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Optimizing sunflower production through the use of GIS-based soil fertility management strategy

Emmanuely Z. Nungula^a , Boniface J. Massawe^b, Luciana R. Chappa^c, Daniel M. Nhunda^b, Mahmoud F. Seleiman^d, Nawab Ali^e and Harun I. Gitari^b 

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ABSTRACT

This study aimed to use a GIS-based approach in producing soil fertility maps and utilize the spatial data on achieving site-specific management of major nutrients in Morogoro, Tanzania. Soil samples were collected in six mapping units and analyzed for chemical properties such as pH, cation exchange capacity and electrical conductivity. ArcGIS 10.8 was used to produce nutrient variability maps of organic carbon, available P, total nitrogen and exchangeable K, Ca and Mg using the Inverse Distance Weight (IDW) interpolation method. The soil pH values ranged from 5.5 to 7.2. OC varied between 1.2 and 4.9g kg⁻¹, TN ranged from low to medium (1.0 to 5.0g kg⁻¹) whereas Av. P varied between 13.3 and 14.3mg kg⁻¹. Exchangeable K, Ca and Mg had ranges (in cmol kg⁻¹) of between 0.1 to 0.8 (low to medium), 3.8 to 15.6 (low to high) and 0.3 to 0.5 (low), cmol kg⁻¹. The recommended amounts were 74, 44, 36, 35 and 12kg ha⁻¹ for N, P₂O₅, K₂O, MgO and CaO, respectively. Conducting soil analysis is key for monitoring the amount of nutrients that are available in the soil at time and space, to achieve site-specific nutrient management.

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1. Introduction

To ensure food security for the rapidly expanding population, addressing the major challenge of declining soil fertility in the 21st century through technological means is necessary (Moges & Ajanaw, 2020). Poor land management brought about by unethical farming methods, such as incorrect fertilizer application rates, crop residue removal and subpar farming technologies, greatly accelerates the problems associated with low nutrient levels. These practices also lead to a decrease in the nutrient contents of the soils, which ultimately lowers crop yields (Gitari et al., 2019; Moges & Ajanaw, 2020). Furthermore, inefficient land management drives up the cost of agricultural inputs, making the adoption of cutting-edge technological fertilizer programs necessary for sustainable crop productivity (Nungula, Mugwe, Massawe, & Gitari, 2024; Raza et al., 2023). Embracing

this need for soil nutrient spatial distribution maps can aid in recommending the proper application of fertilizer (Cheptoek et al., 2021; J. N. Mugo et al., 2020). Effective monitoring of any changes in cropping systems over time is ensured by the mapped soil nutrients.

The availability and accessibility of soil maps and nutrient status maps go hand in hand with the use of GIS technology in precision farming, which gives farmers critical knowledge about soil types, climates and farming economics to make informed decisions (Veysel et al., 2023). Based on the agronomic requirements of the particular crop, a fertilization map can be created using GIS using this information to assist farmers in managing their farms (Jiyun & Cheng, 2002; Johnston et al., 2009). While maintaining the long-term sustainability of the land, precise management seeks to maximize yield potential and guarantee cost-effectiveness in crop production

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(Cheptoek et al., 2022; Maitra et al., 2023). Site-specific nutrient management techniques, according to Veysel et al. (2023), operate on three fundamentals. To obtain information on the current soil fertility status before making any decisions regarding land use or management, a key component of precision farming is the assessment of soil variability (Maitra et al., 2024; Ming, 2010; Misbah et al., 2021; Smaling et al., 1993; Xin, 2009). For this reason, soil variability assessment is an essential step in precision farming. Many accessible methods exist today that have been widely used in precision farming to evaluate and produce data on spatial variation (Otieno et al., 2023). One such technology that helps us manage soil variability in the field is GIS. It allows us to evaluate soil variation and provide recommendations for managing the variability that is specific to each site (Jiyun and Cheng 2002; Rao, 2009; Singh, 2001).

Numerous studies (Kamau et al., 2015; J. W. Mugo et al., 2016; Otieno et al., 2022) have shown that GIS technology is a useful collection of tools for gathering, storing, retrieving, transforming and displaying spatial data. Numerous scientists have employed it to accomplish natural resource management (J. W. Mugo et al., 2016; Nungula et al., 2023; Ogodo, 2018). To achieve site-specific nutrient management programs for precise fertilizer application, GIS is beneficial because it can process a variety of geospatial data and modeling for agricultural development. This can be achieved through the production of soil nutrient maps, which help to give a high insight into the spatial variability of nutrients within a field (Otieno et al., 2022; Verma et al., 2020). Furthermore, according to Waswa et al. (2020), GIS enables accurate mapping of the spatial distribution of farms and soil fertility. Notably, a soil fertility map informs the various stakeholders about the available nutrients, guiding them in making decisions about the management of the soil. This allows planners and the farming community to make decisions based on the limitations of the land's sustainable use and the quality of the soil (Nyawade et al., 2019; Verma et al., 2020).

Utilizing contemporary technologies like remote sensing and geographic information systems (GIS) can help achieve site-specific nutrient management (SSNM), a technique that matches the right amount of nutrients to plants to best meet their needs (Hengl et al., 2021; Nungula, Massawe, et al., 2024; Rao, 2009; Verma et al., 2020). Achieving the site-specific applications of fertilizers and soil amendments to maximize yield requires this kind of intervention (Rao, 2009; Verma et al., 2020). Due to its ability to maximize fertilizer use efficiency, reduce nutrient

losses and facilitate farm planning and management, this technique is essential (J. N. Mugo et al., 2020; Singh, 2001). The information used in the SSNM operational system is the set of data produced by contemporary technology, such as GIS, and will ultimately yield site-specific fertility trend data, which is essential information for attaining precision farming (Otieno et al., 2022; Sarkar et al., 2017; Verma et al., 2020).

GIS-based soil fertility management is a cutting-edge approach to field management that uses specific fields as a homogeneous group of soil when calculating nutrient or fertilizer requirements to meet a given unit's fertilization program (J. W. Mugo et al., 2016; Tashayo et al., 2020). Thus, the soil nutrient spatial distribution maps serve as a foundation for implementing future site-specific nutrient management programs and aid in forecasting the necessary management techniques (AbdelRahman et al., 2018; Nungula, Mugwe, Massawe, & Gitari, 2024). Therefore, to identify the soil nutrient-related constraints limiting sunflower production on the farm, an attempt has been made in the current study to create GIS-based soil fertility maps for various major nutrients. In the end, to maximize sunflower production, a recommendation regarding the site-specific fertility management program is made (Kamau et al., 2015; Nungula et al., 2023).

The sunflower industry in Tanzania presents numerous prospects for enhancing livelihood through the production of essential and valuable oils with significant domestic and international markets (Chappa et al., 2023; Ugulumu & Inanga, 2014). Tanzanian smallholder farmers are estimated to be growing sunflowers for 4 million people (Cleaver et al., 2010). Every year, there is a growing need for edible oil for both industrial and domestic use (Ceballos et al., 2017; Food and Agriculture Organization, 2017). The primary crop that yields edible oil is sunflower, hence it's essential to Tanzania's edible oil supply. Despite Tanzania having a large arable land, and favorable agroecological zones, such opportunities for sunflower exploitation have not been fully utilized. Research indicates that nations like Tanzania that have a relative benefit in agricultural production could become self-sufficient in food commodities by increasing soil fertility (Akhtar et al., 2012; Nungula, 2024). In light of this, increasing production productivity could help to close the significant edible oil deficit caused by rising demand, which would in turn help to lower the amount of edible oil imported (Arouna et al., 2017; Cleaver et al., 2010). Increasing domestic production of

