**ADDIS ABABA UNIVERSITY,**

**COLLEGE OF NATURAL AND COMPUTATIONAL SCIENCES,**

**CENTER FOR ENVIRONMENTAL SCIENCE,**

# SOIL CHARACTERIZATION, INVESTIGATING PHOSPHORUS SORPTION CAPACITY AND RESPONSE OF CROPS TO LIMING AND PHOSPHORUS ON ACID SOILS OF BAKO TIBE AND OMO NADA DISTRICTS OF OROMIA REGION, ETHIOPIA

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**A Dissertation Submitted to the Center for Environmental Science in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Environmental Science**

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**June, 2024**
**Addis Ababa**

# DISSERTATION APPROVAL

## Addis Ababa University

## College of Natural and Computational Sciences

## Center for Environmental Science

This is to confirm the thesis organized by **Berhanu Dinssa Dibssata**: entitled, "**SOIL CHARACTERIZATION, INVESTIGATING PHOSPHORUS SORPTION CAPACITY AND RESPONSE OF CROPS TO LIMING AND PHOSPHORUS ON ACID SOILS OF BAKO TIBE AND OMO NADA DISTRICTS OF OROMIA REGION, ETHIOPIA**". It is submitted in fulfillment of the requirements for the Degree of Doctor of Philosophy (Environmental Science) that complies with the regulations of the University. It satisfies the acknowledged criteria for originality and quality.

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# ***DEDICATION***

This Ph.D. Dissertation is dedicated to my Mother Tayitu Alemi, who passed away during my Ph.D. study. It is also dedicated to my father Dinssa Dibssata, who passed away when I was an MSc student. Also, the dissertation is dedicated to my brother Nuguse Dinssa who always looked after my family during my study and supported me in the economy.

## STATEMENT OF AUTHOR

I declare that the Dissertation hereby submitted for the Degree of Doctor of Philosophy (Ph.D.) in **Environmental Science** to the School of Graduate Studies of Addis Ababa University is my own independent work and has not previously been submitted by me or anybody else at another University. The materials obtained from other sources have been duly acknowledged in the dissertation.

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# LIST OF ABBREVIATIONS

| | |
|---|---|
| AGDB | Aboveground Dry Biomass |
| ATA | Ethiopian Agricultural Transformation Agency |
| AWHC | Available Water Holding Capacity |
| Av. P | Available Phosphorus |
| Av. Fe | Available Iron |
| BD | Bulk Density of Soil |
| Bsl | Below sea level |
| BYLD | Biomass Yield |
| CASCAPE | Capacity Building for Scaling up of Evidence-based Best Practices in Agricultural Production in Ethiopia |
| CCE | Calcium Carbonate Equivalence |
| $Cmol_{(+)}kg^{-1}$ | Centimol per kilogram |
| CSA | Central Statistical Agency |
| $EPR_f$ | Freundlich External Phosphorus Requirement |
| Exch.Ac | Exchangeable acidity |
| EAS | Exchangeable acid saturation |
| Eq. | Equation |
| EthioSIS | Ethiopian Soil Information System. |
| Exch. Al | Exchangeable Aluminium |
| FC | Field Capacity |
| GLM | General Linear Model |
| GYLD | Grain Yield |
| ha | Hectare |
| HI | Harvest Index |
| ISSU | International Union of Soil Sciences |
| Kf | Freundlich Phosphorus Sorption Capacity |
| Kmol | Killo mole |
| Log x | Amount of Phosphorus Adsorbed |
| LSD | Least Significant Difference |

| | |
|---|---|
| Masl | Meters Above Sea Level |
| TN | Total Nitrogen |
| NPSB | Nitrogen, Phosphorus, Sulfur, and Boron blended fertilizer |
| $PBC_f$ | Frundlicch phosphorus Buffering Capacity |
| PBS | Percent Base Saturation |
| PH | Plant height |
| $P_t$ | Total porosity |
| Qt | Quntal |
| r | Correlation Coefficient |
| $R^2$ | Coefficient of Determination |
| SSA | Sub-Saharan Africa |
| SOM | Soil organic matter |
| SOC | Soil organic carbon |
| SYLD | Straw Yield |
| TP | Total Phosphorus |
| TSOC | Total soil organic carbon |
| WD | Well drained |

