

Full Length Research Paper

Soil fertility status and nutrients content in maize (*Zea mays* L.) Tissue at Migna Kura in Wayu Tuka District, East Wollega, Ethiopia

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Soil fertility depletion hinders food production in Wayu Tuka District in East Wollega Zone, Ethiopia. This study assessed soil fertility status with correlation soil and maize ear leaf tissue test tools in Migna Kura Kebele by analyzed; 32 soils and maize ear leaf samples. The finding showed soil properties dominated by clay and clay loam textures, with the soil exposed strongly to slight acidic. Soil Cation Exchange Capacity (CEC) ranged from medium to very high; the essential nutrients, total nitrogen (N) and available phosphorus (P) ranged from extremely low to low. Nutrient deficiencies: maize ear leaf tissue analysis confirmed critical insufficiencies in N and P, alongside restricted deficiencies in zinc (Zn) and Boron (B). Conversely; maize ear tissue concentrations of Calcium (Ca), Magnesium (Mg), Sulfur (S), Iron (Fe), Manganese (Mn), and Copper (Cu) were generally adequate. Maize tissue analysis confirms these findings, showing insufficient levels of N and P, as well as confined to a small area deficiency in B and Zn, despite adequate concentrations of Fe, Mn, and Cu. The study concludes that soil acidity is the primary driver behind the deficiency of six yields limiting nutrients (N, P, Potassium (K), S, B, and Zn) and requires an integrated management approach that combines lime application, organic matter fortification, and site specific with crop response minerals application to restore productivity. To enhance crop productivity, the study advises integrated soil management involving lime application, organic matter incorporation, and NPKSB application to correct specific nutrient imbalances and acidic soil in the study area.

Key words: Soil fertility, macronutrients, micronutrients, maize ear tissue.

INTRODUCTION

Agriculture is the backbone of Ethiopia's economy, yet declining soil fertility remains a major constraint to

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sustainable crop production and food security. Widespread nutrient depletion caused by continuous productivity across many Ethiopian farming systems (Zelleke et al., 2019; Geremu et al., 2021). Although mineral fertilizers have been widely promoted, their effectiveness is often constrained by poor soil health conditions. National evidence indicates that long term farming without adequate nutrient replenishment through manure or compost has led to the loss of essential nutrients and reduced crop response to inputs. The Ethiopian highlands are facing declining soil fertility and severe erosion due to several factors: loss of organic matter, nutrient depletion, soil acidity, topsoil erosion, and poor physical soil properties. Intensive farming on steep land, complete removal of crop residues, and inadequate fertilizer use contribute to these challenges, significantly impacting crop productivity (Alemineh and Alemayehu, 2020; Laekemariam et al., 2016). Addressing this challenge requires an integrated soil fertility management approach that combines organic and inorganic inputs with effective soil and water conservation practices to ensure sustainable agricultural productivity in Ethiopia (Ethiopian Soil Information System (EthioSIS, 2016; Zelleke et al., 2019). Soil nutrient limitations in Ethiopia, fertilizer use has traditionally focused on nitrogen (N) and phosphorus (P) through Diammonium Phosphate (DAP) and urea, often neglecting other essential nutrients; however, recent studies indicate that this unbalanced approach limits crop response, as emerging evidence shows micronutrient deficiencies and site-specific nutrient variability are increasingly important constraints to productivity across Ethiopian farming systems (Erkossa et al., 2022).

Maize (*Zea mays* L.) is the most widely cultivated cereal in Ethiopia, facing productivity challenges due to declining soil fertility and nutrient imbalances. Farmers in western Ethiopia, especially East Wollega, report decreasing maize yields despite applying nitrogen and phosphorus fertilizers due to the depletion of basic cations (Calcium (Ca), Magnesium (Mg), Potassium (K)) and toxic acidic conditions. National soil studies EthioSIS (2015) show that, beyond nitrogen and phosphorus, deficiencies of sulfur, boron, zinc, and potassium, along with soil acidity, are widespread constraints to crop production. This challenge is intensified by the high nutrient demand of maize, which removes about 24 kg Nitrogen (N), 3 kg phosphorus (P), 23 kg K, 5 kg Ca, and 4 kg Mg per ton of grain produced, contributing to continuous nutrient mining under low input systems (Fageria et al., 2011). Several investigators (EthioSIS, 2014; EthioSIS, 2015) reported K deficiencies and micronutrients such as Boron (B), Copper (Cu) and zinc (Zn) (Wondwosen and Sheleme, 2011; EthioSIS, 2015). Consequently, in areas such as Western Ethiopia, including East Wollega, declining yields despite N and P fertilizer use highlight the need for balanced and soil acidity is increasing and basic cation such as Ca, Mg,

and K are deficient while acidic cations are at toxic level (Abdenna et al., 2007). Site-specific nutrient management based on comprehensive soil fertility assessments (EthioSIS, 2014; Erkossa et al., 2022). This has led to the causes of nutrient imbalance.

Site-specific soil fertility information for maize-growing fields in western Ethiopia remains limited, despite its importance for guiding effective nutrient management. Evaluating key soil physical and chemical properties is essential for selecting appropriate agricultural technologies, while plant tissue analysis provides direct information on crop nutrient status and helps identify existing deficiencies when combined with soil tests (Flynn et al., 2004). Soil testing is a practical tool for estimating available nutrient levels, enable farmers to determine suitable fertilizer types, application rates, and improve economic returns (Agegnehu et al., 2016). Although national soil fertility assessments have been conducted, more localized studies are still needed to support precise and sustainable nutrient management recommendations at the field level (EthioSIS, 2016; Jones, 2019). Declining soil fertility combined with the lack of site-specific fertilizer recommendations remains a major constraint to improving crop productivity in Ethiopia (Lelago et al., 2016). According to findings by Mintesinot (2024) in Migna Kura Kebele of Wayu Tuka District, East Wollega, the soils are severely constrained by multiple nutrient deficiencies, including N, P, K, sulfur (S), B, and Zn, in addition to soil acidity problems.

These constraints highlight a complex nutrient limitation scenario that cannot be effectively addressed through blanket fertilizer recommendations alone. In this context, reliance solely on soil analysis is insufficient, as it does not fully capture nutrient uptake and plant nutritional status under field conditions. Therefore, maize plant tissue analysis becomes critically important as a complementary diagnostic tool to confirm actual nutrient uptake and validate soil fertility status in the study area. However, in the study area, there is still weak integration between soil fertility assessment and plant tissue nutrient evaluation, resulting in a significant knowledge gap in understanding soil–plant nutrient interactions in maize-based farming systems. Consequently, farmers continue to apply generalized fertilizer recommendations that may not match the specific nutrient requirements of the soil–crop system, leading to low fertilizer use efficiency and declining yields. Hence, integrated assessment of soil fertility parameters and maize tissue nutrient concentration is essential for accurately identifying limiting nutrients and developing effective site-specific fertilizer recommendations. This study was conducted to assess selected soil fertility status and maize tissue nutrient concentrations, and to evaluate their relationship to generate evidence-based recommendations for sustainable soil fertility management in Migna Kura Kebele.

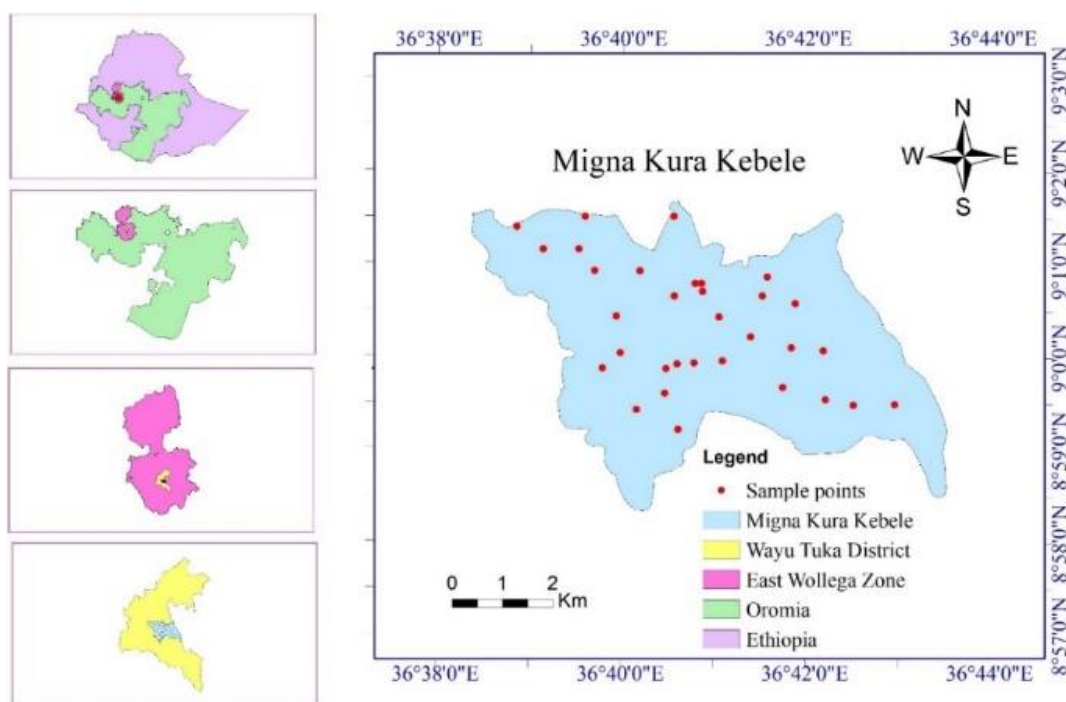


Figure 1. Location map of the study area and sample points.

MATERIALS AND METHODS

Study area

The study was conducted at Migna Kura Kebele in Wayu Tuka District, East Wollega Zone, Oromia Region, western Ethiopia. The district is located in the western highlands of Ethiopia, between 8°56'56"N to 9°07'49"N latitude and 36°32'38"E to 36°49'03"E longitude, with an altitude ranging from 1,300 to 3,140 meters above sea level. Migna Kura Kebele is situated about 5 km west of Gute town and 1 km south of Gaba Jimata town. The area is bordered by Wara Babo Migna and Gaba Jimata in the north, Gara Hudha in the south, Wali Galte in the east, and Gute Badiya in the west. According to WTWAO (2007) the altitude of the district ranges from 1300 to 3140 m.a.s.l. The area has favorable conditions for agriculture and is widely known for crop production, especially maize and other cereals. Figure 1 shows the location map of the study area and sample points.

Climate

The climate of the district is traditionally classified into three main agro-climatic zones: lowland, midland, and highland. Of the total landmass of the district, approximately 49.23% is midland ("Bada daree"), 37.66% is highland ("Baddaa"), and 13.16% is lowland ("Gammojjii"), as reported by WTWAO (2007). Thirteen years of climatic data (2006–2018) from Nekemte Meteorological Station indicate that the area has a unimodal rainfall pattern extending from April to October, with an average annual precipitation of 2,166.43 mm. The highest rainfall is received in June, July, and August. Mean monthly temperatures range from 11.93 to 28.21°C. Figure 2

presents the mean monthly rainfall and maximum and minimum temperatures of the study area (2006–2018).