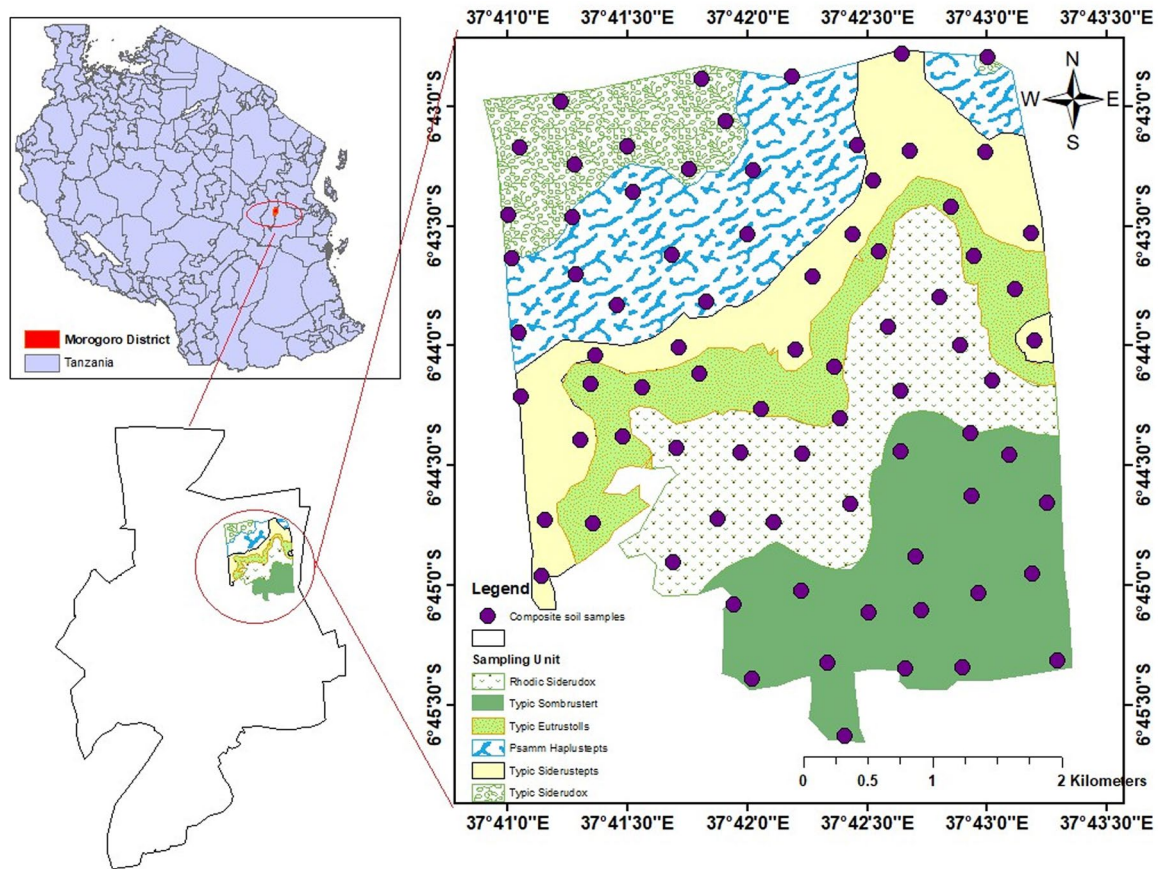


Figure 1. Study area map showing the six mapping units and sampling locations (dots).

edible oil in Tanzania may eventually result in raising agricultural productivity.

The study aimed to examine the soil fertility status in Tungi Farm whose production of sunflower has been established, and to map out the distribution of the nutrients. The nutrient spatial variation maps generated were used in generating site-specific nutrient programs in different sites. It is anticipated that stakeholders will make recommendations and provide advice to farmers regarding the area most suitable for sunflower production as well as any existing constraints that will help in achieving maximum yields and thereby enhancing the crop's potential for production. Developing site-specific nutrient management in various farm units for the effective development of a fertilizer program, will help lessen the region's demand for edible oil and meet oil demand while increasing farmers' income.

2. Methodology

2.1. Study area

The study was carried out in Morogoro District, Tanzania at Tungi Farm, centered at the latitude

Table 1. Parameter and method used for laboratory analysis.

Parameter	Method	References
pH	pH meter	Bremner (1996)
Electrical Conductivity (EC)	Potentiometric method	Bremner (1996)
Total Nitrogen (TN)	Kjeldahl digestion method	Ryan et al. (2011)
Organic Carbon (OC)	Walkley-Black method	Nelson & Sommers (1996)
Av. P and Exchangeable bases (Ca, Mg, K and Na)	Mehlich-3 method (using ICP-OES)	Mehlich (1978); Jackson, (1967)
Fe, Cu, Zn and Mn	Diethylenetriaminepentaacetic acid (DTPA)	Okalebo et al. (2002)
CEC	Ammonium acetate (NH ₄ OAc) method	Chapman (1965)

ranging between 6° 43'0" and 6° 45'30"S and the longitude from 37° 41'0" to 37° 43'30" E (Figure 1). Farm occupies 2000-hectare farmed by smallholder farmers. The Farm experiences two rain seasons the long seasons valid from early March to May with heavy rainfall, and from November to January for the shorter, lighter seasons. The area receives an average precipitation and temperature of 770 mm per year, and 25.1°C on an annual basis

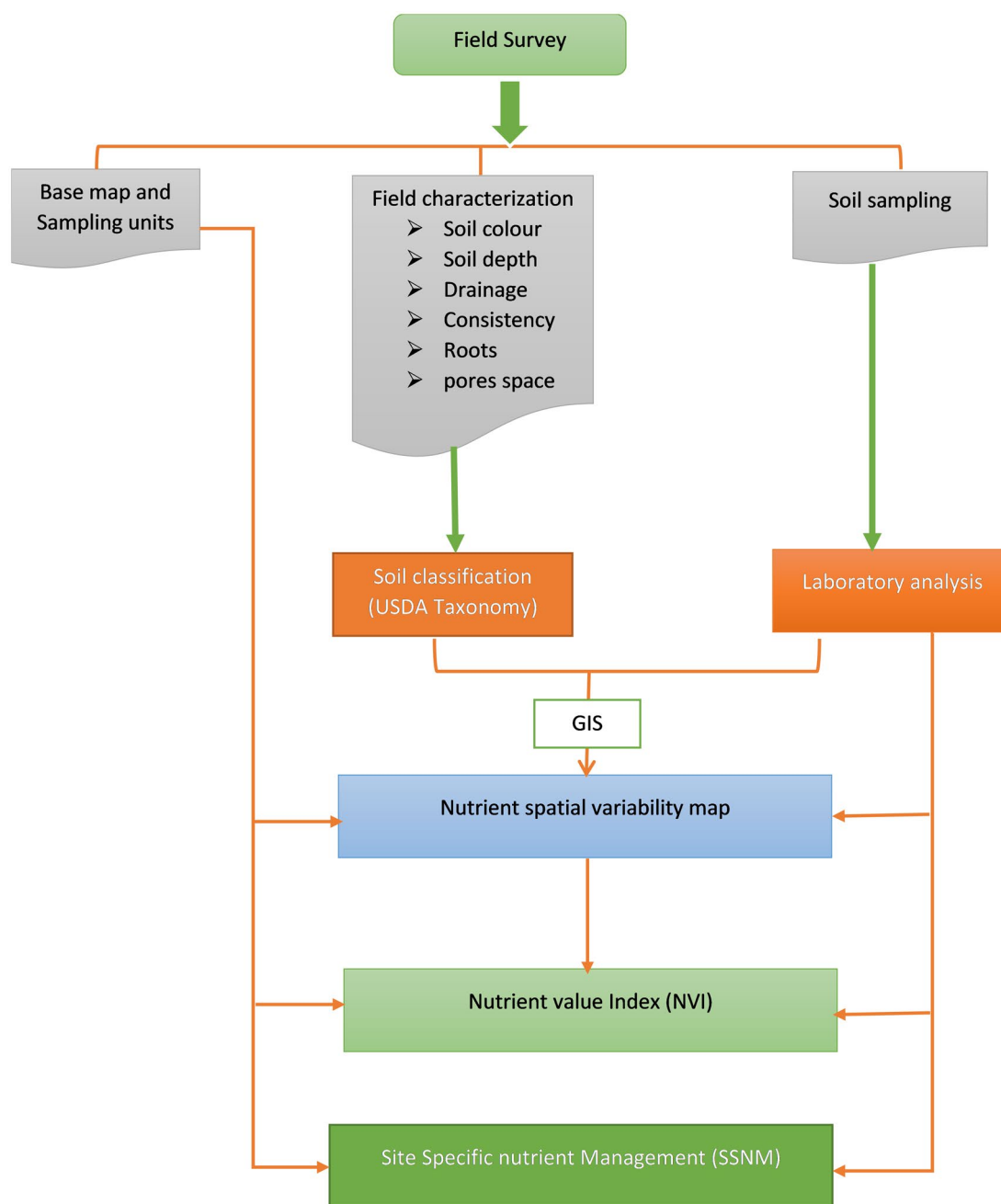


Figure 2. Systematical flow for production of soil nutrient map.

Table 2. Nutrient converting factor.

Element	Oxide form	Converting factor
Calcium (Ca)	CaO	1.3992
Magnesium (Mg)	MgO	1.2912
Phosphorus (P)	P ₂ O ₅	2.2916
Potassium (K)	P ₂ O	1.2046

Source: Al-Mishwat (2016).

respectively. The Vertisols, Oxisols, Mollisols and Inceptisols characterized by Sand and loam-textured soils predominate in the study area. Grass, shrubs, shrubs, lower forest cover and scattered woodlands are the most prevalent vegetation types on the

farm. The primary socioeconomic factor is agricultural production.