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# ABSTRACT

*Soil characterization is essential for understanding the properties, causes, and effects of acidic soils and devising appropriate management options. Soil acidity and phosphorus fixation are major causes of soil fertility decline and crop yield reduction in Ethiopian highlands. The high P-fixing property of soils makes available P below crop demand. A study was conducted to characterize and classify agriculturally potential acid soils, assess phosphorus sorption capacity, determine the external P and lime requirement of different soils, and evaluate the response of wheat to phosphorus application rates in the study area. Four soil types were considered, and twelve representative Pedons were opened and described. A total of 97 (52 disturbed and 45 core ring, undisturbed) soil samples were collected from identified horizons and examined in the field and laboratory for soil characterization. The soils were categorized into different reference soil groups (RSG). Phosphorus-sorption data were obtained by equilibrating 1 g of the 12 soil samples with 25 ml of* $KH_2PO_4$ *in 0.01 M* $CaCl_2$*, having 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, and 330 mg P* $L^{-1}$ *for 24 hours. The relationship between phosphorus sorption and soil characteristics was established by correlation analysis. The magnitude of the soil's phosphorus sorption capacity and external P requirement were affected by clay content, exchangeable acidity, organic matter,* $Al_2O_3$*, and* $Fe_2O_3$*. Alisols had the highest Kf value (413 mg P* $kg^{-1}$*), followed by Luvisols (336 mg P* $kg^{-1}$*), Andosols (280 mg P* $kg^{-1}$*), and Nitisols (280 mg P* $kg^{-1}$*). Nitisols, Luvisols, Alisols, and Andosols, had an external phosphorus requirement of 25, 30, 32, and 26 mg P* $kg^{-1}$ *soil sequentially. After assessing the degree of acidity of the soils, 2.28 t* $ha^{-1}$*, 3.60 t* $ha^{-1}$*, and 4.22 t* $ha^{-1}$ *lime was determined (based on the exchangeable acidity method) for Nitisols, Luvisols, and Alisols respectively. The integrated effects of lime and P fertilizer on maize yield parameters and selected soil chemical properties were examined on Nitisols, Luvisols, and Alisols for two years (2017/18-2018/19) under field conditions. The experiment consisted of eight treatments: (T1) control, (T2) 50% RL + 30 kg P* $ha^{-1}$ *+ 92 kg N* $ha^{-1}$*, (T3) 100% RL +30 kg P* $ha^{-1}$ *+ 92 kg N* $ha^{-1}$*, (T4) twice RL + 30 kg P* $ha^{-1}$ *+ 92 kg N* $ha^{-1}$*, (T5) 50% RL + 15 kg P* $ha^{-1}$ *+ 92 kg N* $ha^{-1}$*, (T6) 100% RL alone, (T7) farmers Practice (200 kg NPSB +92 kg N* $ha^{-1}$*), and (T8) 30 kg P* $ha^{-1}$ *+ 92 kg N* $ha^{-1}$*. Soil analysis results* *after harvesting showed that the addition of lime increased the soil pH and exchangeable* $Ca^{2+}$ *but decreased the levels of soil exchangeable acidity for all soil types. The Olsen available P content of plots treated with recommended lime plus critical P rate increased from 6.69 to 15.42 mg kg-1 in Nitisols, 6.71 to 22.27 mg* $kg^{-1}$ *in Luvisols, and 5.27 to 40.92 mg* $kg^{-1}$ *in Alisols. The application of recommended lime + critical P rates increased maize grain yield by 89.88%, 81.49%, and 84.38% over the control treatments and by 28.35%, 26.53%, and 26.73% over farmers' practices for Nitisols, Luvisols, and Alisols, respectively. Therefore, the use of twice the critical P level (60 kg P* $ha^{-1}$*) alone or the use of critical P level combined with the recommended lime rates by soil types can be used for optimum maize production in the study area. The study also found that the use of 40 kg P* $ha^{-1}$ *which produced the maximum wheat grain yield of all treatments can be recommended for wheat production.*

**Keywords:** *Lime rates, Pedon, phosphorus fixation, Soil characterization, Yield parameters*

# CHAPTER 1: GENERAL INTRODUCTION

## 1.1 NTRODUCTION

The study was conducted to characterize agricultural soils and investigate the lime requirement of acidic soils in the Bako and Omo Nada Districts of Oromia, Ethiopia, where the external P-fertilizer requirement was determined for maize production and the response of wheat to different rates of P fertilizer for optimal wheat production was evaluated. The importance of these findings lies in their potential to improve crop yields and ultimately contribute to food security in Ethiopia.

Soil characterization and classification refer to the process of assessing and categorizing soils based on their physical, chemical, and biological properties (Hartemink & Bockheim, 2013). It plays a crucial role in various fields such as agriculture, engineering, and environmental science. By understanding the characteristics and classification of soil, scientists and professionals can make appropriate decisions regarding land use planning, crop selection, construction projects, and environmental management. Overall, soil characterization and classification provide valuable insights into the properties and capability of soil for crop production, ultimately contributing to sustainable development and resource management.

Soil acidity is one of the major constraints that affect field crop production. It covers more than 43% of the land masses in Ethiopia. Maintaining soil fertility and soil health are the major factors in increasing agricultural yields in order to meet the food demand and raw materials for an ever-increasing population. In order to achieve maximum agricultural production, knowledge of soil acidity and the method of its mitigation has to be applied properly (Agegnehu et al., 2019). The farming communities prefer sustainable and easily practiced technologies to increase crop yield and ameliorate soil acidity.

Farmers in Ethiopia are facing challenges with soil acidity that is limiting their crop yields, leading to a need for sustainable and easy-to-implemented practices to address this issue. The introduction of lime as a soil amendment has shown promise in raising soil pH levels and improving crop productivity in acidic soils. Integrated soil fertility management techniques could be key in addressing the gap between potential and actual crop yields caused by soil acidity in Ethiopia. Research on crop varieties that are tolerant of acid soils could provide farmers with additional options for boosting yields in challenging conditions. Continued efforts to improve methods for estimating lime requirements will be essential for effectively neutralizing acid soils and increasing agricultural productivity in Ethiopia.