Soil, land use and farming system

The topography of the study area ranges from very gently sloping to strongly sloping, as classified by Food and Agriculture Organisation (FAO) (2006b). Nitisols predominantly cover the western region of Ethiopia (Abebe, 2007). The soils at the study site are identified as Nitisol, which is the primary soil group found in most of the East Wollega zone, as referenced by Chimdi et al. (2012). The predominant land uses in the region include cultivated fields and grazing areas. The main annual crops cultivated under rain-fed conditions in this area consist of maize (*Z. mays* L.), pepper, and potato (*Solanum tuberosum* L.). The principal economic activities of the local population revolve around a mixed farming system. In Ethiopia, the nutrients typically utilized as fertilizers for crop production are nitrogen and phosphorus.

Site selection and soil and plant sampling

Migna Kura Kebele was purposively selected from Wayu Tuka District because it is one of the major maize-producing areas of the district. Following a preliminary survey on land use, topography, and field conditions, 32 representative maize-growing farmers' fields were selected using a stratified random sampling method from three zones: Gergo, Kilil, and Migna Kura. From each field, composite surface soil samples (0 to 20 cm depth) were collected during the maize flowering stage, while maize ear leaf samples were

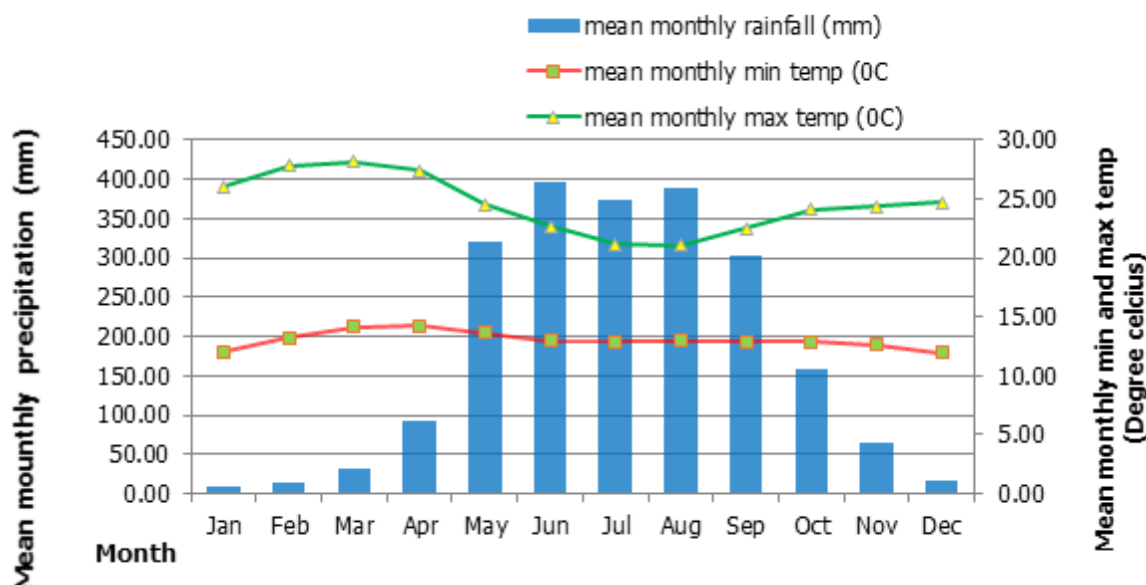


Figure 2. Mean monthly rainfall, max and min temperatures of the study area (2006 – 2018).

simultaneously taken for plant nutrient analysis. All sampling locations were geo-referenced using GPS, and samples were analyzed at the Nekemte Soil Research Center Laboratory. The soil physicochemical data used in this study were adopted from the findings of Mintesinot (2024), which reported that the soils of Migna Kura were acidic and deficient in six major yield-limiting nutrients, namely N, P, K, S, B, and Zn. To complement the soil results, maize ear leaf tissue analysis was included in the present study to directly assess plant nutrient status and nutrient uptake under field conditions. The combined use of soil and plant analysis provides a more reliable basis for diagnosing nutrient limitations and developing site-specific fertilizer recommendations for improved maize productivity.

Soil sample preparation and physicochemical analysis

Soil samples were air-dried at room temperature. The samples were ground using a pestle and mortar and passed through a 2 mm sieve for selected soil physicochemical analyses, while soil organic carbon (SOC) and total nitrogen (TN) were sieved using a 0.5 mm mesh. Soil texture, bulk density, pH, EC, organic carbon (OC), TN, available P, K, and micronutrients (Cu, Mn, Zn, Fe, and B), exchangeable bases (Ca^{2+} , Mg^{2+} , K^{+} , and Na^{+}), and cation exchange capacity (CEC) were analyzed at the Nekemte Soil Research Center. Soil texture was determined using the Bouyoucos hydrometer method (Day, 1965). After determining particle size distribution as percentages of sand, silt, and clay, soil textural classes were identified using the United States Department of Agriculture (USDA) soil textural triangle classification system, which is widely used for classifying soils based on the relative proportions of mineral particles (USDA, 2014). Soil bulk density (Bd) was determined from the weight of undisturbed core soil samples, which were first weighed at field moisture content and then oven-dried at 105°C until a constant weight was obtained (Baruah and Barthakur, 1998). Total porosity (TP) was estimated from bulk density (Bd) and particle density (Pd), expressed in Mg m^{-3} , with particle density assumed to be the

commonly used value of 2.65 g cm^{-3} , as follows:

$$\text{TP (\%)} = \left[1 - \left(\frac{\text{Pb}}{\rho_s} \right) \right] \times 100$$

Soil bulk density was determined by the undisturbed core sampling method and calculated by the following formula indicated by FAO (2006b):

$$\text{Pb} = \frac{(\text{wt.})}{V(\text{cm}^3)}$$

where Wt.=Weights of oven-dry soils (g) and V=The volume of the cylindrical core (cm^3).

The major soil chemical properties such as soil pH, OC, OM, TN, exchangeable acidity, exchangeable bases (Ca, Mg, Na and K), CEC, available P, available potassium, S, and available micronutrients (B, Cu, Mn, Zn, and Fe) were analyzed following the standard laboratory procedures. Soil pH measured potentiometrically in the supernatant suspension of 1:2.5, soil to water ratio as described by (Moberg, 2000). SOC content (OC%) was analyzed by the dichromate oxidation method as described by (Walkley and Black, 1934). Total nitrogen was determined by wet digestion followed by distillation and titration using the Kjeldahl method (Sahlemedhin and Taye, 2000). Available P was analyzed by the Bray II method; using 1Mole HCl and 1M NH_4F solutions as extract soil having pH values equal to 1.8 (Bray and Kurtz, 1945). Available potassium concentration was analyzed by $\text{CH}_3\text{COONa} \cdot 3\text{H}_2\text{O}$ solution extracted method. The soil exchangeable bases (Ca, Mg, K and Na) were determined by saturating the soil samples with 1M NH_4OAc solution at pH 7.0. Then, Ca and Mg were determined by using atomic adsorption spectrophotometer (ASS) while exchangeable Na and K were measured by flame photometer from the same extract as described by (Sahlemedhin and Taye, 2000). For the determination of CEC, the soil samples were leached with 1N ammonium acetate solution and washed with ethanol (97%) to remove excess salt followed by leaching with sodium chloride to

displace the adsorbed (NH_4^+). The quantity adsorbed of ammonia was then measured through the procedure of the micro-Kjeldahl methods, distillation, and titration with 0.1N NaOH as described by (Chapman., 1965; Sahlemedhin and Taye, 2000). Soil percent base saturation (PBS) was calculated by dividing the sum of the base forming cations (Ca^{2+} , Mg^{2+} , K^+ , and Na^+) to the CEC of the soil and multiplying by 100 (41):

$$\text{PBS} = \frac{100 \times (\text{Ca} + \text{Mg} + \text{K} + \text{Na})}{\text{CEC}}$$

Soil exchangeable acidity (Al^{3+} and H^+) was determined by saturating the soil sample with 1N KCl solution and titrating with 0.02 N NaOH as described by (Rowell, 1994). From the same extract, exch. aluminum (Al) was measured by titrating the solution samples with a standard solution of 0.02N HCl. The soil ECEC was determined by the summation of exchangeable bases and acidity according to Sahlemedhin and Taye (2000). Available micronutrients were extracted using diethylene tri amine penta acetic acid (DTPA) as described by Lindsay and Norvell (1978), and micronutrients in the extracts were determined using AAS at 248.3 nm, 279.5 nm, 324.7 nm, and 213.9 nm wavelength for Fe, Mn, Cu, and Zn, respectively. Soil available Boron was measured by calorimetrically using the Azomethine-H method with Ultraviolet (UV) spectro photometer according to (Gupta and Hettiarachchi, 1993). Available Sulfur concentration was extracted by mono calcium phosphate was determined through turbidmetrically using the barium sulfate precipitation method (Motsara and Roy, 2008). Available S content in the extract was determined turbid metrically and the turbidity was measured by a spectrophotometer at the wavelength of 420 nm.

Sampling and plant tissue analysis

Maize ear leaf samples were collected simultaneously from 32 farmers' plots at the same time as soil sampling. Leaf tissue samples were taken at the initiation of the flowering stage (early silking) following the methods described by Campbell and Plank (2000) and Ramulu and Raj (2012). Leaves were collected from 25 selected plants per plot, homogenized, and combined into one composite sample for each farmer's field using a two-diagonal sampling technique. Both plant and soil sampling points were geo-referenced using GPS. The maize leaf samples were washed with distilled water and oven-dried at 60 to 70°C until a constant weight was achieved. The dried samples were then ground and stored in paper bags for subsequent nutrient analysis. Leaf samples were analyzed using the dry ashing method. The samples were calcined in a muffle furnace at 550°C, dissolved in nitric acid, and filtered for nutrient determination. The analyzed nutrients included macronutrients (Ca, Mg, K, N, P, and S) and micronutrients (B, Fe, Mn, Cu, and Zn). TN was determined using the Kjeldahl digestion method as described by Sahlemedhin and Taye (2000). For the analysis of Ca, Mg, Mn, Fe, and Zn, ground samples were digested using concentrated HNO_3 and 30% H_2O_2 and measured with an Atomic Absorption Spectrophotometer. Phosphorus concentration was determined using a UV spectrophotometer, while potassium was measured using a flame photometer. Boron concentration was determined colorimetrically using the Azomethine-H method with a UV spectrophotometer, following Gupta and Hettiarachchi (1993). Total sulfur content was determined using the di-acid digestion method as described by Motsara and Roy (2008).

Data analysis and interpretation

Simple linear correlation analysis was performed to assess relationships among soil and maize tissue nutrient contents diagnosis of soil fertility status of the study area. The variation in soil properties were determined using the coefficient of variation (CV) based on rated of described as low (< 20%), moderate (20 to 50%) and highly variable (>50%) according to Amuyou et al. (2013) rating described. Data analyzed were performed using Microsoft excel and statistical package for social sciences (SPSS) software version 20.