2.2. Soil sampling

A reconnaissance survey was carried out to determine the farm's location and the main landform features. Farm boundaries were marked with points and key leads using a GARMIN Extrex 20 GPS. With ArcGIS 10.8, a base map with a 90m spatial resolution was created. Based on the subgroup level of USDA Soil Taxonomy, six mapping units were identified: Rhodic

Table 3. Bulk density (0–15 cm) and corresponding weight of soil per hectare.

Soil unit	Horizon	BD (g cm ⁻³)	BD (kg m ⁻³)	Soil volume (m ³ ha ⁻¹)	Soil weight (kg ha ⁻¹)
Rhodic Siderudox	Ah	1.23	1230	1500	1845000
Typic Sombrustert	Ah	1.37	1370	1500	2055000
Typic Eutrustolls	Ah	1.22	1220	1500	1830000
Psamm Haplustepts	Ah	1.21	1210	1500	1815000
Typic Siderustepts	Ah	1.26	1260	1500	1890000
Typic Siderudox	Ah	1.36	1360	1500	2040000

BD= Bulk density.

Table 4. Sunflower plant's nutrient uptake and removal in the study area.

Nutrient	Uptake kg ha ⁻¹	Removal with grains
N	125	74
P ₂ O ₅	44	24
K ₂ O	90	36
CaO	84	12
MgO	35	8

Siderudox, Typic Sombrustert, Typic Eutrustolls, Psamm Haplustepts, Typic siderustepts and Typic Siderudox (Figure 1). To obtain composite samples for each mapping unit, soil samples were taken at a depth of 0 to 30 cm using the zigzag method. For analysis, 80 soil composite samples were gathered in the field. Geographical coordinates (latitude and longitude) from each sampling location were also noted during the soil sampling process. The composite samples were taken to Kenyatta University Soil Laboratory for analysis.

2.3. Laboratory analysis

Soil pH was determined using a pH meter with a 1:2.5 ratio of soil/water while Electrical conductivity was assessed using the potentiometric method by measuring the electrical resistance of a 1:2 soil: water suspension in an air-dried sample (Bremner, 1996) (Table 1). Kjeldahl digestion method was used for total nitrogen determination (Ryan et al., 2011). Soil Organic Carbon (OC) analysis was performed by the Walkley-Black method (Nelson & Sommers, 1996). Available phosphorus was measured by UV-vis spectrophotometer (Mehlich, 1978). The Flame Photometry method was used for exchangeable bases (potassium and sodium) while Atomic Absorption Spectrophotometry was employed for the evaluation of calcium and magnesium (Jackson, 1967). Cation Exchange Capacity (CEC) was measured by the ammonium acetate method (Chapman, 1965). Diethylenetriaminepentaacetic acid (DTPA) was used for extraction of Fe, Cu, Zn and Mn, which finally were detected in the Atomic Absorption Spectrophotometer (Okalebo et al., 2002).

2.4. Statistical analysis

Statistical analysis was done from the laboratory results of soil nutrients by involving descriptive statistics using GenStat 15.

2.5. Production of soil nutrient maps

Based on geographical coordinates (latitude and longitude) taken during the soil sampling process and soil nutrient results from soil analysis, soil nutrient maps were prepared in ArcGIS 10.8 using the IDW interpolation method. Soil nutrient values were classified with different colors during the production of the soil nutrient spatial distribution map (Figure 2). Nutrient Index Value (NIV) was computed to evaluate the soil's nutritional status as described by Otieno et al. (2022) using Equation (1).

$$NIV = \frac{(X*1) + (Y*2) + (Z*3)}{TNS} \quad (1)$$

where; X, Y and Z denote the number of samples in the low, medium and high categories, respectively. TNS=Total number of samples. The nutrient index value for each nutrient was computed and the obtained value was then ranked as described by Parker et al. (1951). In this case, the value < 1.67 is classified as low, 1.67–2.33 as medium and > 2.33 as high.

2.6. Site-specific nutrient management for sunflower production

The average nutrient plant nutrients from each of the six mapping units were calculated based on the soil test values obtained during the laboratory analysis to generate site-specific nutrient recommendations (Figure 1). While cmol kg⁻¹ for the exchangeable base was converted into mg kg⁻¹ using the formula (Equation (2)) as stated by Deenik (2005), total nitrogen was converted from g kg⁻¹ to mg kg⁻¹. Except for nitrogen, values in mg kg⁻¹ were multiplied by their corresponding factors to convert them into their oxide forms (Table 2). The weight of the soil per hectare was then multiplied by 106 to convert the

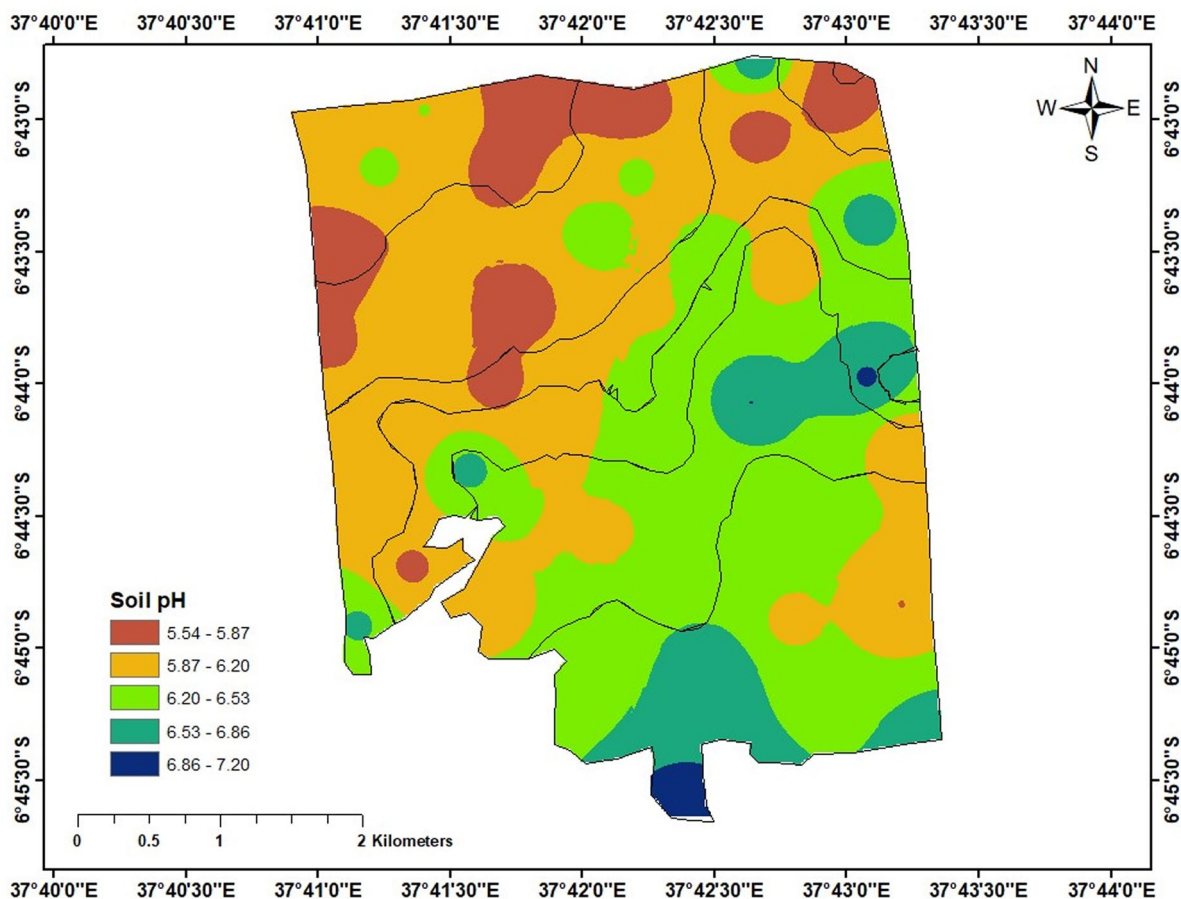
Table 5. Descriptive statistics of soil chemical properties (N=80).

