalances in the soils of the Lake Liambezi maize farming area, with some nutrients falling below critical levels while others exceed optimal thresholds. To ensure sustainable maize production and long-term soil fertility, a well-structured fertiliser application programme is essential. This programme should be tailored to address specific nutrient deficiencies and excesses, optimising application rates to maintain soil health and productivity. Implementing a sustainable soil fertility management system will not only enhance maize yields but also conserve essential soil resources, contributing to long-term food security at both household and national levels in Namibia.

5. RECOMMENDATIONS

Based on the study findings, the following recommendations are made for the analysed soil parameters:

- √ **Soil texture** - The results show that the soil texture in the Lake Liambezi area is dominated by Loam soil and Sandy Clay Loam, which are suitable for maize crop production. However, there are noticeable amounts of sand in the soil; thus, continuous soil management, including the addition of organic matter, is required to maintain or improve layer content (du Plessis, 2003).
- √ **Soil pH** - pH levels in the soil should be balanced between 5.5 to 6.5, the average recorded pH level in Lake Liambezi maize farming soil is between pH level of 7.0 – 7.5 which is slightly alkaline and requires the application of organic matter content such as mulching to reduce the

pH level to slightly lower than pH 6.0 for best nutrients absorption and optimised maize production (Subedi, 2009).

- √ **Soil Organic Matter** - The recorded average Soil Organic Matter levels within Lake Liambezi maize farming soil of 1.7% – 1.8% is slightly below recommended values of 2% – 5% (Power, 1997), therefore, the application of compost and mulching materials like leaves, straw, hay, bark and wood shavings will be of significant benefit to the maize crop by increasing soil organic content in the soil while conserving water and reducing weed growth and eventually contributing to sustainable maize production at Lake Liambezi farming area. The introduction of cover crops or green manure will significantly provide food for soil microorganisms, ultimately increasing soil organic matter and microbial activity. Furthermore, animal manure is another source of organic matter that could be added to the soil in the Lake Liambezi maize-producing area. Four tons of organic fertiliser per hectare is recommended.
- √ **Phosphorus** – Optimum phosphorus values in the soil for sustainable maize crop production range from 25 - 70 ppm (50 - 150kg/ha)(Muthaura, 2017) but recorded average phosphorus levels of 4 ppm – 7 ppm are critically low requiring phosphorus application rate of over 50-100kg/ha per cropping season to optimize maize production at Lake Liambezi maize farming area sustainably.
- √ **Potassium** - Optimum potassium values for sustainable maize crop production range from 40 - 120 ppm (Muthaura, 2017). The recorded average potassium levels of 563-694 ppm in the soils of clusters 1 and 2 in the Lake Liambezi maize farming area are incredibly high. This might promote nutrient imbalances and threaten the availability of other trace elements in the soil for plant uptake. Thus, it is advisable to avoid chemical potassium fertiliser application, instead loosening the soil and increasing irrigation to flush out potassium while deploying organic fertiliser avenues.
- √ **Magnesium** – An ideal level of magnesium in the soil should range from 25 - 45 ppm (do Moraes Gatti et al., 2023; Bai et al., 2013; Syngenta, 2018). Therefore, recorded magnesium levels of 220-230 ppm are extremely high, and remedial measures are required to lower them to the optimum. These should be altered and monitored continuously to maintain them within the optimum range through the application of organic content into the soil. The magnesium fertiliser application rate should be less than 125 kg/ha of magnesium sulfate.
- √ **Calcium** – Optimum calcium value levels for sustainable maize crop production range from 100 - 400 ppm. The recorded average calcium levels of 3233-3880 ppm in the soils of clusters 1 and 2 in the Lake Liambezi maize farming area are extremely high (Bai et al., 2013). This might promote nutrient imbalances and pose a toxicity threat, and the unavailability of other elements in the soil for plant uptake. Therefore, available calcium levels in the soils of both clusters 1 and

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2 in the Lake Liambezi maize farming area should be reduced and continuously monitored. The excessive present calcium value should be neutralised using various organic fertilisers, and avoiding acidic fertilisers, and the application of mulch is once again an important avenue. The calcium fertiliser application should not exceed 100kg/ha.