RESULTS AND DISCUSSION

Soil management practices in the study area

The survey data revealed different soil management and crop production practices maize variety sown among maize fields in the study area. About 50% in the study area farmers have been practicing a repetition of the same cropping in a year per field and 100% completed removal of crop residues has been commonly practiced in the study area. The farmers have never used lime to correct soil acidity problems and farmers have been using DAP and Urea for many years until a recent time a national blend fertilizer recommended in the study area. Other uncontrolled variations of topographical, elevation and high rainfall received per annually in the study area. These variations among the maize fields created different soil physicochemical properties in soils of the maize fields. Soil nutrients depletion in the study area might be due to un appropriated soil fertility management in the study area. During the survey, different topographical categories and elevations were observed among maize fields in the study area. The slope gradients varied from 1.08 to 14.58% with a mean value of 9% among the selected maize fields as established by FAO (2006b). The topographical of maize fields were categorized from very gently sloping to strong slopping in the study area (Mintesinot, 2024). According Mintesinot (2024) finding soil fertility management practices were not sufficient to meet the crop nutrient demand in the study area. Mono cropping practice in the study area; might lead to heavy nutrient depletion and associated yield losses, particularly for maize, for its high nutrient requirements.

Selected soil physical properties

Particle size distribution

Soil particle size distribution varied among the maize fields in the study area. The coefficients of variation were 38.61% for clay, 18.95% for sand, and 12.8% for silt. The values ranged from 27 to 59% for clay, 25 to 45% for sand, and 12% to 30% for silt, with mean values of $39.69 \pm 1.10\%$, $37.63 \pm 0.77\%$, and $22.69 \pm 0.63\%$ for clay, sand,

Table 1. Soil physical properties of maize fields in Migna Kura Kebele.

Descriptive statistics, N (32)	Sand	Silt	Clay	Textural class	Pb (gcm ⁻³)
		%			
Mean	37.63	22.69	39.69	Clay and Clay loam	1.29
Min	25.00	12.00	27.00		1.13
Max	45.00	30.00	59.00		1.46
Std. mean error	0.77	0.63	1.10		0.02
SD	4.35	3.58	6.21		0.10
CV (%)	18.95	12.80	38.61		0.01

Pb = Bulk Density; Std. mean error = Standard mean error; SD = Standard deviation; CV = Coefficient of Variation; N (320 = Total soil samples; Min = minimum; Max = Maximum.

And silt, respectively. The mean particle size distribution of soils in the maize fields followed the order: clay > sand > silt, indicating the dominance of clay-sized particles over the other fractions. The relatively higher clay content is consistent with the findings of Dagne (2016), who reported higher clay content relative to sand and silt-sized particles in Nitisols. Soil textural classes varied across the maize fields. According to the USDA soil texture classification system described by Rowell (1994), two soil textural classes, clay loam and clay were identified in the study area. Among the total samples, 65.63% and 34.37% of the maize fields were classified as clay loam and clay, respectively. There was considerable variation in soil separates among the sampled soils. The coefficients of variation were 38.6%, 12.8%, and 18.95% for clay, silt, and sand contents, respectively. These differences in soil textural classes may be attributed to variations in soil fertility management practices, parent material, topography, and elevation. Additionally, such variation may result from clay translocation from upper to lower slope positions due to erosion. Selassie (2015) reported the highest clay content at foot slope positions and the lowest at upper slope positions. Therefore, soil texture variation can be attributed to differences in parent material, topography, in situ weathering, and the translocation of clay to foot slopes and lower elevations.

Bulk density

Soil bulk density values across the maize fields ranged from 1.13 to 1.46 g cm⁻³, with an overall mean value of 1.29 ± 0.02 g cm⁻³. Based on the rating recommended by Hazelton and Murphy (2025), the bulk density values were classified as low to moderate. The variation in bulk density (Pb) among the maize fields may be attributed to slight differences in clay content and organic matter, as higher levels of organic matter and clay are associated with increased pore space. Low bulk density values indicate

that the soils are not compacted and possess higher porosity. Hazelton and Murphy (2025) reported critical bulk density values of 1.6 g cm⁻³ for loam soils and 1.4 g cm⁻³ for clay loam and clay soils. The mean bulk density value of the soils in the maize fields was below the critical threshold for agricultural use (1.40 g cm⁻³), indicating the absence of excessive compaction or restrictions to root development. Optimal bulk density reflects lower compaction, which facilitates easier movement of water and nutrients, thereby promoting root growth. The results of this study indicate that bulk density levels in the maize fields are favorable for root activity, water infiltration, and overall crop growth in the study area. Table 1 shows the soil physical properties of maize fields in Migna Kura Kebele.

Selected soil chemical properties

Soil pH and available P, K and S

Soil pH (H₂O) across the maize fields in the study area showed high spatial variability. The pH values ranged from 4.91 to 6.70, with a mean value of 5.62 ± 0.07. According to the ratings established by Tekalign (1991) for Ethiopian soils, the soil reaction of the study area falls into three categories: strongly acidic, moderately acidic, and slightly acidic. Of the total soil samples, 31.25% were strongly acidic, 56.25% moderately acidic, and 12.5% slightly acidic. The observed variation in soil pH may be attributed to differences in topography, elevation, soil properties, and long-term crop management practices in the maize fields. Soil pH directly affects soil biological activity and the availability of essential nutrients to plants. Factors such as parent material, rainfall, and vegetation type play major roles in determining soil pH. Under continuous cultivation, however, organic acids from plant roots, repeated application of acid-forming fertilizers, nutrient removal through harvesting, and the replacement of calcium and

Table 2. Soil pH, available phosphorous, potassium, and sulfur of maize fields in Migna Kura Kebele.

Descriptive statistics N (32)	pH-H ₂ O	Av. P (mg kg ⁻¹)	Av. K (mg kg ⁻¹)	Av. S (mg kg ⁻¹)
Mean	5.62	8.85	153.24	5.43
Min	4.91	6.71	27.57	1.34
Max	6.70	13.44	290.78	13.76
Std. Mean Error	0.07	0.30	13.78	0.60
SD	0.41	1.69	77.95	3.39
CV (%)	0.17	2.85	-	11.52

Av. P = available phosphorous, Av. K= Available potassium, Av. S= Available sulfur, Std.= Standard Mean error; SD = Standard deviation; CV =Coefficient of variation; N (32) = Total soil samples; Min= minimum; Max= Maximum.

magnesium with hydrogen ions contribute to a decline in soil pH. The strongly acidic condition observed in some maize fields may be due to the depletion of basic cations through crop harvest and the continued use of ammonium-based fertilizers, which release hydrogen ions into the soil solution and lower pH, as suggested by Chimdi et al. (2014). In addition, high annual rainfall can lead to the leaching of base cations and increased activity of Al³⁺ and H⁺ ions in the soil solution. Weil and Brady (2016) reported that heavy rainfall promotes the leaching of calcium and magnesium, which are replaced by aluminum on exchange sites, thereby increasing soil acidity. According to Landon (2014), most nutrients for field crops are optimally available at a soil pH range of 5.5–7.5, while values below this range can be too acidic for some crops. In this study, 46.9% of the sampled soils had pH values below 5.5. Similarly, Haile et al. (2017) estimated that about 43% of Ethiopian cultivated land is affected by soil acidity due to high rainfall and the greater removal of base cations than their replenishment. Over time, excessive rainfall leaches essential base elements (Ca, Mg, Na, and K), which help neutralize soil acidity.

Soil pH is a key factor influencing soil fertility, as it affects nutrient availability. In strongly acidic soils, there is a risk of aluminum toxicity and excessive concentrations of Cu, Fe, and Mn, along with deficiencies of Ca, Mg, K, N, P, S, and B (Landon, 2014). Therefore, the application of agricultural lime is essential to reduce soil acidity and improve soil conditions in the study area. Available P in the soils ranged from 6.71 to 13.44 mg/kg, with a mean value of 8.85 ± 0.30 mg/kg across the maize fields. The variation in available P among the soils may be due to differences in soil pH, exchangeable acidity, aluminum content, and organic matter levels. According to the rating by Jones (2019), the Bray II extractable phosphorus levels in these soils indicate phosphorus deficiency. The available phosphorus status of the study area was classified as very low to low, with the mean value falling in the very low category. Specifically, about 75% of the soil samples were rated as very low, while 25% were classified as low in

available phosphorus content. Table 2 presents the values of soil pH, available phosphorus, potassium, and sulfur in the maize fields of Migna Kura Kebele.

Soil chemical properties that influence the concentration of acidic cations such as Al³⁺ and Fe²⁺ can also affect the availability of P. In this study, the presence of high levels of Aluminum (Al), Fe, and Mn in the soils may explain the low availability of P. The low available P observed in the study area is consistent with findings reported by Jones (2019) for soils of Wayu Tuka District in the East Wollega Zone. Similarly, Agegnehu et al. (2015) and Hailu et al. (2015) reported low soil available P, attributing it to low pH and high exchangeable acidity. In acidic soils, where P fixation is a major constraint, the application of organic matter is important. During decomposition, micro-organisms release organic acids that form stable complexes with Al and Fe, thereby reducing P fixation and improving its availability and use efficiency, as noted by Agegnehu and Amede (2017). According to Musefa (2016), the critical level of soil P determined by the Bray II extraction method for maize fields was 14.6 and 12 mg kg⁻¹ in Nitisols of northwestern Ethiopia. Similarly, Agegnehu et al. (2015) reported a critical Bray II extractable P level of 12 mg kg⁻¹ for malt barley in Ethiopian highland Nitisols. The mean available P values in the maize fields of the present study fall below these critical levels. Therefore, to ensure sustainable crop production, the application of phosphorus through inorganic fertilizers, manure, and crop residues, together with lime (especially in strongly acidic soils), is essential to improve soil P levels. Laekemariam et al. (2016) also recommended the combined use of lime, crop residues, and inorganic phosphorus sources to enhance P availability under acidic soil conditions. The addition of organic matter and lime is thus crucial for maintaining and improving phosphorus availability in the soils of the study area.

Soil available K showed high variability among the maize fields, with values ranging from 27.57 to 290.78 mg kg⁻¹ and a mean value of 153.24 ± 13.78 mg kg⁻¹. This

indicates substantial spatial variation in available K within the study area. Based on the rating established by Horneck et al. (2011), the available K levels in the soils were classified as very low to low. In tropical regions, low available potassium is often associated with soil type and mineralogy, the intensity of weathering, climatic conditions, intensive cultivation, and the use of acid-forming fertilizers, all of which contribute to K depletion (Shazana et al., 2013). Therefore, potassium deficiency is evident in the maize field soils of the study area. Soil available S ranged from 1.34 to 13.76 mg kg⁻¹, with a mean value of 5.43 ± 0.60 mg kg⁻¹. The CV was low (< 20%), indicating relatively uniform distribution. According to the rating by Horneck et al. (2011), available sulfur levels in the soils ranged from very low to medium. Specifically, about 56.25, 9.37, and 34.38% of the samples were classified as very low, low, and medium, respectively, with the overall mean falling in the low category.