In this introduction, an overview, the appropriate review of the literature to justify the study and knowledge gaps regarding the problems related to soil acidity, the extent of acid soils in Ethiopian soils, the reclamation of soil acidity in agricultural soils, and the effect of lime on crop yield and selected soil chemical properties were highlighted. The role of phosphorus in plant growth, phosphorus fixation problems in acid soils, and its management were discussed. Finally, the objectives and methodology of the study, which aims to provide appropriate soil management options to sustain land productivity, and practical solutions for farmers to improve their crop yields and livelihoods, were outlined.

## 1.2 Background and Justification

The backbone of the Ethiopian economy is agriculture which contributes to over 40% of the country's GDP, creating job opportunities for 75% of the population, and 80% of national export commodities. Around 95% of Ethiopian agriculture is rain-fed subsistence farming with low input and low production (Tamene & Ali, 2022). However, agriculture in the highlands of Ethiopia faced critical problems, such as soil erosion, soil crusting, soil acidity, nutrient deficiency particularly P and other macronutrients, and soil fertility decline. Soil is a natural capital that gives a sustainable flow of goods and services such as human foods, fresh water, wood, fiber, and fuel (Adhikari and Hartemink, 2016). The global food production system depends more entirely on soil (Koch et al., 2013). It is believed that about 98.8% of everyday food consumption by the human population is obtained from the soil (2849 kcal per person) and only 1.2% is obtained from water (35 kcal per person) (Kopittke et al., 2019).

Phosphorus (P) is strongly fixed (tied-up) in the soils because of the precipitation of P with $Ca^{2+}$ in alkaline soils, and the adsorption of P with Fe- and Al-oxides and hydroxides in acid soils (Dotaniya et al., 2014; Schoumans & Chardon, 2015). Therefore, compared to the amount of P applied to the soils in the form of chemical fertilizers, a small quantity of P (10-20%) is available to crop plants (Menezes-Blackburn et al., 2018; Helfenstein et al., 2018). To overcome the problem of P fixation in agricultural soils, in the past few decades, a huge amount of P has been applied to the soils to increase the level of plant-available phosphorus (Jiang et al., 2015; Bouwman et al., 2017).

However, the excessive application of P in agricultural soils more than the plant requirement increases the chance of loss through erosion, flooding, and leaching losses which cause the fertility of the water body (eutrophication) (Lambers et al., 2013; Menezes-Blackburn et al., 2018; Ibrahim et al., 2022). Furthermore, the rock phosphate resources from which P fertilizers are manufactured are finite resources and depleted (Li et al., 2016; Khabarov & Obersteiner, 2017). The intensive use of rock phosphate for crop production and industrial raw materials creates pressure on the world P market and is assumed to be finished in the coming 40 to 400 years (Mardamootoo et al., 2021). P inadequacy is one of the most limiting factors for future food security (Y. Wang & Lambers, 2020). These disagreeing issues necessitate the wise use of P to meet the additional food requirements for the ever-growing human population.

Soil acidity is a major constraint to sustainable crop production in the southwestern region of the country. The low pH of these soils limits the availability of essential plant nutrients, particularly phosphorus, which is crucial for plant growth and development (Agegnehu et al., 2021). In addition, the high aluminum and manganese content in the soil further exacerbates the problem by inhibiting root growth and nutrient uptake. Therefore, there is a need to develop appropriate soil management strategies, including the use of lime and other soil amendments, to improve soil pH and nutrient availability for sustainable crop production in the southwestern region of the country (Enesi et al., 2023). This will not only increase crop yields but also ensure the long-term health and productivity of the soils.

In areas where soil pH levels are often below 5.5 and aluminum toxicity is a common problem, practices such as regular liming improve soil pH and reduce aluminum toxicity (Opala, P. A. 2017). The growing of acid-tolerant crop varieties Tandzi et al., (2018) is another option when lime is not affordable by some farmers due to economic reasons. These practices have led to increased crop yield and positively contributed to the food self-sufficiency of the nations while also improving soil health for future generations.

## 1.3. Literature Review

### *1.3.1 Soil Characterizations and Classification*

A large portion of Ethiopian land resources are not correctly identified, managed, and wisely utilized (Simachew, 2020). Soil characterization is used to classify soil and determine physicochemical characteristics that can not be seen in field soil description (Yitbarek et al., 2016). It plays a crucial role in agricultural practices, soil conservation, and land development. By understanding the composition and properties of soil, decision-makers, researchers, and farmers can make the right decisions to optimize crop production, prevent soil degradation, and promote sustainable land use practices. There is a need for continued exploration and advancement of soil characterization techniques to address environmental concerns and enhance engineering practices. Overall, soil classification is used to assess the properties, composition, function, and nature of the soil as part of landscapes and ecosystems. Understanding the characteristics of the soils used to devise effective management strategies for sustainable agricultural production and resource conservation. Soil characterization and classification provide basic information used for evaluating the fertility status of soils.

### *1.3.2 Soil Morphological Properties*

The soil morphological characteristics such as depth, structure, texture, and consistency influence the productive potential and fertility status of any soil. These properties in turn affect the cation exchange capacity, water-holding capacity, aeration, porosity, and temperature of the soil. The soil’s morphological properties that are assessed for characterization of the soils for the current study are briefly discussed as follows.