- √ **Nitrogen** – The optimal nitrogen content for maize farming is 2,000 ppm, yet cluster 1 and 2 soils exhibit excessively high concentrations (3268–2860 ppm), leading to nutrient imbalances, delayed maturity, and increased lodging risk (Dahiya, Kumar, Chaudhary, & Chaudhary, 2018). To mitigate these effects, incorporating cover crops and organic matter will absorb excess nitrogen, enhance soil structure, and prevent leaching. Crop rotation and diversification will further balance soil nutrients, thereby improving maize productivity and ensuring long-term soil health. These sustainable practices optimise nitrogen use while promoting resilient agricultural systems (Bashir et al., 2013).
- √ **Electrical Conductivity** – For optimal plant growth, soil electrical conductivity (EC) should be maintained within the range of 800 – 2500 µS/cm (do Moraes Gatti et al, 2023). Low EC levels can signal nutrient deficiencies, whereas elevated EC levels typically indicate salt buildup or inadequate drainage. To prevent salinity issues and promote healthy root growth, irrigate with low-salt water, avoid excessive watering, and maintain good drainage. Adding organic matter also improves soil structure, reduces compaction, and increases nutrient availability, thus helping maintain balanced soil fertility.

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ANNEXES

ANNEX 1: DETAILED SOIL LABORATORY TEST RESULTS FOR STUDY SITES

A. Cluster 1A

Site	Identification Segment	pHw	ECw µS/cm	OM %	P ppm	K ppm	Ca ppm	Mg ppm	Na ppm	Texture	Sand %	Silt %	Clay %
Site 1	A1	6.66	180	1.94	0.0	277	3079	140	25	Loamy sand	84.1	10.4	5.5
	A2	7.30	216	1.49	0.0	693	4279	231	28	Sandy loam	66.7	23.8	9.4
Site 2	A1	6.23	1352	2.34	0.0	780	1939	198	307	Loamy sand	44.1	35.0	20.8
	A2	5.40	797	2.04	11.5	554	3098	177	159	Clay	35.8	5.9	58.3
Site 3	A1	6.73	443	1.56	0.0	384	3677	69	246	Loamy sand	79.7	15.2	6.0
	A2	8.04	582	1.79	22.4	922	44	88	199	Sandy loam	66.8	22.0	11.3
Site 4	A1	7.49	658	1.92	35.9	452	4666	226	154	Sandy clay loam	48.9	27.5	23.6
	A2	7.70	1065	1.45	42.9	595	203	265	105	Loam	50.1	33.2	16.7
Site 5	A1	7.75	402	1.86	2.2	680	4609	198	106	Sandy clay	52.2	4.3	43.5
	A2	7.71	924	2.14	10.4	913	163	221	168	Sandy clay	55.3	3.1	41.6
Site 6	A1	7.67	1472	1.81	0.0	860	4819	267	335	Loam	42.5	43.5	14.0
	A2	6.91	950	1.62	0.0	773	289	246	724	Loam	45.9	36.6	17.5
Site 7	A1	7.23	538	1.88	0.0	718	4228	212	217	Clay loam	29.6	42.9	27.5
	A2	7.53	487	1.96	0.0	873	4949	250	138	Clay loam	48.0	2.6	48.5
Site 8	A1	8.79	182	1.09	0.0	447	3207	94	268	Loam	75.3	16.5	8.2
	A2	8.34	183	1.21	2.4	442	3289	88	371	Loamy sand	79.9	13.3	6.9
Site 9	A1	8.39	168	1.15	0.0	196	3329	104	382	Loamy sand	81.6	6.3	12.2
	A2	8.31	125	1.26	0.0	95	3268	70	93	Sand	87.4	9.1	3.5
Site 10	A1	7.71	360	1.90	8.5	797	4974	226	15	Sandy loam	51.7	29.5	18.8
	A2	7.93	894	2.36	7.9	2230	5114	270	61	Loam	40.3	38.4	21.3
Site 11	A1	7.38	203	2.12	4.9	838	3954	264	29	Silty loam	28.4	50.4	21.2
	A2	6.97	155	1.60	4.4	741	3944	244	17	Loam	36.2	42.7	21.1
NOTE: A1 - Topsoil A2 - Subsoil													