The critical soil sulfur level for Ethiopian soils is reported to be 11.3 mg kg⁻¹ (Horneck et al., 2011). Based on this threshold, most soil samples were below the critical level, with approximately 93.75% of the maize field soils being deficient in available S. Kidanu and Achalu (2018) also reported S deficiency in similar soils. The low sulfur content may be associated with acidic soil conditions, which enhance sulfate adsorption by aluminum and iron compounds. In general, low S availability in the soils may result from crop residue removal, leaching losses, and limited application of sulfur-containing fertilizers. To address this deficiency, the use of S-containing fertilizers is recommended. In addition, incorporating organic matter and maintaining crop residues should be part of an integrated soil fertility management strategy. Overall, the combined use of organic and inorganic fertilizers is recommended to improve and sustain the availability of P, K, and S in the soils. Chala and Gurmu (2018) demonstrated that the application of organic fertilizers enhances soil available P in Nitisols. Therefore, integrating chemical fertilizers with locally available organic materials is an effective approach for improving soil fertility and promoting sustainable nutrient recycling in the study area.

Exchangeable acidity and percent acid and aluminium saturation

Soil exchangeable acidity (Exch. A), percent acid saturation (PAS), and Al saturation showed considerable variation across the maize fields. The values ranged from 0.00 to 2.46 cmol(+) kg⁻¹ soil for exchangeable acidity, 0.00 to 9.48% for percent acid saturation, and 0.00 to 6.28% for Al saturation. These results are consistent with the findings of Chimdi et al. (2014), who reported that soil acidity is a major constraint to crop production in the western areas of the Oromia Region. The observed

variability may be attributed to the use of acid-forming fertilizers as sources of nitrogen and phosphorus in maize production within the study area. Other probable causes of soil acidity include inheritance from acidic parent materials, application of ammonium-based fertilizers, wet climatic conditions, high rainfall, and the removal of basic cations through continuous harvesting of high-yielding crops. Weil and Brady (2016) and Agegnehu et al. (2019) also reported similar factors contributing to soil acidity. Al saturation ranged from 0.00 to 6.28%, with a mean value of 1.06% ± 0.31 and a low coefficient of variation (3.02%), indicating relatively uniform distribution across the fields. To mitigate the adverse effects of soil acidity and make the soils more suitable for crop production, the application of lime and organic materials is recommended. Table 3 presents the values of soil exchangeable acidity, percent acid saturation, and aluminum saturation in the maize fields.

Soil organic carbon, total nitrogen, and carbon to nitrogen ratio

SOC content in the maize fields of the study area showed low variability (CV < 20%). The SOC values ranged from 1.79 to 3.51%, with a mean of 2.64 ± 0.08%. According to the rating established by Tekalign (1991), the SOC levels of the soils were classified as medium to high. The relatively high SOC content may be attributed to lower temperatures, which reduce microbial decomposition of organic matter and promote its accumulation in the soil. Similarly, World Reference Base for Soil Resources (WRB) (2006) reported high organic carbon content in the surface layers of Nitisols. Soil TN in the study area ranged from 0.11 to 0.19%, with a mean value of 0.14 ± 0.00%. Based on the ratings of Tadesse et al. (1991), TN levels were categorized as low to medium. Accordingly, 71.88% of the soil samples were classified as low, while 28.12% were classified as medium, with the overall mean falling in the low category. At soil pH values below 5.5, bacterial activity declines and the nitrification of organic matter is significantly reduced (Landon, 2014). Therefore, the low TN content observed in the maize fields may be associated with the acidic soil conditions of the study area. These findings are consistent with reports by Wondwosen and Sheleme (2011) and Laekemariam et al. (2016). The coefficient of variation for TN was low (CV < 20%), as classified by Amuyou et al. (2013). The TN levels observed are similar to those of many cultivated soils in Ethiopia (Hailu et al. 2015; Laekemariam et al. 2016), which are often characterized by low organic inputs and complete removal of crop residues. Practices such as continuous nutrient mining without legume integration, limited or no application of organic fertilizers, residue removal, and leaching losses are major contributors to low soil TN

Table 3. Soil exchangeable acidity, percent acid, and aluminum saturation of maize fields.

Descriptive statistics N (32)	cmol (+) kg ⁻¹ soil		%	
	Exch. A	Exch. Al	PAS	PAIS
Mean	0.42	0.28	1.58	1.06
Min	0.00	0.00	0.00	0.00
Max	2.46	1.63	9.48	6.28
Std. Mean error	0.11	0.08	0.41	0.31
SD	0.61	0.46	2.34	1.74
CV (%)	0.37	0.21	5.49	3.02

Exch. A= Exchangeable acidity; Exch. Al= Exchangeable aluminum; PAS= Percent of Acid Saturation; PAIS=Percent of Aluminum Saturation; Std.= Standard Mean error; CV= Coefficient of variation; N (32) = Total samples, Min= minimum, Max= Maximum.

Table 4. Organic carbon, total nitrogen, and C: N in soils of maize fields.

Descriptive statistics, N (32)	OC (%)	TN (%)	C: N
Mean	2.64	0.14	18.49
Min	1.79	0.11	14.02
Max	3.51	0.19	25.49
Std. Mean Error	0.08	0.00	0.55
SD	0.44	0.02	3.12
CV (%)	0.20	0.00	9.71

OC= Organic Carbon; TN= Total Nitrogen; C: N = Carbon to Nitrogen Ratio, Std.= Standard Mean error; SD = Standard deviation, CV = Coefficient of variation, N (32) = Total soil samples, Min= minimum, Max= Maximum.

levels. In line with this, Abera and Wolde-Meskel (2013) and Agegnehu and Amede (2017) reported reduced TN levels due to intensive cultivation, low input use, and reduced mineralization rates in high rainfall areas of Ethiopia. To maintain soil nitrogen balance and achieve optimal crop production, regular application of nitrogen-containing fertilizers is recommended. The soil carbon-to-nitrogen (C:N) ratio varied among the maize fields but showed low variability (CV < 20%). The values ranged from 14.02 to 25.49, with a mean of 18.48 ± 0.55 . According to the classification by Landon (1991), the C:N ratio of the soils was categorized as medium to high, with the mean value falling in the medium range. The relatively high C:N ratio may be due to the slow decomposition of crop residues, possibly resulting from limited microbial activity in the soil. Table 4 presents the values of soil organic carbon, total nitrogen, and C:N ratio in the maize fields of the study area.

Exchangeable bases, CEC, and PBS

High variability in exchangeable bases was observed in the soils of the maize fields in the study area. The variation

in the distribution of exchangeable bases may be attributed to differences in clay content, soil reaction, exchangeable acidity, soil textural class, parent material, slope gradient, and elevation. The dominant exchangeable base was Ca^{2+} , followed by Mg^{2+} , while the monovalent cations (K^{+} and Na^{+}) were present in relatively lower proportions in the study area. This distribution may be related to charge density, as divalent cations (Ca^{2+} and Mg^{2+}) have a higher affinity for colloidal surfaces than monovalent cations (K^{+} and Na^{+}).

This finding is consistent with the order of cations reported by Laekemariam et al. (2016) and Mohammed et al. (2018). Soil exchangeable calcium (Ca^{2+}) exhibited high spatial variability among the maize fields, with values ranging from 6.93 to 51.15 cmol(+) kg⁻¹ soil and an overall mean value of 16.27 ± 0.02 cmol(+) kg⁻¹ soil. The CV was very high (96.40%), confirming CV > 50%. According to the rating developed by FAO (2004), soil exchangeable Ca^{2+} was classified as medium, high, and very high, with the mean value falling in the high category. Relatively lower values of exchangeable Ca^{2+} were observed at higher slope positions, while higher values were recorded at lower slope positions. This may be due to the removal of exchangeable base cations by erosion from upper slopes

and their accumulation in lower slope areas. Similarly, Mohammed et al. (2018) reported variation in exchangeable bases such as Ca^{2+} and Mg^{2+} along elevation gradients in the Becheke sub-watershed, East Hararghe Zone of the Oromia Region. The status of soil exchangeable Ca^{2+} was found to be optimal for maize production in the study area.

Soil exchangeable magnesium (Mg^{2+}) values also varied among the maize fields, ranging from 2.85 to 23.63 $\text{cmol}(+) \text{kg}^{-1}$ soil, with an overall mean value of $6.51 \pm 0.95 \text{ cmol}(+) \text{kg}^{-1}$ soil. Based on the rating by FAO (2004), exchangeable Mg^{2+} was categorized as medium, high, and very high, with the mean value falling in the high category. In terms of distribution, 12.5, 75, and 12.5% of the samples were classified as medium, high, and very high, respectively. The coefficient of variation (28.65%) indicates moderate variability ($\text{CV} = 20\text{--}50\%$). Higher exchangeable Mg^{2+} values were associated with soils having higher clay content and gently sloping terrain. Mohammed et al. (2018) also reported that exchangeable base cations are removed from steep slopes by erosion and accumulate in lower slope areas. The status of soil exchangeable Mg^{2+} was adequate to support maize growth in the study area. Soil exchangeable K^+ showed high variability among the maize fields, ranging from 0.21 to 1.76 $\text{cmol}(+) \text{kg}^{-1}$ soil, with a mean value of $0.91 \pm 0.09 \text{ cmol}(+) \text{kg}^{-1}$ soil. Based on the rating developed by FAO (2004), 9.4, 25, 37.5, and 28.1% of the samples were classified as low, medium, high, and very high, respectively. The mean value was categorized as high and above the critical threshold level of 0.38 $\text{cmol}(+) \text{kg}^{-1}$ soil for most crops, as reported by Barber (1984). However, five samples had exchangeable K^+ values below the critical level, while the majority of samples (28) were within the optimal range.

Soil exchangeable sodium (Na^+) showed low variability among the maize fields, with values ranging from 0.05 to 0.71 $\text{cmol}(+) \text{kg}^{-1}$ soil. According to the rating by Food and Agriculture Organization (2004), exchangeable Na^+ was classified as very low to medium. Specifically, 31.25, 62.5, and 6.25% of the samples were categorized as very low, low, and medium, respectively. The low levels of exchangeable Na^+ may be attributed to high annual rainfall, which enhances leaching losses in the soils of the maize fields. From a soil fertility perspective, the mean values of exchangeable Ca^{2+} , Mg^{2+} , and K^+ were within the medium to high range, although about 9.4% of the samples indicated potassium deficiency. Overall, the mean values of exchangeable Ca^{2+} , Mg^{2+} , and K^+ (16.27 ± 1.74 , 6.51 ± 0.95 , and $0.91 \pm 0.09 \text{ cmol}(+) \text{kg}^{-1}$ soil, respectively) were rated as adequate to support crop production, based on soil fertility ratings established by Food and Agriculture Organization (2006b) and EthioSIS (2016). Soil CEC showed high variability among the maize fields, with

values ranging from 22.19 to 77.42 $\text{cmol}(+) \text{kg}^{-1}$ soil and a mean value of $35.02 \pm 2.55 \text{ cmol}(+) \text{kg}^{-1}$ soil. Based on the rating by Landon (2014), 16.63, 59.38, and 25% of the samples were categorized as medium, high, and very high, respectively, with the mean value falling in the high category. The high coefficient of variation (96.04%) indicates substantial variability in CEC among the soils. Mohammed et al. (2018) also reported similar variability in CEC due to differences in clay content, slope gradient, and elevation.