Property	Min	Max	Mean	Std. dev	Std. error	CV (%)	Skewness	Kurtosis
pH	5.86	6.49	6.19	0.24	0.10	4.00	-0.29	-1.51
EC	0.2	0.37	0.25	0.06	0.03	26.00	2.05	4.37
CEC	3.16	4.41	3.61	0.46	0.19	4.00	1.23	0.93
OC	3.57	4.07	3.79	0.18	0.07	11.00	0.54	0.48
TN	4.72	6.16	5.11	0.56	0.23	5.00	1.81	3.2
Av. P	0.41	0.57	0.49	0.07	0.03	11.00	0.16	-2.17
Exch. K	7.3	11.28	9.43	1.34	0.55	20.00	-0.46	0.86
Exch. Ca	0.31	0.38	0.35	0.02	0.01	14.00	-0.87	0.74
Exch. Mg	6.19	6.93	6.64	0.26	0.11	7.00	-1.1	1.33
Exch. Na	0.27	0.35	0.29	0.03	0.01	7.00	1.35	1.24
Cu	1.87	3.3	2.4	0.58	0.24	24.00	0.66	-1.05
Zn	15.32	17.72	16.63	0.99	0.4	6.00	-0.16	-2.22
Fe	172	236	198.67	24.99	10.2	13.00	0.36	-0.99
Mn	160	209	188.17	19.19	7.83	9.00	-0.68	-1.26

Table 6. Nutrient index values for soil samples in Tungi Farm, Morogoro District.

Soil property	Rhodic Siderodox	Typic Sombrustert	Typic Eutrastolls	Psamm Haplustepts	Typic Siderustepts	Typic Siderodox
OC	1.33 <i>l</i>	1.00 <i>l</i>	1.16 <i>l</i>	1.00 <i>l</i>	1.10 <i>l</i>	1.33 <i>l</i>
TN	2.00 <i>m</i>	2.00 <i>m</i>	1.83 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>
Av. P	1.14 <i>l</i>	1.00 <i>l</i>	1.00 <i>l</i>	1.00 <i>l</i>	1.00 <i>l</i>	1.00 <i>l</i>
K	2.00 <i>m</i>	2.28 <i>m</i>	2.14 <i>m</i>	1.29 <i>l</i>	1.85 <i>m</i>	2.00 <i>m</i>
Ca	2.29 <i>m</i>	3.00 <i>h</i>	2.28 <i>m</i>	1.86 <i>m</i>	2.18 <i>m</i>	2.57 <i>h</i>
Mg	1.00 <i>l</i>	1.10 <i>l</i>	1.14 <i>l</i>	1.2 <i>l</i>	1.00 <i>l</i>	1.00 <i>l</i>
Na	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>
Fe	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>
Mn	2.1 <i>m</i>	2.17 <i>m</i>	2.17 <i>m</i>	2.13 <i>m</i>	2.14 <i>m</i>	2.18 <i>m</i>
Cu	1.72 <i>m</i>	1.5 <i>l</i>	1.58 <i>l</i>	1.67 <i>m</i>	1.5 <i>l</i>	1.64 <i>m</i>
Zn	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>	2.00 <i>m</i>

h = High, *m* = Medium, and *l* = Low, Rating is according to Otieno et al. (2022).

**Figure 3.** pH distribution at Tungi Farm.

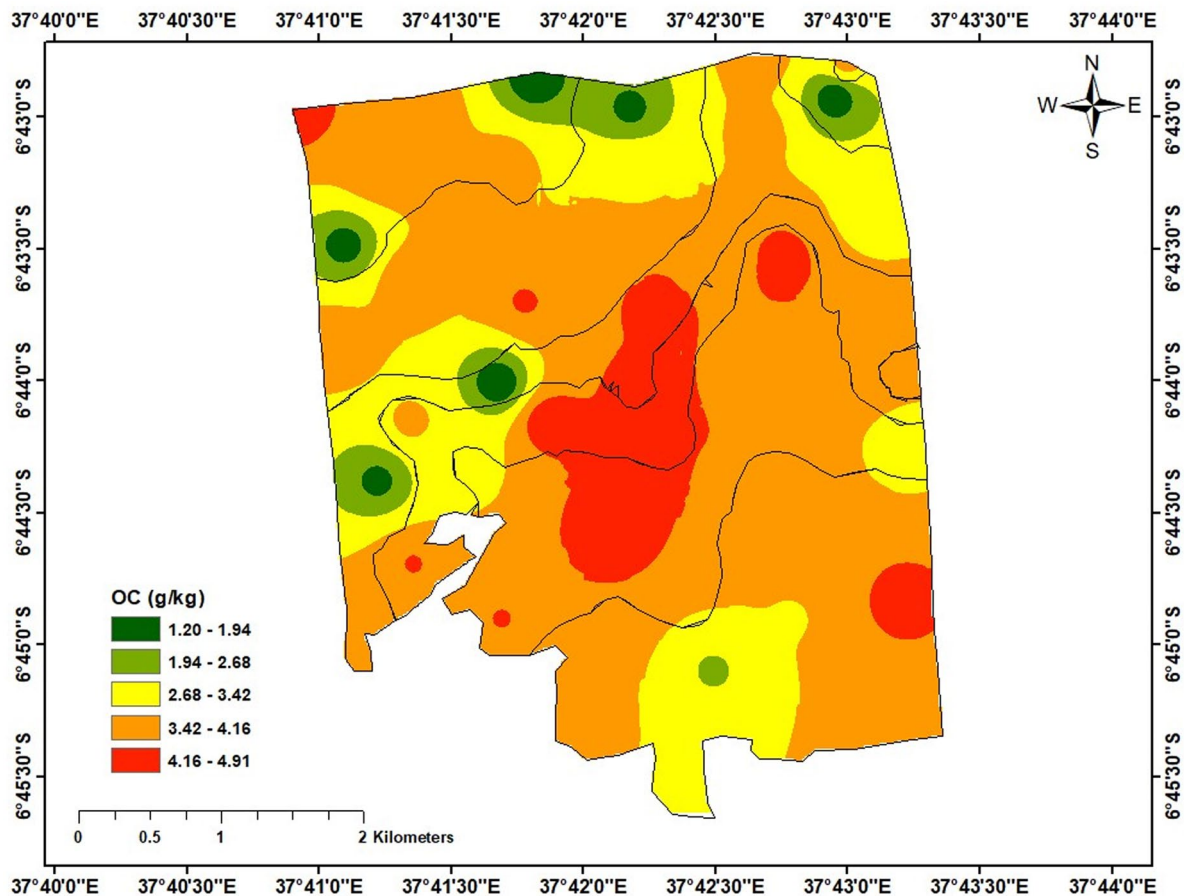


Figure 4. Organic carbon distribution at Tungi Farm.

values to kg ha^{-1} . The proper weight of the mapping unit was determined using the bulk density (Table 3) for each mapping unit in the plow depth.

$$\text{mgkg}^{-1} = \text{cmolkg}^{-1} * \text{Ew} * 10 \quad (2)$$

Recommendation of nutrients was done based on the plant's nutrient uptake and removal by sunflower as shown in Table 4. For instance, if the value presented is very low to low, the recommended value must be equal to the crop uptake. If the present value is medium the recommended value must be equal to crop removal, if the present value is high to very high, the recommended value must be equal to 0.5 and 0.25 for crop removal, respectively and if the present value is excessively high on recommended value is given (Bender et al., 2015).

3. Results

3.1. Descriptive statistics of soil chemical properties

The nutrient trend shows the range of pH values from 5.86 to 6.49 (Table 5). Electrical conductivity had a

range of between 0.2 and 0.37 dS m^{-1} whereas CEC ranged from 3.16 to 4.41 cmol kg^{-1} . The OC and TN had ranges of 3.57–4.07 and 4.72–6.16 g kg^{-1} , respectively. Av. P ranged from 0.41 to 0.57 mg kg^{-1} whereas Exch. K, Ca, Mg, Na and had ranges (in cmol kg^{-1}) of 7.3–11.28, 0.31–0.38, 6.19–6.93 and 0.27–0.35, respectively. In addition, the farm had soil with Cu, Zn, Fe and Mn with ranges of 1.87–3.3, 15.32–17.72, 172–236 and 160–209 mg kg^{-1} .

The nutrient index value (NIV) shows the uniform and non-uniform trend of nutrients in the six soil units; OC, Av. P and Mg revealed a low nutrient index value in all units with a value of less than 1.67: OC (1.00 to 1.33), Av. P (1.00 to 1.14) and Mg (1.00 to 1.14), implying a low nutritional amount of these nutrients in the soil. TN, Na, Fe, Mn, Zn and K show medium nutrient index values ranging between 2.00 and 2.29. Calcium shows a different trend with high NIV in Typic Sombrustert and Typic Siderudox and medium NIV in the remaining units (Table 6). The implication of NIV is to indicate the nutritional status of each soil nutrient for making strategies for managing those with low nutritional status (low NIV) (Otieno et al., 2022).