Based on the variation in topography and exposure to soil erosion, soils with different depths can be formed (Sheleme et al., 2023). Soil depth has a significant relationship with Soil physicochemical properties such as sand, silt,  OM, TN, AP, Mg$^{2+}$, K$^{+,}$ and Mg$^{2+}$ quantities that significantly decrease with increasing soil depth (Adugna & Abegaz, 2015). Likewise, Seuradge et al., (2017) stated, the number and species of soil microorganisms often decrease with increasing soil depth. The depth of the soil can determine the farming activities, the nutrient content, the plant's available water-holding capacity, and the plant root growth (Sheleme et al., 2023; Mengistu et al., 2017).

Soil color varies based on the type of parent materials from which soils are formed, the oxidation-reduction reaction that takes place in the soil, the types of minerals present, and the quantity of OM in the soil (Mathewos et al., 2023). Soil color is one of the criteria used for soil identification and classification based on the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2022).  During the weathering and soil formation process, soil colors are developed and distributed across the soil profile.

Soil structure refers to the way the sand, silt, and clay particles are arranged together into aggregates of different sizes and shapes (Tiecher et al., 2022). It is associated with the soil texture and the organic matter content of the soil (Sheleme et al., 2023), Soil structure is highly affected by soil management practices and differs significantly in response to land use change and with soil depth. The soil structure and consistency attributes of most Ethiopian soils are associated with their texture and content of OM (Sheleme et al., 2023). For instance, Alemayehu et al., (2023) stated, that surface soils with high clay content exhibit medium to strong coarse, angular, or subangular blocky structures. Weak and fine subangular blocky structures are associated with horizons that contain a high percentage of silt and sand. Mathewos, (2023) also reported that soil with more clay percentages (such as montmorillonite) have hard and extremely hard dry consistencies, while soils with more percentage of sand and coarse fragments have slightly hard dry consistencies (Mathewos, 2023).

### *1.3.3 Soil Physical Properties*

Some selected soil physical properties such as texture, bulk densities (BD), and water-holding capacity are briefly reviewed in this section. Soil texture can be defined both in quality and quantity. Qualitatively, it indicates the feel of the soil whether it is coarse and gritty or fine and smooth or sticky when rubbed between the forefinger and the thumb (V.K. Phogat et al., 2015). Soil texture is defined quantitatively as the percentage of sand, silt, and clay particles in the soil (Weil & Brady, 2017). Various types of soil forming factors and processes resulted in the formation of a wide variety of soil particle size distribution in Ethiopia. The soil texture affects all other characteristics of soil particularly those related to soil fertility and quality, CEC, porosity, water holding capacity, and gaseous diffusion. It is a static soil attribute and the one most often used to characterize the soil's physical properties. The texture has a significant impact on the land use capability and how the soil is managed (Mohan & Prasadini, 2019).

According to Walter et al., (2016), bulk density (BD) is determined as the ratio of the oven-dry mass of soil to its bulk volume (the solids as well as pores volume) and it can be expressed in $g/cm^3$ or 1000 $kg/m^3$. Information on soil BD is essential for understanding the soil's physical, chemical, and biological properties. The major soil properties that are significantly influenced by soil BD are infiltration rate, rooting depth, plant available water content, pore space and aeration, and microbial activity. Sols with high OM content are porous and low in bulk density. The values of BD that limit the growth of plant roots are influenced by the soil textural class. Loose and porous soils have lower bulk densities than more compacted soils (Hao et al., 2019). The soil BD increases with increasing the soil depth (USDA-NRCS, 2019).

Soil moisture is the amount of water present in soil pore space (Liu, Q. et al., 2022). It determines the availability of water for crop requirements. The soil's moisture content is significantly affected by some soil properties including soil depth, texture, structure, bulk density, and soil organic matter content. The soil textural class and total soil depth are evaluated relative to water holding capacity. For example, the soil texture is assessed to 1 m depth for its capacity to retain water since most crops fulfill their major water requirements at 1 m soil depth. Also, coarse-textured soils (sandy soils) usually have maximum infiltration rates and the least water storage capacities; medium-textured soils show medium storage capacities while the heavy clay soils mostly the montmorillonitic clay minerals have low infiltration rates show maximum water holding capacity (Easton & Bock, 2016).

Soil porosity is a changeable soil characteristic that is influenced by soil properties such as soil bulk density, structure,  and texture (Sheleme et al., 2023).  According to Nimmo (2004), the porosity of the mineral soils is influenced by packing density, shape, size of soil particles, and cementing agents. Similarly, Feto, (2016)  reported farming operations with heavy machinery compact the soil and adversely affect the soil porosity. With increasing soil depth, the soil's total porosity decreases because, with decreasing soil OM content of the soil, there is an increase in the soil’s compaction and BD (Semu et al., 2022).

### *1.3.4 Soil Chemical Properties*

Soil pH, known as soil reaction, is the measure of acidity or alkalinity of the soil (K. T. Osman, 2018). It is an indicator of $H^+$ activity, that interacts with soil constituents, nutrient solutions in the root environment, and the plant roots (Getachew et al., 2021). Soil pH is the "master variable" because it affects a wide range of biological, chemical, and physical soil characteristics and functions that affect plant development and biomass production (Neina, 2019). As stated by the same author, soil pH affects different biochemical processes in the soil such as mineralization of OM, nitrification and denitrification, ammonium volatilization, soil enzyme activities, rhizosphere procedures, and many other processes. The solubility and availability of most plant nutrients (particularly, the available P), and the activities of the soil microorganisms are also determined by the range of soil pH. (Penn & Camberato, 2019).