This variation may be attributed to differences in clay content, soil reaction, exchangeable acidity, soil textural class, slope gradient, and elevation in the study area. High CEC values indicate a greater buffering capacity against changes in soil properties. In agreement with this finding, Chimdi (2015) reported high CEC values for soils in the Wayu Tuka District. The results of this study indicate that the soils of the maize fields possess adequate levels of basic cations. Effective cation exchange capacity (ECEC) values were also found to be closely associated with CEC and exchangeable base values. PBS showed very high variability among the maize fields, with a coefficient of variation of 218.54% ($\text{CV} > 100\%$). This high variability may be due to differences in basic cations, soil reaction, clay content, CEC, and exchangeable acidity. The trend of PBS in the study area was similar to that of CEC and exchangeable bases, as these properties are influenced by similar factors (Chimdi et al., 2012). The minimum and maximum PBS values were 42.13 and 98.30%, respectively, with a mean value of $65.41 \pm 2.61\%$. Higher PBS values may be attributed to high CEC, which helps retain basic cations against leaching losses, whereas lower PBS values observed in some maize fields may be associated with low soil pH. According to the rating by Hazelton and Murphy (2025), PBS values were categorized as moderate, high, and very high. Based on PBS as an indicator of leaching intensity, the soils were classified as very weakly leached (21.13%), weakly leached (56.25%), and moderately leached (22.62%).

These findings indicate that soil pH (H_2O) is a major factor influencing exchangeable bases and CEC in the study area. This is supported by a significant ($P \leq 0.01$) positive correlation between soil pH and exchangeable bases, CEC, and PBS. Conversely, a highly significant ($P \leq 0.01$) negative correlation was observed between soil pH and exchangeable acidity, percent aluminum saturation, and the availability of Fe and Mn. Table 5 presents the values of exchangeable bases, CEC, ECEC, and PBS in the soils of maize fields in the study area.

Status of micronutrients in soil of the study area

Soil available micronutrient results mean values were in the order $\text{Mn} > \text{Fe} > \text{Cu} > \text{Zn} > \text{B}$. The DTPA extractable

Table 5. Exchangeable bases, CEC, ECEC and PBS in soils of maize fields of the study area.

Descriptive statistics, N (32)	Exchangeable bases (cmol (+) kg ⁻¹)				Cmol (+) kg ⁻¹		%
	Ca ²⁺	Mg ²⁺	Na ⁺	K ⁺	CEC	ECEC	
Mean	16.27	6.51	0.16	0.91	35.02	24.26	65.41
Min	6.93	2.85	0.05	0.21	22.19	13.59	42.13
Max	51.15	23.6	0.71	1.76	77.42	76.10	98.30
Std. Mean Error	1.74	0.95	0.02	0.09	2.55	2.59	2.61
SD	9.82	5.35	0.12	0.48	14.42	14.68	14.78
CV (%)	96.4	28.6	0.01	0.23	207.95	215.39	218.5

CEC= Cation exchangeable capacity, ECEC= Effective Cation exchangeable capacity, PBS= percent base saturation. Std.= Standard Mean error; SD=Standard deviation, CV = Coefficient of variation, N (32) = total soil samples, Min= minimum, Max=Maximum.

iron values indicated variations among the maize fields and ranged from 12.07 to 33.59 mg kg⁻¹ soil with a mean value of 21.98 ± 1.02 mg kg⁻¹. According to a rating described by Jones (2019), DTPA extractable iron in soil of maize fields was categorized as high. Value of CV (32.97%) showed moderate variability in iron content of soil among maize fields. This variability among the fields might be due to the variation of soil pH and soil OM contents of the study area. There might be a high possibility for the stress of iron toxicity as well as deficiency of antagonistic elements in plants in the study area. High iron availability might reduce the uptake of different nutrients such as P, K, and Zn; thus, deficiency of these elements in the plants (Fareria et al., 2008). All soil samples were not deficient in Fe as the amount of iron required by crops, so deficiency of Fe was not a serious problem. DTPA extractable Mn values ranging from 16.02 to 48.26 mg kg⁻¹ soil with a mean value of 30.72 ± 1.70 mg kg⁻¹. According to the ratings suggested by Jones (2019); soils sampled from maize fields categorized as high soil Mn; this is due to the low level of soil pH in the study area. Soil available manganese values showed a high coefficient of variability (92.52%) among the maize growing fields in the study area. This shows high variation in available manganese content of soil, which could be attributed to variation in soil reaction, and soil exchangeable acidity. The availability of Mn decreased with an increase in soil pH (Friedrich and Catalano, 2012). The soil available Mn and Fe were sufficient in the soil of the study area. Results of this finding further supported by similar findings reported by different authors who identified adequate and higher extractable Mn for most soils of Ethiopia by (EthioSiS, 2016; Hailu et al., 2015). DTPA extractable soil Zn values in soils of maize fields varied from 0.18 to 0.62 mg kg⁻¹ with a mean value of 0.39 ± 0.02 mg kg⁻¹ soil. The mean value of Zn in soil of the study area (0.39 ± 0.02 mg kg⁻¹ soil) was lower. According to Jones (2019); soil available Zinc was categorized into very low, low, and medium; a mean value was categorized in low.

About total soil samples, 100 % of samples were found to be deficient in DTPA extractable Zn. This finding agrees with low DTPA extractable Zn values in different Ethiopia soils were also identified by Abate et al. (2016), EthioSiS (2016) and Hailu et al. (2015). Similarly, Kidanu and Achalu (2018) reported deficiency of Zn in the soil of Wayu Tuka District.

DTPA extractable Zn Values showed little variability among maize fields in the study area (CV>20%). Zinc has low mobility in soils and a tendency of being adsorbed on clay size particles as suggested by Alloway (2008). Deficiency of Zn was the highest among all the DTPA extractable micronutrients. There is a need for Zn fertilization at regular intervals to maximize yield and to reduce zinc stress in plants growing in the study area. Soil DTPA extractable Cu values investigated in maize fields ranged from 1.09 to 3.68 mg kg⁻¹ with a mean value of 2.0 ± 0.10 mg kg⁻¹ soil. According to Jones (2019) soil fertility rating of soil available Cu of study area was categorized into medium, high, and very high and a mean value was categorized into high range. A mean value of the study area further showed that Cu deficiency was not a problem in these soils as no samples were found to be below the critical limit, about all total soil samples of maize fields falling in sufficiency categories. According to the suggestion of Horneck et al. (2011), soil available copper values above 0.6 mg/kg soil using the DTPA extraction method are considered sufficient. Based on this criterion, 100% of the total soil samples were sufficient in copper content. The results obtained in this study are similar to the findings of Hailu et al. (2015). Hot water extractable soil available boron showed variability among maize fields in the study area. The B values ranged from 0.19 to 0.62 mg kg⁻¹ soil, with a mean value of 0.38 ± 0.13 mg kg⁻¹ soil. Based on the soil fertility rating by Tadesse et al. (1991), available B levels in the study area were classified as very low to low. In terms of sample distribution, 59.37% of the soil samples were classified as very low, while 40.63% were classified as low in available boron. Recent studies

Table 6. Micronutrients in soil of maize growing fields in Migna Kura Kebele.

Descriptive statistics, N (32)	Micronutrient (mg/kg)				
	B	Fe	Mn	Cu	Zn
Mean	0.38	21.98	30.72	2.00	0.39
Min	0.19	12.07	16.02	1.09	0.18
Max	0.62	33.51	48.26	3.68	0.62
Std. mean Error	0.02	1.02	1.70	0.10	0.02
SD	0.13	5.74	9.62	0.55	0.12
CV (%)	0.02	32.97	92.52	0.30	0.02

Min= Minimum, Max= maximum, Std.= Standard, SD= standard deviation, CV= Coefficient of variation, B= available boron; Fe= Available iron, Mn= available manganese; Cu= available copper; Zn= available zinc; N =number of total samples.

on macro- and micronutrient deficiencies have reported that B, Zn, and S deficiencies are common in most agricultural lands in neighboring kebeles of the study area, as reported by Kidanu and Achalu in Wayu Tuka District. B deficiency was identified as a serious problem in the study area, as 100% of the soil samples were found to be deficient in boron. The intensive cultivation of crops without the application of B-containing fertilizers, low soil organic matter content, leaching losses of boron, and continuous crop uptake in maize fields may be the main causes of boron deficiency. In agreement with this observation, B deficiency is commonly reported in high rainfall areas with low soil organic matter content. This finding is consistent with the results reported by Lelago et al. (2016) and EthioSiS (2016), which indicated B and Zn deficiencies, while Fe and Mn were sufficient in soils from different parts of Ethiopia. The sufficiency of Fe and Mn may be related to the acidic nature of the soils in the study area. Therefore, regular application of boron-containing organic and inorganic materials is recommended to maintain adequate B levels in the soils of the study area. Soil micronutrient contents are influenced by several factors, including organic matter content, sand and clay fractions, and soil pH, as suggested by Geremu et al. (2021). Micronutrient deficiencies often occur due to low soil nutrient reserves and nutrient removal through crop harvest, as reported by Vijayakumar et al. (2011). Thus, the soils of the study area had adequate levels of DTPA-extractable Fe, Mn, and Cu, while zinc (Zn) and boron (B) were at deficient levels. Table 6 presents the micronutrient status of soils in maize-growing fields of Migna Kura Kebele.

Simple correlation for selected soil physico chemical properties

The correlation matrix coefficients (r) among selective

physicochemical properties of soil results of the study area revealed significant correlation among each other. Soil clay content was highly significantly ($P \leq 0.01$) and positive correlation with, Exch. bases, CEC, PBS, and ECEC. Soil clay contents highly significantly at ($P \leq 0.01$) and positive correlation with, available P, exchangeable Ca, Mg and CEC. These results showed that amount of clay in soil determined the availability of these nutrients in the soils. The positive relationship between soil clay and soil chemical nutrient contents confirms that the more soil clay contents the more potential of the nutrient reservoir of the soil and increasing nutrients in the soils. Soil pH was highly significantly ($p \leq 0.01$) and positively correlated associated with available P, K, exchangeable K, exchangeable Ca and Mg, CEC, CECE, and PBS and not significantly, but positively correlated with OC, OM, TN, available S, and exchangeable Na. The positive relationship between pH and OM may indicate that OM retains exchangeable bases that increase soil pH. The soil pH in also co-varied and influenced CEC, exchangeable bases (Ca, Mg, K), available P, S, and K. These are evidenced with the strongly significant ($P \leq 0.01$) and positive correlation between soil pH and CEC, exchangeable bases (Ca, Mg, K), available P, S and K. Soil pH was significantly ($p \leq 0.05$) and negatively correlated with sand contents and not significant, but positively correlated associated with clay contents.