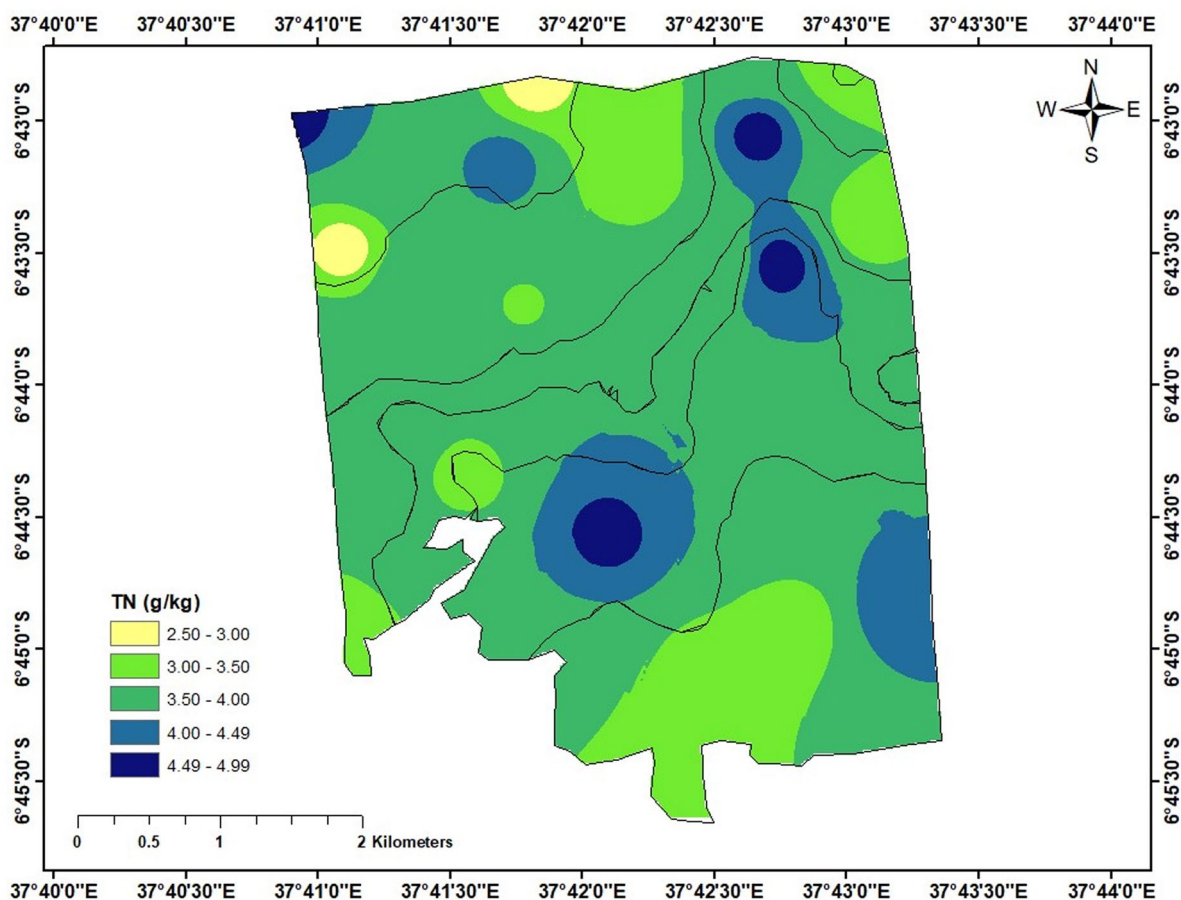


Figure 5. Total nitrogen distribution at Tungi Farm.

3.2. Major soil nutrient spatial variation

3.2.1. Soil pH

The Tungi Farm's soil pH ranges from 5.54 (moderately acidic) to 7.2 (neutral), with a mean of 6.28 (slightly acidic) (Figure 3). The pH value is in favor of sunflower production because it cannot restrict the availability of other nutrients, such as phosphorus, and is considered adequate for sunflower production (Kalala et al., 2017). According to J. W. Mugo et al. (2016), soil pH affects plant uptake of nutrients from the soil and gives previous information about fertility status.

3.2.2. Organic carbon

According to Nyawade et al. (2019), organic carbon (OC) serves as a bank to hold nutrients that are typically released gradually for plant uptake while giving soil microbes energy and nutrients. Furthermore, according to Kalala et al. (2017), OC is the most important factor to take into account when locating the ideal land for crop production. Tungi Farm's soil organic carbon (OC) ranges from 1.2 to 4.91 g kg⁻¹, with an average of 3.5 g kg⁻¹, considered low (Figure 4). According to Nyawade et al. (2019), the low level

of OC is caused by insufficient fertilizer addition to replace the lost nutrients.

3.2.3. Total nitrogen (TN)

The farm's TN values were rated as medium, averaging 3.51 g kg⁻¹, with a range of 1.00 g kg⁻¹ (low) to 5.00 g kg⁻¹ (medium). The nitrogen trend in the study area suggests that the fertilizer program was not implemented properly because not enough fertilizer was added to replace the nitrogen lost as a result of frequent and prolonged cultivation, the removal of crop residue, and water leaching (Gitari et al., 2017; Hailu et al., 2015; Heydarzadeh et al., 2023) (Figure 5).

3.2.4. Available phosphorus

According to Marx et al. (1999), the area's available phosphorus ranged from low to medium (3.34 to 14.34 mg kg⁻¹), with an average of 6.28 mg kg⁻¹ (Figure 6). Phosphorus is a vital component of plants that helps them perform photosynthesis, which is the process by which they transform solar energy into food, fiber and oil as well as energy

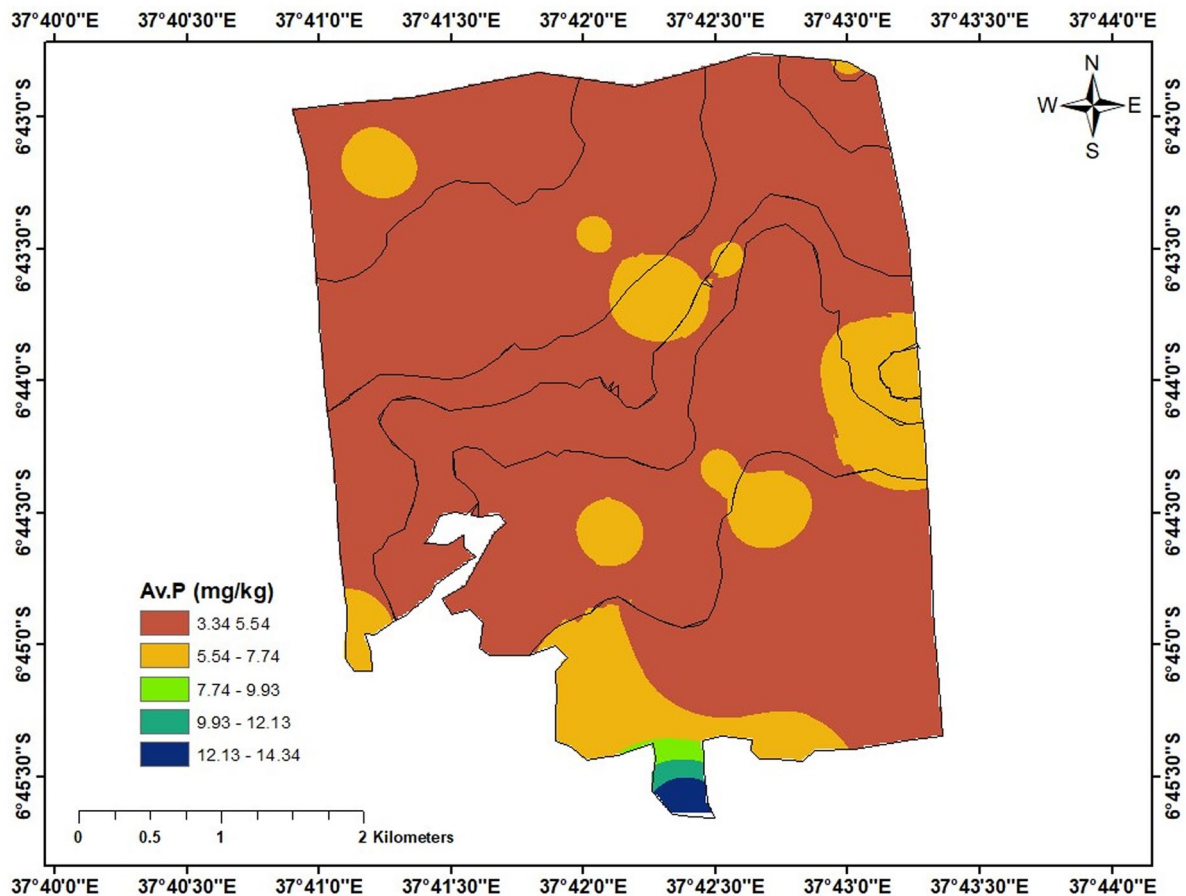


Figure 6. Available phosphorus distribution at Tungi Farm.

storage and transfer and sugar metabolism. To achieve the best sunflower production in the study area, fertilizer addition is therefore necessary to address the current low-level status of this nutrient (Fullen and Catt, 2005; Gitari et al., 2019).