The organic component of soil that decays and reaches the stage of no longer being recognized is known as soil organic matter (SOM). It is obtained from plant and animal remains in various stages of decomposition, soil organism cells and tissues, and chemicals produced by soil organisms (Sheleme et al., 2023). Soil OM has a significant qualitative impact while being present in the soil in small quantities. It is important to maintain the chemical fertility of the soil by adsorbing the positively charged ions ($Ca^{2+}$, $K^+$, $Mg^{2+}$) on their negatively charged surfaces and supply nutrients (N, P, and S) in mineralization processes and maintain the physical fertility of the soil by improving water retention, soil aggregate stability, and minimizing soil erosion (Chenu et al., 2015). The level of soil OM in the soil is used as the criteria in the FAO WRB soil classification (IUSS Working Group WRB, 2022). It decreases with increasing soil depth (Kunlanit et al., 2020). The soil OM content is commonly determined from the values of its most abundant element, C and SOM = SOC x 1.724 (Chenu et al., 2015).

Nitrogen (N) is one of the most limiting macronutrients in crop productivity (Anas et al., 2020). Nitrogen is involved in many physiological processes such as the photosynthetic process, phyto-hormonal, protein production, and growth-development of plants to complete their lifecycle. Additionally, it can promote root development, and enhance root volume, area, diameter, total length of roots, and dry mass. The soil total N and organic matter content are strongly and positively correlated and decrease with soil depth (Lepcha & Devi, 2020).

In nature, phosphorus occurs in the earth's crust, water, and all living things. Apatite ($Ca_5$ (PO4)) is the principal mineral that contains a significant amount of phosphorus (Karamesouti & Gasparatos, 2017). About 0.1% of the total phosphorus becomes available for plant absorption in surface soil which typically contains 50 to 3000 mg $kg^{-1}$ of phosphorus (Karamesouti & Gasparatos, 2017). Even though phosphorus exists in soil both in inorganic and organic forms, the inorganic phosphorus such as orthophosphate ions ($H_2PO_4^-$ and $HPO_4^{2-}$) is absorbed by the plant roots (Fageria et al., 2017). According to the report of Tian et al., (2021), the quantity of available P in the soil decreases with increasing the soil depth while more quantity of available P in the surface soil (Yang, L. et al., 2021).

Phosphorus is a crucial element for all living organisms and also for crop production (Elser, 2012). Still, it is the most deficient and yield-limiting element since P-fixation (adsorption) is a common problem mainly in Tropical and Sub-tropical environments. In Ethiopian major agricultural soils such as Luvisols, Nitisols, Alisols Andosols, Cambisols, and vertisols, phosphorus is deficient and the most limiting nutrient for crop production (Alemayehu et al., 2023). Low P availability associated with P-fixation which resulted in crop yield reduction can be improved by liming, integrated use of lime and chemical fertilizers, and a high amount of P-fertilization **(**to satisfy the high P-fixing capacity of the soils), Antoniadis et al., (2015), and use of slow soluble chemical P fertilizers such as rock phosphates to minimize the rate of P-fixation (Teles et al., 2020).

Cation exchange capacity (CEC) is the sum of the negatively charged exchange sites on the soil colloidal surfaces. It is a measure of soil's capacity to retain and release cations. (Weil & Brady, 2017). Commonly, the cations present in the soil are calcium ($Ca^{2+}$), magnesium ($Mg^{2+}$), potassium ($K^{+}$), sodium ($Na^{+}$), hydrogen ($H^{+}$), and aluminum ($Al^{3+}$), and less abundant are ammonium ($NH_4^{2+}$), Fe, Mn, Cu, and Zn (Winfried, 2018; Aprile & Lorandi, 2012). The term "effective cation exchange capacity" (ECEC) refers to the CEC calculated from the total of all cations in the soil. CEC is expressed in centimol of charges per kilogram of soil ($cmol_{(+)}\ kg^{-1}$). Soils with high clay and OM content tend to have a high CEC while sandy soils have low CEC (Astera, 2018). Usually, the value of CEC in the surface soil is associated with the OM content of the soils, but the CEC of subsurface soils is more closely related to the clay content of the soils (Weil & Brady, 2017). Studies on the CEC values of major RSGs of Ethiopian soils revealed higher CEC values for Vertisols (Yihenew, 2002), Fluvisols, Cambisols, Leptosols, and Regosols (Gebeyaw, 2015), but low CEC values for Acrisols and Nitisols (Yihenew, 2002).

Percent base saturation (PBS) is the percentage of the cation exchange capacity occupied by the basic cations other than hydrogen (H) and aluminum (Al) (Hazelton & Murphy, 2016). Soils with low base saturation generally are acidic and high base saturation indicates neutral to alkali soils as base saturation and pH increase together (Tiecher et al., 2022). As stated by Hazelton and Murphy, (2016), the base saturation percentage is a good indicator of the level of leaching of the cations from the soil system, and an important criterion in soil classification systems of the World Reference Base (IUSS Working Group WRB, 2022). Based on their location and agroecological zones, there are differences in the percent base saturation (PBS) of the Ethiopian soils. In the highlands of Ethiopia, where there is high annual rainfall, the PBS is usually low (<50%) and on the other hand, in arid and semi-arid regions of the country, (where the evapotranspiration is higher than the amount of rainfall) there is high values of PBS (Alemayehu et al., 2023).