Conversely, soil pH values highly significantly ($p \leq 0.01$) and negatively correlated with exchangeable acidity, Al, and percent of acid saturation. These showed under strongly acidic soils, hydrolysis of Al and a sharp increase in exchangeable Al are expected at lower soil pH. This process releases H^+ ions that further lower the soil pH to a level that seriously affects the availability of certain nutrient elements, such as P, and increases Al and Fe toxicity. Significant ($p \leq 0.01$) and positive correlation between pH and available P were also recorded in the study area.

Although, soil pH values showed a negative correlation with available Fe and Mn. The available Fe and Mn were inversely proportional to soil pH. It increases with increasing organic matter but decreases with an increase in soil pH. The CEC depends on the soil type and proportion of clay minerals and organic matter present in the soil. Clay soils have a higher CEC than do sandy soils. Simple linear correlation analysis results revealed that soil CEC was highly significantly at ($P \leq 0.01$) and positively correlated with MOC, clay, soil pH-H₂O, EC, available P, and PBS and highly significant ($P \leq 0.01$) negative relationships with sand, BD, Exch. acidity and Al, Fe and Mn. The association among clay contents and CEC implies that clay contents are a major contributor for the soil CEC as evidenced shows on the significance and correlation between these two parameters. The results observed variation in the soil CEC along with soil pH. Similarly, also CEC has been significantly at ($P \leq 0.01$) and positively associated with exchangeable Ca, Mg, K, and Na. These positive relationship between soil CEC and exchangeable basic confirm that the more soil exchangeable basics the more potential of the nutrient reservoir of the soil.

Soil OC was found to significantly ($P \leq 0.01$) and positively correlated with TN, C: N, available K and Zn and significantly ($P \leq 0.05$) and positively correlated with available P and S, exchangeable K, and sand contents. This implies that organic carbon could be the source of soil nutrients content. This conforms with the findings of Jembere Tiruneh and Mamo (2017) reported that a high correlation between OC and TN. Conversely, OC was significantly and negatively correlated with the following soil properties: percent clay contents at ($P \leq 0.01$), while exchangeable Ca and Mg, CEC, available Fe and Mn were not significantly but negatively correlated. The observed negative correlation between OC and the listed soil properties could be related to the relatively higher degree of soil disturbance and related mineralization of OC on intensively cultivated, clay, and Exch. Ca and Mg rich very gently sloping to sloping on maize fields. This finding is in line with the results of Jembere Tiruneh and Mamo (2017) also reported that intensive cultivation of agricultural lands substantially decreases the quantity of soil OC in soils. Similarly, cultivation induced soil disturbances could increase the rate of OC mineralization and related high CO₂ flux to the atmosphere not mentioning the inevitable decrease in soil aggregate stability by Jembere Tiruneh and Mamo (2017).

The correlation between PBS (%) and Al saturation (%) showed that PBS correlated negatively and significantly with aluminum saturation (%), ($p \leq 0.01$) indicating that higher values of base saturation are associated with lower levels of aluminum saturation. The soils that have high base saturation have low aluminum saturation and high pH values and vice versa. In agreement with the findings of

(Streck et al., 2008) also stated that low saturation of bases could be traced to high Al saturation and low pH in Oxisols and Alfisols. Higher values of base saturation were associated with higher levels of soil pH. Pearson correlation matrix coefficients also showed significant ($p \leq 0.01$) and positive correlation ($r=0.777$) between available P and soil pH. The available P was found to significantly ($p \leq 0.01$) positive correlate with Exch. Ca, Mg, and K, CEC, and PBS and the available P was found to significantly ($p \leq 0.05$) positive correlate with OM. These imply that they have no antagonistic effect on these nutrients. The available P was found to significantly ($p \leq 0.01$) negative correlate with Exch. Acidity, Exch. Al, PAS, PAIS, Fe, and Mn, these results showed that soil available P inversely related to these soil parameters. The soil pH in the present study also co-varied and influenced CEC, exchangeable bases (Ca, Mg, K), available P, S, and K. This is evidenced with the significant ($P \leq 0.01$) and positive correlation between soil pH and available P, K, and exchangeable bases. Similarly, percent base saturation was significantly and positively correlated with soil pH. This might be in the East Wollega Zone, Nitisols are dominant (Chimdi et al., 2012) in which their clay assemblage is dominated by kaolinite. The association between soil pH and increase in the soil CEC might be linked with the presence of pH dependent charges, probably on kaolinite clay mineralogy. Table 7 shows the Pearson correlation matrix coefficients (r) among selectively soil physicochemical properties.

Concentration of nutrients in maize leaf tissue

Macronutrients

Nitrogen: Maize leaf N concentration ranged from 0.19 to 3.20%, with a mean value of $2.48 \pm 0.06\%$. According to the sufficiency ranges suggested by Campbell and Plank (2000), maize leaf N concentrations in the study area varied from sufficiency to deficiency levels, with the mean value falling below the critical level of 3% N concentration. In terms of total samples, 18.75% were within the sufficiency range, while 81.25% were below the sufficiency level. These variations may be attributed to differences in maize varieties, the amount of available nitrogen and soil organic carbon, and soil acidity conditions in the study area. Similarly, nitrogen deficiencies in wheat plants were reported by Hailu et al. (2015), while deficiencies in maize plants were reported by Laekemariam et al. (2016) and Wondwosen and Sheleme (2011). The observed N deficiency in maize leaves may be mainly due to low soil N content. To improve the availability of nitrogen in the soil and enhance plant uptake, appropriate soil fertility and maize management practices should be implemented. These include the application of inorganic nitrogen fertilizers, intercropping, crop rotation with legumes, and

Table 7. Pearson Correlation matrix coefficients (r) among selectively soil physicochemical properties.

Soil parameter	Sand	Silt	Clay	pHH ₂ O	Ex. A	Av. P	Ex. K	Ex. Ca	Ex. Mg	CEC	PBS	Av. Fe	Av. Mn
Sand	1	0.220	-0.827**	-0.320*	0.230	-0.201	-0.183	-0.519**	-0.536**	-0.499**	PBS	Av. Fe	Av. Mn
Silt		1	-0.730**	0.010	-0.073	0.096	0.411**	-0.436**	-0.505**	-0.374*	-0.343*	0.309*	0.296*
Clay			1	0.218	-0.120	0.085	-0.109	0.614**	0.666**	0.565**	-0.229	-0.159	-0.121
pHH ₂ O				1	-0.786**	0.777**	0.715**	0.752**	0.569**	0.672**	0.372*	-0.125	-0.138
Exch. A					1	-0.532**	-0.569**	-0.472**	-0.332*	-0.379*	0.694**	-0.852**	-0.868**
Av. P						1	0.545**	0.671**	0.432**	0.621**	-0.621**	0.803**	0.776**
Ex. Na							0.190	0.486**	0.758**	0.525**	0.516**	-0.709**	-0.637**
Ex. K							1	0.388*	0.275	0.359*	0.486**	-0.667**	-0.600**
Ex. Ca								1	0.863**	0.935**	0.682**	-0.611**	-0.642**
Ex. Mg									1	0.843**	0.694**	-0.461**	-0.454**
CEC										1	0.453**	-0.524**	-0.586**
PBS											1	-0.699**	-0.603**
Av. Fe												1	0.936**
Av. Mn													1

** Correlation is significant at the $P \leq 0.01$ level (1-tailed), * at the $P \leq 0.05$ level (1-tailed). Av. P = Available Phosphorous; Ex.= exchangeable (Ca, Mg, K); CEC = Cation Exchange Capacity; Ex A =Exchangeable Acidity= PBS=Percent Base Saturation; Av. Fe= Available Iron; Av. Mn= Available Manganese.

the use of bio-fertilizers by maize farmers in the study area.

Phosphorous: Maize leaf of concentration of P varied from 0.07 to 0.21 % with a mean value of $0.12 \pm .03\%$. Maize leaves concentrations of P below the sufficiency range and a critical value as per rating of P level in maize tissue suggested by Campbell and Plank, 2000). Maize leaf samples' phosphorous concentrations below the critical level of 0.25 % as set by (Fageria et al., 2011). Maize leaves phosphorous deficiency confirmed with soil available phosphorous deficiency in the study area (Mintesinot, 2024). Similarly, different authors have reported a positive correlation between P in soil and in maize ear tissue (Laekemariam et al.,

2016).

Sulfur: Maize leaf concentration of S varied from 0.05 to 0.48 % with a mean value of $0.2 \pm 0.13\%$. In maize leaves, concentrations of sulfur varied below sufficiency-to-sufficiency range and the overall mean value categorized in sufficiency range and above critical values of 0.12% as per rating of S level in maize leaf developed by (Campbell and Plank, 2000). In terms of total maize leaves samples about 53.12% were in S sufficiency range and 46.88% were below sufficiency. The observed deficiency of sulfur in maize tissue was predicted by soil sulfur analysis results as 71.9% soils were deficient in sulfur.

Potassium: Maize leaf concentration of potassium

ranged from 0.69 to 2.89% with a mean value of $1.87 \pm 0.49\%$. In maize leaf samples, concentration of K ranged from sufficiency to deficiency with a mean value at sufficiency range as per the rating of K level in maize tissue suggested by (Campbell and Plank, 2000). In terms of total maize leaves samples, 56.25% were sufficient whereas 43.73% were below the sufficiency range. Maize leaves tissue concentrations of K showed similar trends of the soil test available K. Similarly, based on the adequate levels of soil exchangeable K, about 31.25 % of leaf samples were found to be deficiency in K compared to the critical level of 1.7 (Fageria et al., 2011). This might be due to K fixation by clay minerals induced K deficiency that could limit K uptake and lead to K deficiency in the

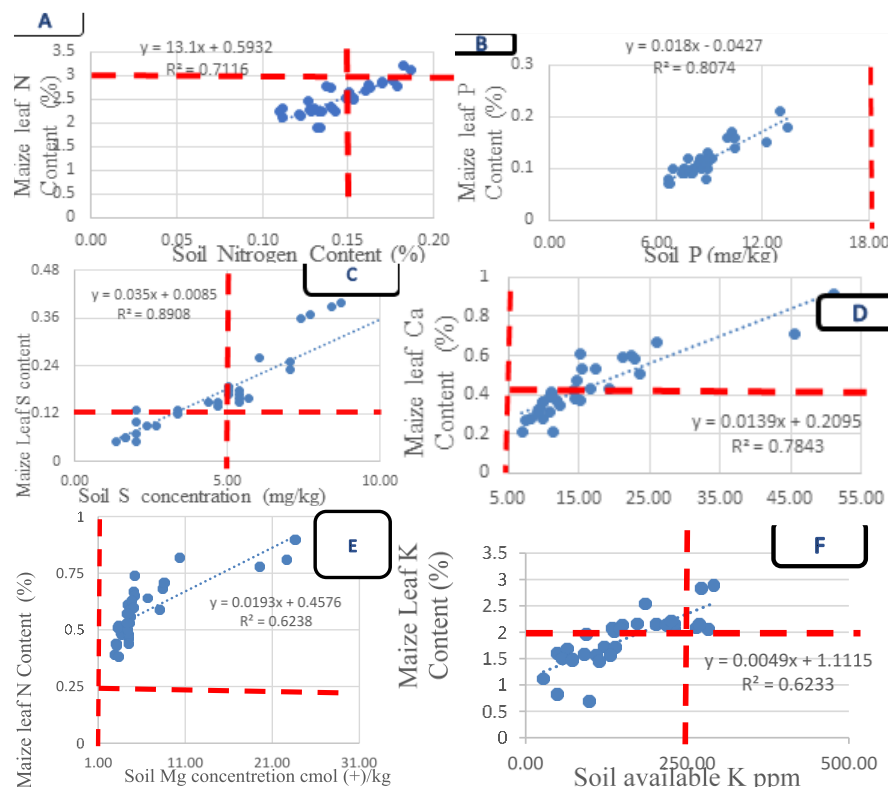


Figure 3. Relationship between soil macro and maize leaf nutrients concentration.

maize leaves.