3.2.5. Potassium

The potassium values were found to be low to medium, ranging from 0.14 to 0.84 cmol kg^{-1} , (Marx et al., 1999) (Figure 7). In addition to aiding in photosynthesis, potassium affects how chemicals and water are absorbed by and circulated throughout the plant. Thus, ensuring this element is absorbed efficiently is crucial (Gitari et al., 2019; J. N. Mugo et al., 2020).

3.2.6. Exchangeable calcium

The exchangeable Ca of Tungi Farm shows spatial distribution from 3.60 to 15.59 cmol kg^{-1} cmol and is rated as medium (Figure 8) (Marx et al., 1999). According to Landon (2014) and Kalala et al. (2017), a medium level of exchangeable Ca is favorable for crop production since a higher level of Ca may limit phosphorus availability in the soil for plant uptake.

3.2.7. Exchangeable magnesium

The farm's exchangeable magnesium is rated as low (Figure 9) and exhibits spatial variability ranging from 0.25 to 0.45 cmol kg^{-1} . Large concentrations of calcium in the soil are linked to low magnesium levels, which can lead to magnesium deficiency and impair crop productivity (Tenga et al., 2018).

3.3. Available nutrients

Nutrient available shows that total nitrogen, rated medium with the value of 3.57, 3.86, 3.64, 3.79, 4.07 and 3.75 g kg^{-1} for Rhodic Siderodox, Typic Sombrustert, Typic Eustrustolls, Psamm Haplustepts, Typic Siderustepts and Typic Siderodox, respectively (Table 8). Available P is rated low in all units with the values ranging from 4.72 mg kg^{-1} for Typic Siderodox to 6.16 mg kg^{-1} for Rhodic Siderodox. Exchangeable K-rated medium Rhodic Siderodox, Typic Sombrustert, Typic Eustrustolls, Typic Siderustepts and Typic Siderodox with the value of 0.57, 0.56, 0.45, 0.41 and 0.41 cmol kg^{-1} , respectively while Psamm Haplustepts rated low (0.33 cmol kg^{-1}) (Table 6). Exchangeable Ca was 11.28 cmol kg^{-1} rating high for Typic Sombrustert and low for

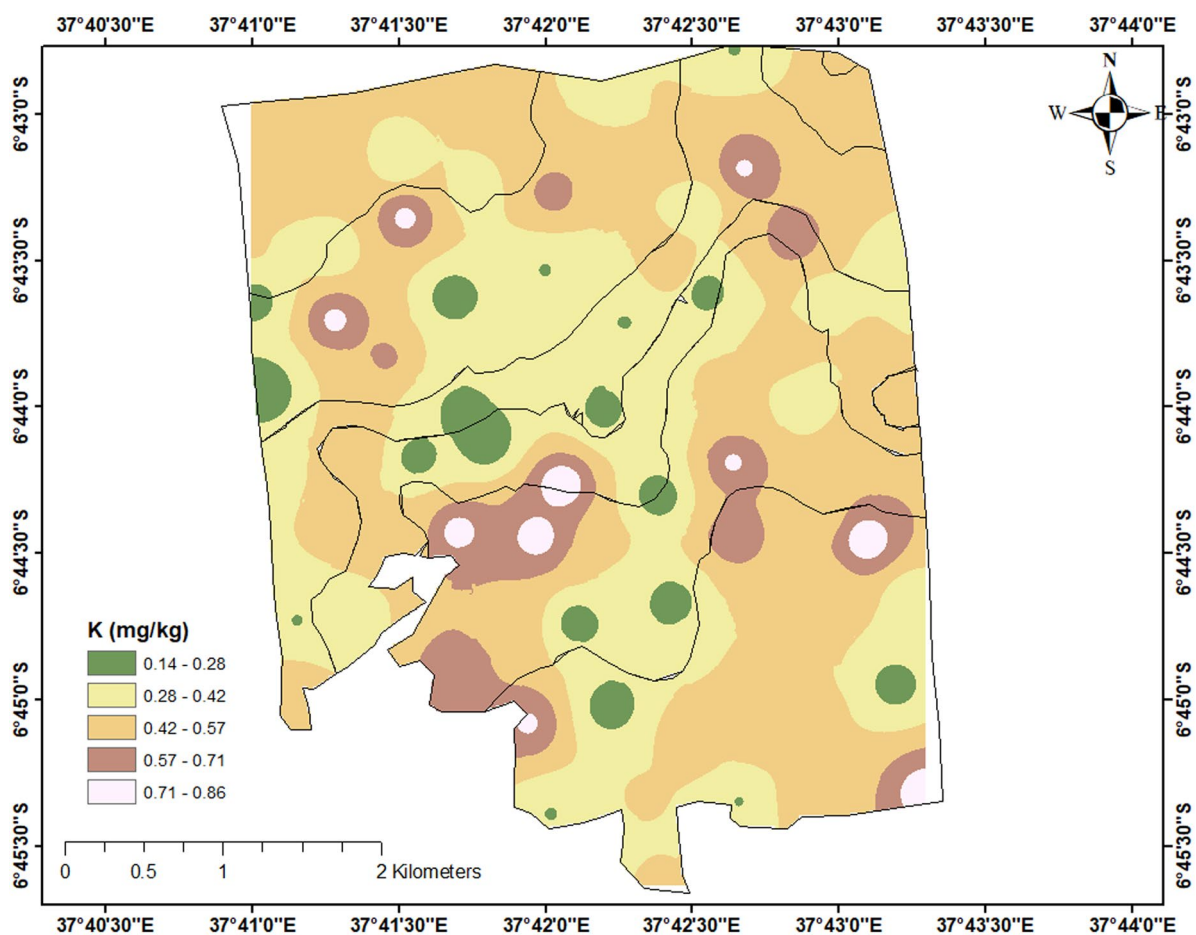


Figure 7. Spatial variability map for potassium.

Rhodic Siderodox, Typic Eustrustolls, Psamm Haplustepts, Typic Siderustepts, and Typic Siderodox with values of 9.70, 8.65, 7.30, 9.73 and 8.93 cmol kg^{-1} , respectively. Exchangeable Mg was low in all units between 0.31 and 0.38 cmol kg^{-1} . Soil test results reveal that some nutrients were not at optimum levels to support sunflower plant growth and reduce its potential yields. Nutrient available shows that nitrogen, Exch. K, and Exch. Ca were generally medium except for one mapping unit (Rhodic Siderodox) that had high Exch. Ca. Exch. Mg and Av. P were low, and K was low to medium (Marx et al., 1999).

Topsoil element results were then converted to milligrams per kilogram (Table 7), the bulk density of the areas, and their corresponding soil weight per hectare (Table 8). The soil results in milligrams per kilogram were used to convert the nutrients available into kilograms per hectare (Table 9).

3.4. Nutrient recommendations for sunflower

The nutrient recommendation for sunflowers in each sampling unit is given in Table 10. In achieving

site-specific recommendations, it is vital to place the correct amount of nutrients as per the crop's need with much consideration of the nutrients that already exist in the soil (Cottenie, 1980; Otieno et al., 2022). Whenever the present value is observed to be very low to low, the recommended value ought to be equal to the crop's nutrient uptake. If the present value is medium, the recommended value must be equivalent to the crop's nutrient removal. Finally, if the present value is high to very high, the recommended value must be equal to 0.5 and 0.25 for crop removal, respectively and if the present value is excessively high no recommendation is given (Tisdale et al., 1999; Bender et al., 2015).