Exchangeable acidity (EA) is primarily associated with the exchangeable Al and H ions that are present in large quantities in highly acidic soils. It is the sum of Al and H ions in the soil exchangeable complex and is inversely related to the base saturation and pH of the soil (Weil & Brady, 2017). In Southwestern Ethiopia, the level of exchangeable acidity is in the range of very high (6–8 cmolc kg-1) to extremely high (>8 cmolc kg-1) (Sheleme et al., 2023).

### *1.3.5 The Extent and Magnitude of Soil Acidity in Ethiopia*

Worldwide, soil acidity has become a global problem. About 30% of the world's total area and 40-50% of the world's potential agricultural land is acidic ($pH < 5.5$) (Dai et al., 2017; Osman, 2018). Also, 35% of the soils in Sub-Saharan Africa (SSA), the sub-humid, and humid parts of West and South Africa, and East and Central Africa are acidic (Getachew et al., 2021). Soil acidity extends and covers a vast area from southwestern (Ilubabor, Wollega, and Keffa) to north-western (Gojam and Gonder), southern (North Bale, North Sidamo), and central (Arsi and Shewa) regions of Ethiopia that receive a high amount of rainfalls that washdown soluble salts and exchangeable bases from the upper layers to the bottom layers of the soil (Tigist et al., 2019).

In Ethiopia, from the total area coverage (111.8 million hectares), about 70.66% of the land is suitable for agricultural activities. Different researchers reported that the extent and coverage of acid soils in Ethiopia are increasing from time to time and limit the productivity of agricultural lands. For instance, Mesfin (2007) stated that soil acidity affected about 41% of Ethiopia's total landmass. EthioSIS, (2015) also reported that acid soils of Ethiopia account for about 43% of the agricultural land. According to Desta et al., (2021) currently, 47% of the total landmass of Ethiopia is in the range of slightly (pH < 6.5) to strongly acidic soil (pH 4.1-5.5) while 45% of the rainfed agricultural land of Ethiopia is in the range of extremely acidic (pH < 4.5) to slightly acidic (pH < 6.5). The Vast area of land at high altitudes found in almost all regions of Ethiopia is under the impact of soil acidity (Getachew & Tilahun, 2017; Mosissa, 2019).

In the Western highlands of Oromia, Nitisols with acidic reactions cover the largest area in the region (Desalegn et al., 2017; Eyasu, 2016). In the Bako Tibe district, the soils were acidic in reaction (the pH was in the range of 4.5 - 6.4). About 46% of the soils were strongly acidic and 54% were moderately acidic in reaction (Gezu & Tekalign, 2019). Agricultural soils within the pH range of 6-8 are the most conducive for crop production since the plant nutrients are at maximum availability (Jackson M. L., et al., 2018)**.**

### *1.3.6 Major Causes of Soil Acidity*

#### *1.3.6.1 Natural processes*

As illustrated in Figure 1, there are various natural processes and man-made activities that cause soil acidity (Holland et al., 2018; Sanchez, 2019). Naturally, soil acidity develops gradually over time as part of the soil development process and other natural phenomena (Franklin Obiri-Nyarko, 2012). In Tropical regions, acid soils are formed due to hot temperatures and high precipitation that favors the weathering of acid-forming parent materials (Rengel, 2011) accompanied by remarkable base leaching ($Ca^{2+}$, $Mg^{2+}$, $K^+$, and $Na^+$) and substitutions of $Al^{3+}$, $Fe^{2+}$, and $H^+$ ions on the soils exchange sites

(Olego et al., 2021; Sisay, 2019, and Hue, 2022). During the decomposition of OM, $H^+$ which is the source of soil acidity is released (Zhang et al., 2020). Similarly, previous studies by Guo et al., (2010) in China revealed that N cycles such as N-fertilizer application and nitrification add 20–30 kmol $H^+$ $ha^{-1}$ $yr^{-1}$ into the soil.

### *1.3.6.2 Man-made activities*

Human activities such as intensive cultivation and continuous crop production can enhance the formation of acid soils. Rapid population growth and various human activities to feed the ever-increasing population have increased the rate of soil acidification and worsened its impact on agricultural activities. Continuous use of inorganic nitrogen and sulfur fertilizers particularly ammonium sulfate aggravates the problems of soil acidity Yuan et al., (2018. ); Zhu et al., (2019), Cai et al., (2019) due to the release of a proton ($H^+$) during the nitrification of ammonium ($NH_4^+$) Dai et al., (2017); Zhang et al., (2020) indicated as: $NH_4^+ + 2O_2 \Leftrightarrow NO_3^- + 2H^+ + H_2O$. Indirectly, N fertilizer application causes soil acidification by increasing crop growth, as the uptake of base cations releases comparable amounts of $H^+$ to the rhizosphere (Zhang et al., 2020).