Calcium and magnesium: Maize leaf concentrations of Ca and Mg ranged from 0.21 to 0.91%, with a mean value of $0.44 \pm 0.15\%$, and from 0.38 to 0.90%, with a mean value of $0.58 \pm 0.13\%$, respectively. According to the Ca and Mg rating levels in maize leaves suggested by Campbell and Plank (2000), the mean Ca value fell within the sufficiency range. However, about 6.25% of maize leaf samples were slightly below the lower limit of sufficiency, while 93.75% of the samples were within the sufficiency range for Ca concentration. Ca deficiency in maize tissue was not indicated by exchangeable Ca (Exch. Ca) soil tests. Maize leaf Mg concentrations were also within the sufficiency range. Similarly, sufficiency levels of Ca and Mg in wheat plants were reported by Hailu et al., 2015 and in maize plants by Wondwosen and Sheleme (2011) and Laekemariam et al. (2016). The mean values of Ca and Mg in maize leaves were therefore considered sufficient in the study area when compared with the critical levels of 0.25 and 0.15%, respectively, as suggested by Laekemariam et al. (2016). Overall, the macronutrient concentrations of Ca, Mg, S, and K in maize leaves were within the sufficiency range. However, S was close to the

lower limit of sufficiency, while N and P were deficient in 81.25 and 100% of maize leaf samples, respectively, according to the rating by Campbell and Plank (2000). The study of nutrient levels in maize leaf analysis indicates that N, S, K, and P require supplementation through both organic and inorganic fertilizer applications to ensure sustainable maize production in the study area. In the graphs, the red line represents the critical values of plant nutrient concentrations in maize tissue. The relationships between soil and maize leaf nutrient concentrations are illustrated in Figure 3. Table 8 presents the mean values of macronutrient concentrations in maize leaves in Migna Kura Kebele.

Micronutrients

Boron: Maize leaf boron concentrations ranged from 2.43 to 8.02 mg kg⁻¹, with an overall mean value of 5.11 ± 0.24 mg kg⁻¹. B concentrations in maize leaves ranged from sufficiency to below sufficiency levels according to the rating of boron in maize tissue suggested by Campbell and Plank (2000). This variation may be attributed to the very low to low available boron content in the soil. A

Table 8. Mean values of macronutrient Concentration of maize leaf at Migna Kura Kebele.

Descriptive statistics, N (32)	Nutrients (%)					
	N	P	S	K	Ca	Mg
Mean	2.48	0.12	0.20	1.87	0.44	0.58
Min	1.90	0.07	0.05	0.69	0.21	0.38
Max	3.20	0.21	0.48	2.89	0.91	0.90
Std. mean error	0.06	0.01	0.02	0.09	0.03	0.02
SD	0.33	0.03	0.13	0.49	0.15	0.13
CV (%)	0.11	0.00	0.02	0.24	0.02	0.02

Min= Minimum, Max= maximum, Std. mean error= standard mean error, SD= standard deviation, CV=coefficient of variation, N (32) =Total sample, N=Nitrogen, P=phosphorous, S=Sulfur=Potassium, Ca=Calcium, Mg=Magnesium.

significant positive correlation ($p \leq 0.01$) was observed between soil test boron and maize leaf boron ($r = 0.876$), indicating that low soil boron contributes to low boron concentration in maize leaf tissue. In contrast to soil analysis results, which indicated 100% boron deficiency, maize leaf tissue analysis did not show complete deficiency in all samples. This suggests that boron sufficiency in plant tissue was not fully predicted by soil available B tests. This may be due to the application of boron-containing fertilizers, differences in maize hybrids, and acidic soil conditions, which can enhance boron availability and uptake.

Iron: Maize leaf Fe concentrations ranged from 96.36 to 190.38 mg kg⁻¹, with a mean value of 145.39 ± 4.62 mg kg⁻¹. Manganese (Mn) concentrations ranged from 32.43 to 226.01 mg kg⁻¹, with a mean value of 98.51 ± 8.73 mg kg⁻¹. Both Fe and Mn concentrations in maize leaves were within the sufficiency range according to the rating suggested by Campbell and Plank (2000). The mean values were above the critical level of 15 mg kg⁻¹. The sufficiency of Fe and Mn in maize leaves was consistent with their adequate levels in the soils of the maize fields. The results of this study indicate that higher Fe and Mn concentrations in maize leaves are expected where these elements are sufficient in the soil.

Copper: Maize leaf Cu concentrations ranged from 18.70 to 44.38 mg kg⁻¹, with an overall mean value of 32.35 ± 1.28 mg kg⁻¹. Copper concentrations in maize leaves were at sufficiency levels according to the rating suggested by Campbell and Plank (2000). The mean value was above the critical level of 5 mg kg⁻¹. In all maize leaf samples, copper concentrations were within the sufficiency range. This sufficiency was also reflected in soil analysis results, where copper was found in adequate levels in 100% of soil samples.

Zinc: Maize leaf Zn concentrations ranged from 15.87 to 45.40 mg kg⁻¹, with a mean value of 25.16 ± 1.41 mg kg⁻¹.

Zinc concentrations in maize leaves ranged from sufficiency to deficiency levels according to the rating at the tasselling stage suggested by Campbell and Plank (2000). The mean value indicated sufficiency and was above the critical level. The relatively adequate Zn concentration in maize leaves was not consistent with soil Zn deficiency, possibly due to the application of zinc-containing fertilizers. The variation in maize leaf micronutrient concentrations may be attributed to differences in maize variety, soil reaction, exchangeable acidity, organic matter content, and imbalanced fertilizer application in the study area. Overall, maize leaf concentrations of Fe, Mn, and Cu were above the critical levels of 21, 20, and 6 mg kg⁻¹, respectively, as suggested by Campbell and Plank (2000) and Fageria (2016). This indicates that deficiencies of these elements are unlikely in the study area. Similar findings of sufficient Fe, Mn, and Cu concentrations in maize leaves were reported by Laekemariam et al. (2016), Wondwosen and Sheleme (2011) and Geremu et al. (2021). In general, maize leaf analysis showed that, except for boron and Zn, most micronutrients were within the adequate range. The concentrations of Fe, Mn, and Cu in maize leaves were consistent with their levels in the soils of the study area. This indicates sufficient availability of these nutrients for maize production, and their deficiencies are not expected under current conditions. Micronutrient solubility and uptake are influenced by soil pH. This is supported by the maize leaf tissue analysis, which showed highly significant negative correlations ($P \leq 0.01$) between soil pH and Fe ($r = -0.881$), Mn ($r = -0.884$), and Cu ($r = -0.891$). Mean concentrations of Zn and B in maize leaves indicated deficiency. Therefore, the application of zinc and boron fertilizers, together with the addition of organic matter, is recommended to improve maize yield and ensure sustainable soil fertility in the study area. In the graphs, the red line represents the critical values of plant nutrient concentrations in maize tissue. The relationships between soil and maize leaf micronutrient concentrations in the study area are illustrated in Figure 4.

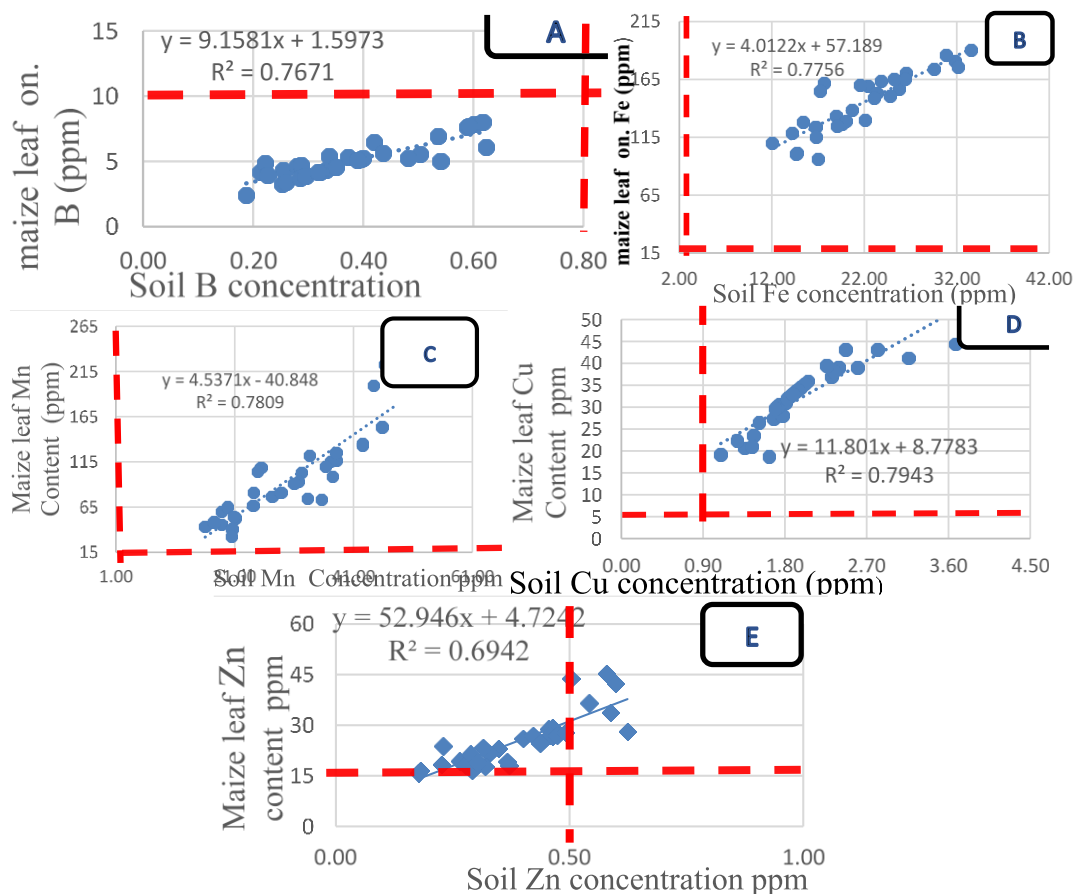


Figure 4. Relationship between soil microand maize leaf nutrients concentration.