4. Discussion

The farm mapping units' chemical properties differ from one another. This may be explained by the fact that some regions have seen very little crop cultivation and that management techniques have changed since the lands were first used for the production of

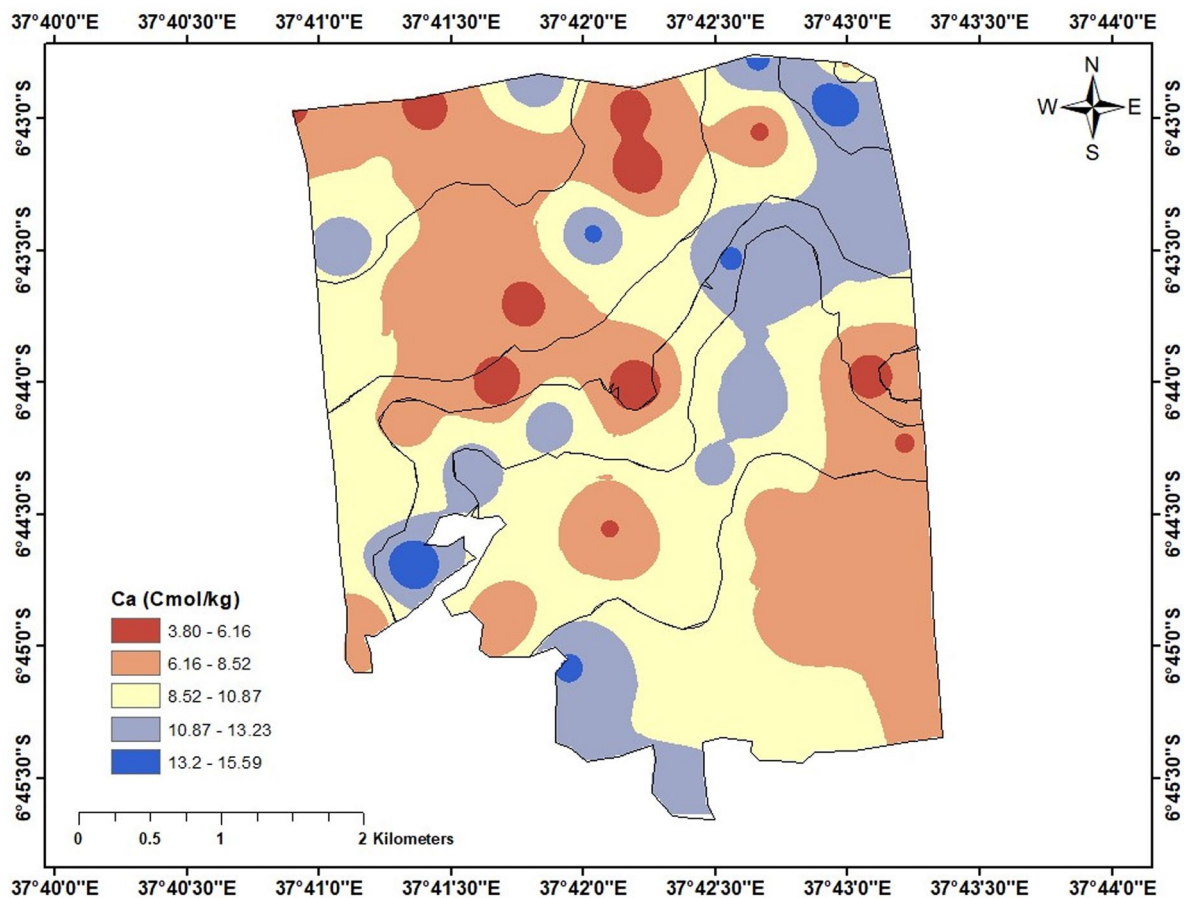


Figure 8. Calcium distribution at Tungi Farm.

sisal before people started cultivating them for food. This is mostly because the areas have grown and are being utilized for food production due to population pressure (Murungweni et al., 2016; Seleiman et al., 2021). Furthermore, the ongoing use for crop production has caused the soil's nutrient levels to decline (Mirriam et al., 2023; Yousaf et al., 2017). The farm's soils were generally moderately to slightly acidic. Furthermore, the farm's soils lacked sufficient amounts of organic carbon and readily available phosphorus. This might be explained by the high temperatures and little to no organic matter added to the soils, which accelerates the rate at which organic matter decomposes (Nyawade et al., 2019; Rahimi et al., 2023). Furthermore, since organic matter contributes significantly to the P pool, low OC levels in the soils may also be linked to low available P levels (Nasar et al., 2021; Sahoo et al., 2024). The percentage of nitrogen added to the soil increases as organic carbon increases. The soil in the medium contained K, Ca, Fe, Mn, Na and Zn in medium concentrations while Cu was in low levels.

According to Ochieng' et al. (2021) and Parecido, Soratto, Perdoná, Gitari, et al. (2021), among other

factors, the type of soil and its nutrient status affect the amount of nutrients that crops, including sunflowers, require. Using the nutrient uptake and removal approach, the fertilizer program was created (Pariera & Jones, 2021). The amount of nutrients in the soil, plant uptake, and the amount of nutrients removed that the crop required were all taken into account. Laboratory soil analysis provided a reference for the nutrient thresholds needed by sunflower plants. This cutoff point was used to calculate the amount of nutrients that would be required for the soil to produce at its best. The suggested action was taken to address the soils' deficiencies in available P, magnesium and organic carbon. To build the soil levels, available phosphorous and magnesium were recommended at the rate of 44 kg ha⁻¹ and 35 kg ha⁻¹ respectively. Supplies of phosphorus (P) roughly at the rate between 35 to 45 kg P₂O₅ ha⁻¹ are needed by sunflower crops (Njira & Nabwami, 2015). Furthermore, according to Alberio et al. (2015), the crop needs secondary macronutrients like calcium (Ca) and magnesium (Mg) for growth, so the supply of magnesium that is deficient is quite a vital process to accomplish.

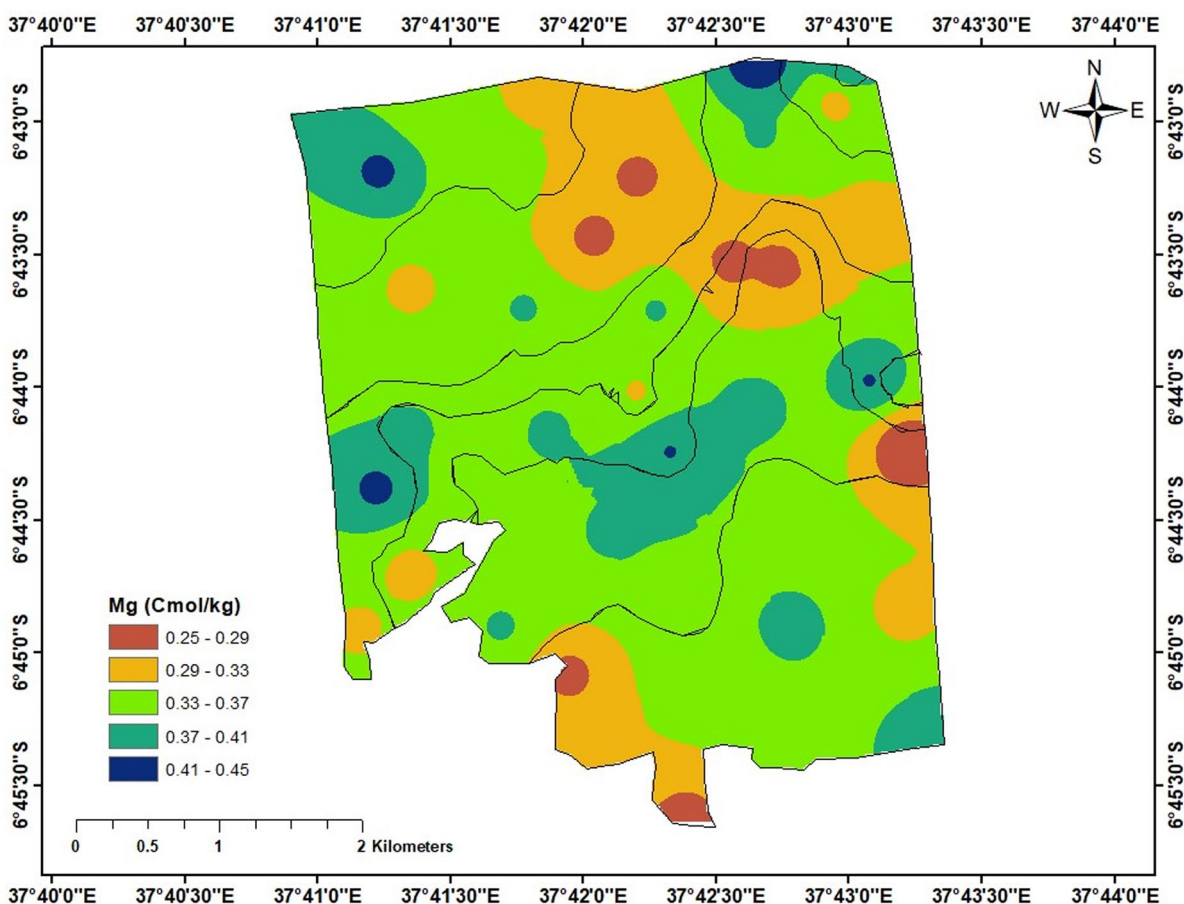


Figure 9. Magnesium distribution at Tungi Farm.

Table 7. Topsoil (0–15 cm) elements as analyzed at Tungi Farm.