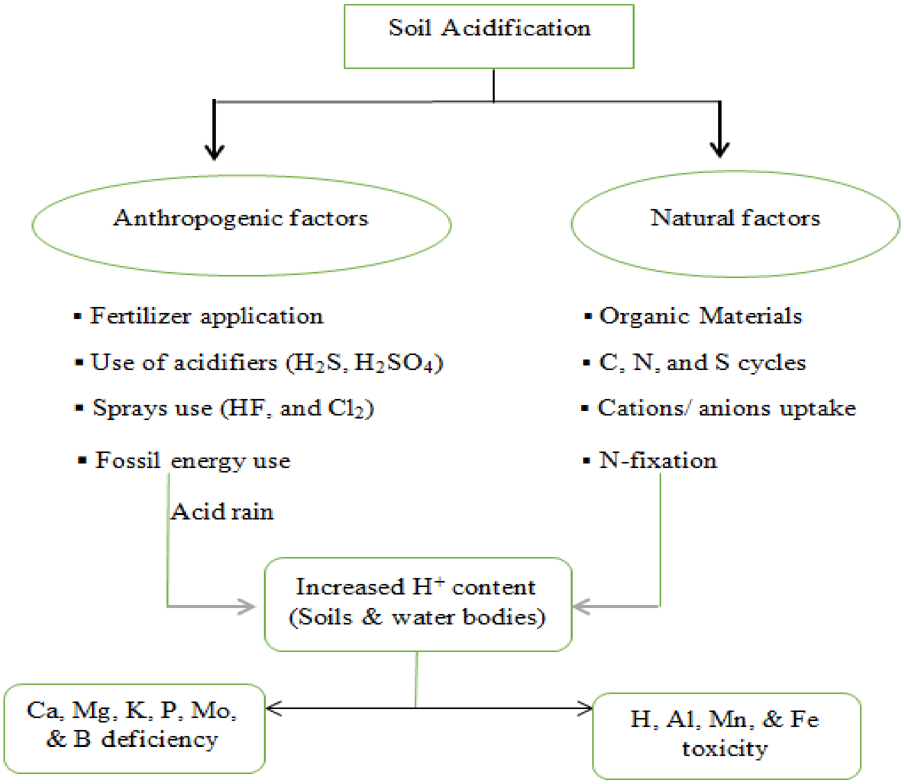

Figure 1.1 Some of the natural and anthropogenic factors that cause soil acidification. Source: Bojórquez-Quintal et al., 2017

### *1.3.7. Impacts of Soil Acidity*

Acid soils are widely spread in terrestrial ecosystems and highly challenge human food self-sufficiency through the reduction of crop production (Liu, X. et al., 2020). Acid soils are deficient in major plant nutrients such as Ca, Mg, P, and Mo and an excess supply of Al or Mn (low soil fertility); and decreased rate of nitrification, nodulation, mineralization, and mycorrhizal infection Kunhikrishnan et al., (2016; Peter et al., (2018); Desta et al., (2021) and significantly affects the nations' food self-sufficiency. Soil acidity and related nutrient deficiency limit land productivity and crop production and also affect plant distribution all over the world.

#### *1.3.7.1 Toxicity of specific elements*

In very acidic soil reactions (< 5.0 pH), the solubility and availability of Al, Fe, and Mn increase and reach a toxic level (K. T. Osman, 2018). In this strongly acidic soil reaction (pH < 5.0**),** the clay minerals such as feldspars start to hydrolyze and $Al^{3+}$ is released into the soil solution. High levels of $Al^{3+}$ and Mn reduce root growth and the plant's ability to absorb water and essential nutrients from the soil and finally decrease the growth and yield of crops (Arshad et al., 2012).

### *1.3.7.2 Competing for exchange sites of soil colloids*

The uptake of some macronutrients ($Ca^{2+}$, $Mg^{2+}$, and $K^+$) and micronutrients (Zn and Mn) are adversely impacted by toxic concentrations of $Al^{3+}$ in the soil (Sade et al., 2016). Gupta et al., (2013) reported the absorption of cations such as $Ca^{2+}$**,** $Mg^{2+}$**,** $K^+$, and $NH_4^+$ decreased by 69 %, 29 %, 13 %, and 40 % respectively when plants are under $Al^{3+}$ toxicity stress in acidic soils. Also, Yang, D. et al., (2017) found that the $NO_3^-$ uptake was minimized as the concentration of Al increased in the soil solution.

### *1.3.7.3 Phosphorus-fixation problem*

Even though phosphorus (P) is the most yield-limiting element next to nitrogen (N), it is the most deficient plant nutrient in the soil. The extensively weathered Tropical acid soils such as Kaolinitic clays are rich in Al-and Fe-oxides and hydroxides (Gerard, 2016; Spohn, 2020, Gupta et al., 2020). The low availability of P in acid soils is usually due to the fixation of P by iron (Fe) and aluminum (Al) and the formation of AI or Fe-phosphate complex which is insoluble in soil solution and the quantity of available P can be reduced (Johan et al., 2021).

The phosphorus sorption capacity of the soils is mainly determined by the soil's physico-chemical properties such as textural class, Fe and Al oxide content, the types of clay minerals present, and the soil's pH and organic matter content (Hanyabui et al., 2020; Getie et al., 2021). Adsorption which is the net accumulation of chemical species at the interface between a solid phase and an aqueous solution phase determines the availability of native soil P and the rate of P applied to soils in fertilizers (Hanyabui et al., 2020). Phosphorus fixation is used to express both phosphorus sorption and P-precipitation. As P availability is reduced both by phosphorus sorption and P-precipitation reactions, a soil with a greater P-fixation capacity has lesser available P after the addition of P fertilizers compared to soils having a lower P-fixation capacity. Determination of the phosphorus sorption capacities of soils is essential for a better understanding of P, wise utilization of P resources, determining the optimum rate of P fertilizer, and designing the best management options of P for high P-fixing soils (Fikre et al., 2019).