Relationship of nutrients concentration in soil and maize leaf tissue

Interpretation of soil test results and plant analysis data is essential. A simple correlation analysis between nutrient concentrations in soil and maize leaves was performed. The results of soil–plant relationships for all investigated nutrients showed positive correlations with their respective nutrient concentrations. Mengel and Kirk (1987) also reported positive correlations between soil and plant tissue nutrient concentrations. The relationship between macro-nutrient concentrations in maize leaves and soil test results revealed significant ($P \leq 0.01$) positive correlations, with correlation coefficients of $r = 0.862, 0.899, 0.651, 0.944, 0.886$, and 0.789 for N, P, K, S, Ca, and Mg, respectively. Similarly, micronutrient concentrations in maize leaves showed significant ($P \leq 0.01$) positive correlations with soil test results, with correlation coefficients of $r = 0.876, 0.881, 0.884, 0.891$, and 0.834 for B, Fe, Mn, Cu, and Zn, respectively. Table 9 presents the mean values of micronutrient concentrations in maize

leaves in Migna Kura Kebele.

The positive correlation between nutrient concentrations in maize leaf tissue and soil test results indicates that maize nutrient uptake largely depends on the nutrient content of the soil (Getachew and Taye, 2004). The correlation results further indicate that soil properties such as pH, OC, and exchangeable acidity significantly affect nutrient concentrations in maize leaves. Soil pH showed a significant ($P \leq 0.01$) positive correlation with maize leaf concentrations of P, Ca, and Mg ($r = 0.691, 0.798$, and 0.534 , respectively), while it showed a negative correlation with Fe and Mn concentrations in maize tissue. This finding indicates that soil reaction strongly influences nutrient availability to plants. Soil pH was also significantly ($P \leq 0.05$) and positively correlated with maize leaf nutrient concentrations of N and K ($r = 0.341$ and 0.373 , respectively). Therefore, the availability of soil nutrients to maize crops is affected by soil pH, as evidenced by the significant positive correlations between soil pH and maize leaf nutrient concentrations in the study area. The simple correlation matrix further revealed a significant ($P \leq 0.01$)

Table 9. Mean values of micronutrient concentration of maize leaves in Migna Kura Kebele.

Descriptive statistics, N (32)	Nutrients (mg kg ⁻¹)				
	B	Fe	Mn	Cu	Zn
Mean	5.11	145.39	98.51	32.35	25.16
Min	2.43	96.36	32.43	18.70	15.87
Max	8.02	190.38	226.01	44.38	45.40
Std. mean Error	0.24	4.62	8.73	1.28	1.41
SD	1.38	26.16	49.38	7.24	7.95

Min= Minimum, Max= maximum, Std. mean error = standard mean error, SD= standard deviation, CV= Coefficient of variation, N (32) = total sample, B= Boron, Fe=iron, Mn=Manganese, Cu=Copper, Zn=Zinc.

positive relationship between maize leaf concentrations of N and P and soil OC, while a negative relationship was observed with soil exchangeable acidity and Al. On the other hand, S uptake showed a significant ($P \leq 0.05$) positive correlation with soil OC. Geremu et al. (2021) reported that Fe uptake in maize is negatively correlated with soil pH, while Zn shows a positive correlation with soil reaction. In general, this study shows that nutrient concentrations of N, P, K, S, Ca, Mg, B, Fe, Mn, Cu, and Zn in maize leaves and soils follow similar trends with the nutrient status of the maize field soils in the study area. Table 10 presents the correlation matrix coefficients (r) for the relationships between nutrient concentrations in soil and maize leaf tissue.

CONCLUSIONS AND RECOMMENDATIONS

This study revealed that soil fertility decline poses a significant challenge to maize production in Migna Kura Kebele, Wayu Tuka District, East Wollega Zone, Ethiopia. A substantial proportion (46.9%) of the maize-growing soils were acidic ($pH < 5.5$), which likely contributes to reduced nutrient availability and impaired root function. Although soil organic carbon was generally in the medium to high range and CEC ranged from medium to very high, critical deficiencies were observed in available P, K, S, Zn, and B. In contrast, exchangeable Ca, Mg, Fe, Mn, and Cu were present at adequate to high levels.

Maize leaf nutrient analysis at the tasseling stage strongly corroborated the soil results, showing widespread deficiencies or marginal concentrations of N, P, K, S, Zn, and B, while Ca, Mg, Fe, Mn, and Cu remained within sufficiency ranges. These findings confirm a clear relationship between soil nutrient status and plant uptake, indicating that nitrogen, phosphorus, potassium, sulfur, boron, and zinc are the primary yield-limiting nutrients for maize in the study area. The major underlying causes of the observed fertility decline include soil acidity, continuous nutrient mining through intensive cropping and

complete crop residue removal and leaching of basic cations under high rainfall conditions. Overall, the results highlight the limitations of current blanket fertilizer recommendations (mainly N and P) and underscore the urgent need for integrated, site-specific soil fertility management to restore productivity and promote sustainable maize production in East Wollega and similar agro-ecological zones.

To address these constraints, an integrated soil fertility management approach is recommended. Soil acidity should be corrected through the application of agricultural lime to raise soil pH, reduce aluminum toxicity, and enhance the availability of P, K, S, Zn, and B. Lime application rates should be determined based on soil test results and acid saturation levels. Blanket NP fertilizer recommendations should be replaced with balanced, site-specific fertilizer blends containing the deficient nutrients (N, P, K, S, Zn, and B), with application rates tailored to soil test values and expected crop responses to improve nutrient use efficiency. Regular incorporation of organic amendments such as compost, farmyard manure, and crop residues, combined with the use of biofertilizers, is essential to improve soil organic carbon, enhance microbial activity, and support long-term soil health. Furthermore, the integration of legume crops in rotation or intercropping systems should be promoted to enhance biological nitrogen fixation and reduce nutrient depletion associated with continuous maize monocropping. Strengthening farmer training through agricultural extension services on soil testing, balanced fertilization, and integrated nutrient management practices is supported by local soil fertility maps and decision-support tools will be critical for effective implementation. For sustainable intensification of maize production in the region, further multi-location and multi-season field trials are necessary to quantify crop responses to varying application rates of the identified limiting nutrients under different levels of lime and organic amendments. Such studies will generate reliable data for developing precise fertilizer recommendations and validating integrated soil fertility management

Table 10. Correlation matrix coefficients (r) for relationship of nutrients concentration in soil and maize leaf tissue.

Leaf	Nutrient										Soil				
	N	P	K	S	Ca	Mg	B	Fe	Mn	Cu	Zn	Sand	Clay	pH H ₂ O	Ex. A
Leaf. N	1	0.452**	0.484**	0.369*	0.248	-0.152	0.231	-0.453**	-0.401*	0.332*	0.633**	-0.202	-0.146	0.341*	-0.348*
Leaf. P		1	0.598**	0.349*	0.600**	0.242	-0.106	-0.674**	-0.577**	0.254	0.256	-0.244	0.033	0.691**	-0.519**
Leaf. K			1	0.146	0.119	-0.210	-0.173	-0.387*	-0.307*	0.327*	0.214	0.022	-0.311*	0.373*	-0.407*
Leaf. S				1	0.123	0.117	0.409*	-0.242	-0.145	0.238	0.374*	-0.063	-0.094	0.198	-0.130
Leaf. Ca					1	0.666**	-0.075	-0.755**	-0.642**	0.143	0.181	-0.360*	0.406*	0.798**	-0.581**
Leaf. Mg						1	-0.160	-0.481**	-0.430**	-0.068	-0.188	-0.477**	0.532**	0.534**	-0.421**
Leaf. B							1	0.065	0.225	0.066	0.331*	-0.030	0.048	-0.133	0.186
Leaf. Fe								1	0.846**	-0.274	-0.359*	0.498**	-0.327*	-0.893**	0.732**
Leaf. Mn									1	-0.395*	-0.236	0.384*	-0.232	-0.825**	0.862**
Leaf. Cu										1	0.249	0.142	-0.152	0.292	-0.495**
Leaf. Zn											1	-0.138	0.080	0.150	-0.132
Leaf															
	Ex. Al	OC	TN	Av. P	Av. K	Av. S	Ex. K	Ex. Ca	Ex. Mg	Av. B	Av. Fe	Av. Mn	Av. Cu	Av. Zn	
Leaf. N	-0.351*	0.533**	0.862**	0.342*	0.637**	0.406*	0.580**	0.122	-0.028	0.264	-0.453**	-0.390*	0.317*	0.531**	
Leaf. P	-0.503**	0.488**	0.341*	0.899**	0.630**	0.283	0.615**	0.564**	0.321*	0.110	-0.715**	-0.593**	0.205	0.369*	
Leaf. K	-0.412**	0.478**	0.530**	0.393*	0.789**	0.087	0.651**	0.042	-0.187	-0.151	-0.352*	-0.269	0.398*	0.304*	
Leaf. S	-0.115	0.344*	0.462**	0.221	0.238	0.944**	0.181	0.068	-0.008	0.400*	-0.276	-0.199	0.261	0.576**	
Leaf. Ca	-0.564**	0.050	0.056	0.730**	0.282	0.113	0.478**	0.886**	0.789**	0.116	-0.676**	-0.685**	0.051	0.127	
Leaf. Mg	-0.410**	-0.367*	-0.32*	0.320*	-0.058	0.112	0.158	0.649**	0.790**	-0.029	-0.440**	-0.476**	-0.186	-0.206	
Leaf. B	0.174	0.194	0.191	-0.131	-0.045	0.444**	-0.076	-0.069	-0.058	0.876**	0.123	0.136	0.053	0.194	
Leaf. Fe	0.723**	-0.112	-0.357*	-0.70**	-0.515**	-0.249	-0.658**	-0.757**	-0.586**	-0.095	0.881**	0.887**	-0.194	-0.306*	
Leaf. Mn	0.847**	0.001	-0.302*	-0.62**	-0.498**	-0.172	-0.517**	-0.580**	-0.399*	0.104	0.859**	0.884**	-0.294	-0.187	
Leaf. Cu	-0.513**	0.186	0.410**	0.160	0.285	0.228	0.119	0.052	-0.184	0.025	-0.324*	-0.311*	0.891**	0.300*	
Leaf. Zn	-0.138	0.419**	0.624**	0.198	0.297*	0.370*	0.290	0.237	0.084	0.350*	-0.307*	-0.280	0.215	0.834**	

**Correlation is significant at the $P \leq 0.01$ level (1-tailed), *Correlation is significant at the $P \leq 0.05$ level (1-tailed).

options across different soil types in East Wollega Zone and beyond. Moreover, further research across a wider range of maize-growing areas is needed to obtain a more comprehensive understanding of maize nutrition based on application rates of limiting nutrients and crop response under

the soils of the study area.

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CONFLICT OF INTERESTS

The authors have not declared any conflict of

interests.

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