Soil unit	TN (g kg ⁻¹)	Av. P (mg kg ⁻¹)	K	Mg	Ca
			(cmol kg ⁻¹)		
Rhodic Siderudox	3.57	6.16	0.57	0.34	9.70
Typic Sombrustert	3.86	4.75	0.56	0.38	11.28
Typic Eustrustolls	3.64	4.96	0.45	0.37	8.65
Psamm Haplustepts	3.79	4.78	0.33	0.36	7.30
Typic Siderustepts	4.07	5.27	0.41	0.35	9.73
Typic Siderudox	3.75	4.72	0.51	0.31	8.93

Table 8. Nutrients available per hectare at Tungi Farm.

Soil unit	N	P ₂ O ₅	CaO	K ₂ O	MgO
	mg kg ⁻¹				
Rhodic Siderudox	3570	14.12	2714	267.78	52.68
Typic Sombrustert	3860	10.89	3157	263.08	58.88
Typic Eustrustolls	3640	11.37	2421	211.41	57.33
Psamm Haplustepts	3790	10.95	2043	155.03	55.78
Typic Siderustepts	4070	12.08	2723	192.62	54.23
Typic Siderudox	3750	10.82	2499	239.59	48.03

Plant development and production potential are negatively impacted by deficiencies in any of the aforementioned essential nutrients (Mugo et al., 2021; Brady & Weil, 2008). Because different nutrient elements have a functional role in enhancing the biochemical processes occurring within plants, soil

fertility is therefore a crucial component of crop production (Alhammad et al., 2023; Ochieng' et al., 2023). Additionally, farmers will need to apply manure in the soil to address the low organic carbon levels before planting. Manure can also help increase microbial activity, the soil's ability to hold water and

Table 9. Nutrients available per hectare at Tungi Farm.

Soil unit	N	P ₂ O ₅	K ₂ O	CaO	MgO
	kg ha ⁻¹				
Rhodic Siderudox	6586.65	26.05	494.05	5007.33	97.19
Typic Sombrustert	7932.30	22.38	540.63	6487.64	121.00
Typic Eustrustolls	6661.20	20.81	386.88	4430.43	104.91
Psamm Haplustepts	6878.85	19.87	281.38	3708.05	101.24
Typic Siderustepts	7692.30	22.83	364.05	5146.47	102.49
Typic Siderudox	7650.00	22.07	488.76	5097.96	97.98

Table 10. Present values of the macronutrients and their recommendation for Rhodic Siderudox.

Soil unit	Amount	N	P ₂ O ₅	K ₂ O	MgO	CaO
		(kg ha ⁻¹)				
Rhodic Siderudox	Present	6586.85 <i>m</i>	26.05 <i>l</i>	494.05 <i>m</i>	97.19 <i>l</i>	5007.33 <i>m</i>
	Recommended	74	44	36	35	12
Typic Sombrustert	Present	7932 <i>m</i>	22.38 <i>l</i>	540.63 <i>m</i>	121 <i>l</i>	6487.64 <i>h</i>
	Recommended	74	44	36	35	12
Typic Eustrustolls	Present	6661.2 <i>m</i>	20.81 <i>l</i>	386.88 <i>m</i>	121 <i>l</i>	4430.43 <i>m</i>
	Recommended	74	44	36	35	12
Psamm Haplustepts	Present	6878.85 <i>m</i>	19.87 <i>l</i>	281.38 <i>l</i>	101.24 <i>l</i>	3708.05 <i>m</i>
	Recommended	74	44	90	35	12
Typic Siderustepts	Present	6766.2 <i>m</i>	22.83 <i>l</i>	364.05 <i>m</i>	102.49 <i>l</i>	5146.47 <i>m</i>
	Recommended	74	44	36	35	12
Typic Siderudox	Present	7650 <i>m</i>	22.07 <i>l</i>	488.76 <i>m</i>	97.98 <i>l</i>	5097.96 <i>m</i>
	Recommended	74	44	36	35	12

h = high, *m* = medium and *l* = low.

nutrients, and address the low levels of organic carbon in the soil (Alkharabsheh et al., 2023; Parecido, Soratto, Perdoná, Gitari, et al., 2021). Phosphorus and magnesium-containing fertilizers must be included in the fertilizer program because the area's soil did not contain enough of these nutrients to meet the crop's requirements. Fertilizer recommendations aim to balance soils and address the nutrient requirements of sunflower crops (Parecido, Soratto, Perdoná, Guidorizzi, et al., 2021). No fertilizer containing K and Ca should be added to the soil because the amounts of these nutrients in the soil were sufficient to meet the crop's nutrient requirements.

Using a GIS fertility map, data is produced as an essential tool for determining how well the soil can nourish plants and for organizing site-specific nutrient management in areas where nutrient availability is limited to maximize yield potential. By ensuring that fertilizer is applied precisely and in the right amount in each field, site-specific nutrient management lowers production costs while preserving the potential for land productivity (Kumar et al., 2019; Nungula, Mugwe, Massawe, Seleiman, et al., 2024; Oscar Kisaka et al., 2023). Tungi Farm is in the area with the greatest potential for sunflower production, according to the suitability analysis. Nevertheless, the nutrient had certain limitations that site-specific nutrient management techniques had to address. The results indicated that available phosphorus and exchangeable magnesium were lacking in some of

the six mapping units, and they suggested applying 44 and 35 kg ha⁻¹, respectively. Any number of synthetic fertilizers, including magnesium-containing ones like magnesium phosphate and triple super phosphate, could readily be added to meet this requirement.

Additionally, 74, 24 and 12 kg ha⁻¹ of extra nitrogen, exchangeable K, and calcium were required due to the medium level of all three. To attain a high sunflower yield, synthetic fertilizers containing the aforementioned nutrients at optimal levels should be applied. However, based on field observations, inter-graded soil fertility management may also be a practical option, particularly if it incorporates crop rotation, sunflower intercropping with legume crops, and the remaining crop residues (Gitari et al., 2019; Mirriam et al., 2022; Shao et al., 2023). By having an appropriate fertilizer application program, it will be possible to achieve high-yield sunflower production and close the demand gap in the region and the nation. This will be made possible by the data generated by this study on nutrient availability and site-specific nutrient management for sunflower production. The findings are consistent with that of Otieno et al. (2022), who used the Quantum Geographic Information System (QGIS) software to assess the soil fertility status in Nairobi's peri-urban counties (Kiambu, Kajiado and Machakos) to produce capsicums. The data was then used to generate a soil fertility map for the three counties, and a fertilizer

program for growing capsicums was then produced and developed using the sufficiency approach. Khadka (2018) mapped Chungbang Farm in Nepal and assessed the state of soil fertility. The soil had a high acidity level and low levels of organic matter (1.32%), N (0.08%) and Ca (512.5 mg kg⁻¹). P, Fe, Cu and Mn were extremely high in the soil, whereas K and Mg had medium fertility. The information was utilized to create a sustainable fertilizer management system. Also, similar research by Achoki and Gichaba (2015); J. W. Mugo et al. (2016); Forkuo and Nketia (2011); Nungula, Mugwe, Massawe, Seleiman, et al. (2024); Nungula, Massawe, et al. (2024), Isdory et al. (2021) and Mwendwa et al. (2019) using GIS IDW method in the production of fertility maps, aiming at assessing the suitability of the different sites for crop production and then recommending possible soil improvements and fertilizer recommendation to achieve high production.

5. Conclusion

The study area's soils were generally rated as medium on the fertility index because most nutrients were optimal, with the exception of nitrogen and organic carbon, which were deficient. Based on the soil fertility buildup, status and maintenance methodology, the site-specific nutrient recommendations for each unit were created for those nutrients whose interpreted value was rated low or medium during the soil test. Consequently, to enhance the yield of sunflower on the farm, it is prudent to contemplate methods of augmenting soil carbon, phosphorus and magnesium using organic manure/compost and the incorporation of magnesium phosphate fertilizer. Thus, it is advised that soil analysis be utilized as a method to assess the condition of the soil and to inform fertilizer recommendations. Farmers, county governments and other stakeholders would therefore find the study's conclusions helpful in their planning and decision-making processes, as well as to other researchers for future research.

Authors' contributions

The authors confirm contribution to the paper as follows: study conception and design were contributed by EZN, HIG, BHJM, LRC, MFS, DMN, NA and MFS; data collection was contributed by EZN, NA, BHJM, LRC, DMN and HIG; analysis and interpretation of results were contributed by EZN, BHJM, LRC, MFS, DMN and HIG; draft manuscript preparation was contributed by EZN, LRC, DMN, MFS, BHJM and HIG. All authors reviewed the results and approved the final version of the manuscript.

Disclosure statement

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Data availability statement

Data is available from the corresponding author upon reasonable request.

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