Source: MAFWLR (2024)

Cluster 2A

Site	Identification Segment	pHw pHw	ECw µS/cm	OM %	P ppm	K ppm	Ca ppm	Mg ppm	Na ppm	Texture	Sand %	Silt %	Clay %
Site 12	A1	7.38	304	1.65	7.7	696	4874	266	8	Loam	39.9	37.0	23.1
	A2	7.54	335	1.67	0	696	4404	240	20	Clay loam	37.0	34.6	28.4
Site 13	A1	7.16	151	1.52	0	751	4194	251	17	Clay loam	31.5	35.2	33.3
	A2	7.93	285	1.71	0	726	4742	245	47	Loam	42.9	33.2	23.8
Site 14	A1	8.16	179	1.56	6.2	519	4254	233	0	Sandy loam	61.9	24.6	13.5
	A2	8.41	198	1.49	9.2	367	4553	260	0	Sandy loam	61.4	19.8	18.8
Site 15	A1	8.19	208	1.32	11.7	647	4005	225	0	Sandy loam	65.3	23.4	11.3
	A2	8.41	97	0.90	13.9	225	2054	177	0	Loamy sand	83.5	9.1	7.4
Site 16	A1	8.03	558	1.49	1.4	323	4084	96	0	Loamy sand	82.1	12.3	5.6
	A2	7.44	217	1.32	0	403	4514	123	0	Loamy sand	76.6	17.9	5.5
Site 17	A1	5.10	1463	2.60	0.9	685	4674	219	4	Silty loam	25.0	60.2	14.8
	A2	5.80	1278	2.01	3.1	591	4573	101	16	Silty loam	33.8	54.6	11.6
Site 18	A1	6.34	312	1.74	1	583	4500	268	5	Clay loam	21.8	48.4	29.8
	A2	6.56	224	2.02	0	580	2603	346	144	Silty loam	19.8	56.1	24.1
Site 19	A1	7.05	256	1.80	11.2	667	2694	270	205	Loam	42.4	36.9	20.7
	A2	7.34	185	1.75	2.4	419	2123	102	74	Sandy loam	69.6	18.6	11.8
Site 20	A1	4.69	1511	2.82	0	558	2911	213	679	Loam	35.8	1.2	63.0
	A2	4.43	1417	2.10	12.4	583	3354	158	150	Silty loam	36.6	50.1	13.3
Site 21	A1	6.87	531	2.09	3.3	664	4232	306	189	Loam	44.8	43.1	12.1
	A2	7.41	545	2.26	0	573	4260	304	214	Sandy clay	45.1	12.5	42.4
NOTE: A1 - Topsoil A2 - Subsoil													

Source: MAFWLR (2024)

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B. Cluster 1B

Site	Identification Segment	pHw	ECw µS/cm	OM %	P ppm	K ppm	Ca ppm	Mg ppm	Na ppm	Texture	Sand %	Silt %	Clay %
Site 1	B1	6.81	169	1.30	3.8	197	4194	342	795	Clay loam	38.3	23.7	38.0
	B2	7.60	260	1.37	5.3	263	3824	204	267	Sandy loam	68.9	16.6	14.5
Site 2	B1	5.37	987	1.77	135.0	385.0	3752	313	428	Loam	45.4	39.2	15.4
	B2	6.76	744	1.71	14.0	498.0	4311	395	489	Loam	40.8	37.1	22.1
Site 3	B1	7.16	412	1.27	19.0	169.0	211	117	9	Loamy sand	79.3	13.9	6.8
	B2	7.47	474	1.56	0.0	544.0	3693	171	261	Sandy loam	64.7	24.3	11.0
Site 4	B1	7.26	960	1.44	41.5	147.0	4094	360	695	Sandy clay	44.8	16.6	38.6
	B2	7.64	243	1.44	10.9	166.0	3281	118	85	Loamy sand	80.9	9.1	10.0
Site 5	B1	6.98	425	1.67	5.4	372.0	3870	314	441	Clay loam	30.3	35.2	34.5
	B2	7.04	467	2.01	1.3	324.0	3621	190	518	Sandy loam	71.3	14.7	14.0
Site 6	B1	6.57	555	1.64	4.0	291.0	3510	341	515	Clay loam	41.0	31.4	27.6
	B2	8.12	159	0.88	16.3	142.0	3396	82	0	Loamy sand	84.0	7.4	8.6
Site 7	B1	7.53	531	1.54	13.8	584.0	3980	355	299	Silty clay loam	20.1	46.6	33.3
	B2	7.42	501	1.92	12.3	607.0	4105	366	342	Clay loam	31.1	39.1	29.8
Site 8	B1	8.14	155	1.03	13.5	138.0	2926	96	66	Loamy sand	85.6	6.1	8.3
	B2	8.27	160	1.18	14.8	138.0	3144	87	64	Loamy sand	81.6	10.0	8.4
Site 9	B1	8.34	139	0.73	6.2	64.0	2673	64	27	Sand	90.3	5.0	4.7
	B2	8.49	162	1.18	17.0	32.0	3194	61	14	Sand	89.0	7.5	3.5
Site 10	B1	7.54	220	1.31	8.1	161.0	3302	168	73	Sandy clay loam	50.9	25.5	23.7
	B2	7.15	1071	2	0.0	621	4183	355	525	Loam	42.6	34.7	22.7
Site 11	B1	7.09	247	1.78	3.1	483	3570	404	141	Clay	25.9	38.9	35.2
	B2	5.85	200	1.5	0.0	421	3234	301	137	Clay	21.1	40.1	38.8
NOTE: B1 - Topsoil B2 - Subsoil													

Source: MAFWLR (2024)

C. Cluster 2B (40250 – 40269)

Site	Identification	pHw	ECw	OM	P	K	Ca	Mg	Na		Texture	Sand	Silt	Clay
	Segment		µS/cm	%	ppm	ppm	ppm	ppm	ppm			%	%	%
Site 12	B_1	6.69	256	1.60	0.0	402	3962	21	293		Clay	28.2	23.2	48.6
	B_2	7.11	253	1.36	0.0	667	3924	401	220		Clay	32.5	29.8	37.7
Site 13	B_1	6.55	282	1.47	0.0	499	3894	437	219		Clay	23.4	21.1	55.5
	B_2	7.44	335	1.61	0.0	357	3745	352	312		Sandy clay	47.5	6.1	46.4
Site 14	B_1	7.86	120	0.71	0.0	72	1460	139	39		Sand	88.5	3.7	7.9
	B_2	8.05	252	1.04	0.0	214	3373	301	89		Sandy clay loam	59.0	16.4	24.6
Site 15	B_1	8.12	70	0.55	0.0	64	942	16	3		Sand	90.6	5.6	3.8
	B_2	7.67	100	0.47	0.0	105	1570	120	38		Loamy sand	85.6	4.4	10.0
Site 16	B_1	8.40	331	0.80	0.0	103	2620	3	11		Loamy sand	85.1	7.8	7.1
	B_2	8.74	152	0.75	0.0	87	2633	40	0		Sand	90.5	6.9	2.6
Site 17	B_1	5.14	1680	1.70	0.0	417	4281	449	326		Clay	32.6	12.7	54.6
	B_2	5.69	1090	1.66	0.0	789	4290	317	318		Loam	45.8	34.8	19.4
Site 18	B_1	6.69	181	1.50	0.0	546	3334	353	58		Sandy clay loam	18.9	51.4	29.7
	B_2	6.44	446	1.60	0.0	496	3543	431	202		Clay loam	20.8	50.9	28.3
Site 19	B_1	7.48	205	1.60	0.0	103	2871	131	73		Sandy loam	64.5	24.1	11.3
	B_2	7.01	256	1.55	0.0	450	3100	305	155		Loam	35.4	41.2	23.3
Site 20	B_1	4.45	1654	2.43	0.0	715	3603	264	787		Silt loam	37.7	57.7	4.6
	B_2	4.42	1182	1.92	0.0	744	3351	27	216		Silt loam	31.9	52.8	15.3
Site 21	B_1	6.36	537	1.60	0.0	628	4390	300	3		Sandy clay	47.9	9.7	42.4
	B_2	7.62	571	1.97	0.0	1079	4496	334	120		Sandy clay	44.9	10.0	45.1
NOTE: B1 - Topsoil B2 - Subsoil														

Source: MAFWLR, (2025)

D. NITROGEN CONTENT: CLUSTER 1A – 1B AND 2A - 2B

Site	Identification	g/kg	ppm (1g/kg = 1000 ppm)	Site	Identification	g/kg	ppm (1g/kg = 1000 ppm)	Site	Identification	g/kg	ppm (1g/kg = 1000 ppm)	Site	Identification	g/kg	ppm (1g/kg = 1000 ppm)
	Segment				Segment				Segment				Segment		
Site 1	A1	1.0	1000	Site 12	A1	0.4	400	Site 1	B_1	2.8	2800	Site 12	B_1	3.5	3500
	A2	2.0	2000		A2	2.3	2300		B_2	1.5	1500		B_2	2.6	2600
Site2	A1	4.1	4100	Site 13	A1	2.3	2300	Site2	B_1	6.0	6000	Site 13	B_1	2.2	2200
	A2	5.6	5600		A2	1.9	1900		B_2	1.9	1900		B_2	1.1	1100
Site 3	A1	1.4	1400	Site 14	A1	1.4	1400	Site 3	B_1	1.2	1200	Site 14	B_1	0.4	400
	A2	1.9	1900		A2	1.4	1400		B_2	1.1	1100		B_2	1.3	1300
Site 4	A1	6.0	6000	Site 15	A1	1.4	1400	Site 4	B_1	2.7	2700	Site 15	B_1	0.4	400
	A2	6.5	6500		A2	0.5	500		B_2	1.0	1000		B_2	0.3	300
Site 5	A1	4.5	4500	Site 16	A1	0.8	800	Site 5	B_1	2.4	2400	Site 16	B_1	0.6	600
	A2	6.9	6900		A2	0.9	900		B_2	2.3	2300		B_2	0.4	400
Site 6	A1	3.4	3400	Site 17	A1	5.4	5400	Site 6	B_1	1.8	1800	Site 17	B_1	5.1	5100
	A2	2.7	2700		A2	2.4	2400		B_2	0.6	600		B_2	1.5	1500
Site 7	A1	3.8	3800	Site 18	A1	1.6	1600	Site 7	B_1	2.5	2500	Site 18	B_1	2.3	2300
	A2	7.6	7600		A2	2.3	2300		B_2	4.9	4900		B_2	2.1	2100
Site 8	A1	1.0	1000	Site 19	A1	1.9	1900	Site 8	B_1	0.8	800	Site 19	B_1	1.2	1200
	A2	0.8	800		A2	1.2	1200		B_2	0.7	700		B_2	1.9	1900
Site 9	A1	0.9	900	Site 20	A1	8.2	8200	Site 9	B_1	0.5	500	Site 20	B_1	10.6	10600
	A2	0.8	800		A2	8.5	8500		B_2	0.8	800		B_2	7.4	7400
Site 10	A1	1.0	1000	Site 21	A1	6.3	6300	Site 10	B_1	1.1	1100	Site 21	B_1	4.7	4700
	A2	5.6	5600		A2	6.1	6100		B_2	2.9	2900		B_2	6.0	6000
Site 11	A1	2.6	2600					Site 11	B_1	1.9	1900				
	A2	1.8	1800						B_2	1.9	1900				
NOTE: A1 & B2 - Topsoil A2 & B2 - Subsoil															

Source: GIZ (2025)

ANNEX 2: NUTRIENT RECOMMENDATIONS

Parameter	Optimum Range	Unit	Author
Soil Organic Matter, SOM	5	%	Du *et al.*
Phosphorus, P	25 - 70	ppm	Warncke, Dahl, and Jacobs
Potassium, K	40 -120	ppm	Muthaura
Calcium, Ca	100 - 400	ppm	do Moraes Gatti *et al.*
Magnesium, Mg	25 - 45	ppm	Horneck *et al.*
Sodium, Na	40	ppm	do Moraes Gatti *et al.*
Nitrogen, N	2,000 (2)	ppm (g/kg)	GIZ
Electrical Conductivity, EC	800 - 2,500	µS/cm	do Moraes Gatti *et al.*