#### *1.3.7.4 Retardation of soil microorganisms' activity*

Liu et al., (2020) stated that the acidic soil reaction (pH 4.5) inhibits the activity of soil microorganisms. Similarly, Fikre et al., (2019) stated the activities of soil microorganisms are significantly inhibited in acidic soil with a pH of 4.5 in comparison to soil at pH 6.5. Husnain et al., (2021) reported that the microbial community, composition, and their activities are affected by low soil pH. Almost all the microbial processes, such as the rate of decomposition of OM and cycling of nutrients, are lowered in acidic soil reactions since the soil pH limits the growth and reproduction of the soil microbes, particularly bacteria and fungi. A one-unit decrease or increase in the soil pH decreases microbial growth by 50% (Husnain et al., 2021). The optimum range of pH for microbial activities is in the pH range of 6.6 to 7.3. In general, soil acidity and related nutrient deficiency limits land productivity and crop production and also affect plant distribution all over the world.

### *1.3.8 Management of Acid Soils*

#### *1.3.8.1 The use of acid-tolerant crop varieties*

Recently, to overcome the problem of soil acidity, acid-tolerant crop species were developed and can be used as one alternative to acid soil management (Sanchez, 2019) particularly when there is a financial problem that limits the liming of acid soils (Sade et al., 2016). However this approach is not able to reverse acidic soil conditions, it significantly contributes to improving and increasing crop yield on acid soils. Relatively a variety of crops have been found to survive in acid soils because of their varying degrees of tolerance to acidity. Sorghum, millet, potatoes, tomatoes, onions, sugarcane, rye, lupin, and several tropical fruits are examples of acid-tolerant crops that might grow well on low pH soils (4.5 to 7.0) that account for 75% of Ethiopia's rainfed agricultural land (Desta et al., 2021). Getachew et al., (2019) stated that the use of acid-tolerant cultivars of maize resulted in a yield increase of 51% in Cameroon and Kenya.

### *1.3.8.2 Liming*

A well-known acid soil management option is liming, the practice of applying mineral calcium and magnesium compounds (carbonates, oxides, and hydroxides of Ca and Mg) into acidic soils to reduce $H^+$ or raise the pH and maintain an environment that is favorable for the growth of plants and yield increase (Mulugeta, 2021). According to Yuan et al., (2018), the application of lime to acid soil lowers the phytotoxic effects of $Al^{3+}$, and increases pH and the availability of Ca, Mg, and also improves the development of plant root and the P uptake. When dissociated in water, the agricultural limes give negatively charged ions such as carbonates ($CO_3^{2-}$), hydroxides ($OH^-$), and silicates $(SiO_4)^{4-}$which reacts with the $H^+$ and $Al^{3+}$ ions (acid-forming cations) and form insoluble minerals of Al and water and then consequently, reduce the soil acidity (Enesi et al., 2023). Liming acidic soils is commonly promoted as an effective management practice to increase soil pH, and ameliorate toxicity caused by high levels of Al and Mn.

### *1.3.8.3 The use of organic amendments*

The application of OM such as crop residue and other organic materials significantly increases the soil pH, decreases the quantity of aluminum in the soil, and reverses the harmful effect of soil acidity (Butterly et al., 2013). In highly acidic soils, aluminum chelated with OM has no phytotoxic effect (Nogueirol et al., 2015). In addition, $Al^{3+}$ is complexed with organic functional groups (e.g. -O, -OH,-COOH) through specific adsorption (Dai et al., 2017).

### *1.3.9 Phosphorus sorption capacity of acid soils*

The phosphorus sorption capacity (Kf) of soil is defined as the capacity of the soil to tie up phosphorus added to it (Gonzalez-Rodriguez & Fernandez-Marcos, 2018). The external P requirement (EPR) refers to the standard P requirement (SPR), which is the quantity of P that has to be absorbed by the soil to retain the soil solution P level of 0.2 mg P $L^{-1}$ (Wolde & Haile, 2015). Phosphorus-buffering capacity (PBC) is defined as the ability of soil to resist changes in the concentration of soil solution P (Shirvani et al., 2013).

Usually, Vertisols and Mollisols contain more of a 2:1 clay mineral and have low phosphorus-fixation capacities if not they are calcareous. Iron and aluminum oxides are more common in Ultisols and Oxisols. Andisols, characterized by high amounts of amorphous oxides and allophane, have the highest phosphorus-fixing capacity, and their productivity is mostly restricted by this property (Weil & Brady, 2017).

## 1. 4 GENERAL METHODOLOGY

### *1. 4.1 Description of the Study Area*

#### *1.4.1.1 Location*

The sites considered in the present study are among the agriculturally important soils in the Bako Tibe and Omo Nada Districts. Bako Tibe District is found in the West Shewa Administrative Zone of the Oromiya region (Figure 1.1). It is 250 km from Addis Ababa to the West direction, on the main road to Nekemt. Geographically the district is situated between 9°12'35"- 9°7’30’’N and 37°58’25’’- 37$^{o}$13’40’’E. Bako Tibe district is bordered on the South by Boneya Boshe district of the East Welega Zone, West by Gobu Seyo of the East Welega Zone, on the North by Gudeya Bila of Horo Gudru Welega Zone, and the East by Cheliya district of West Shewa zone.

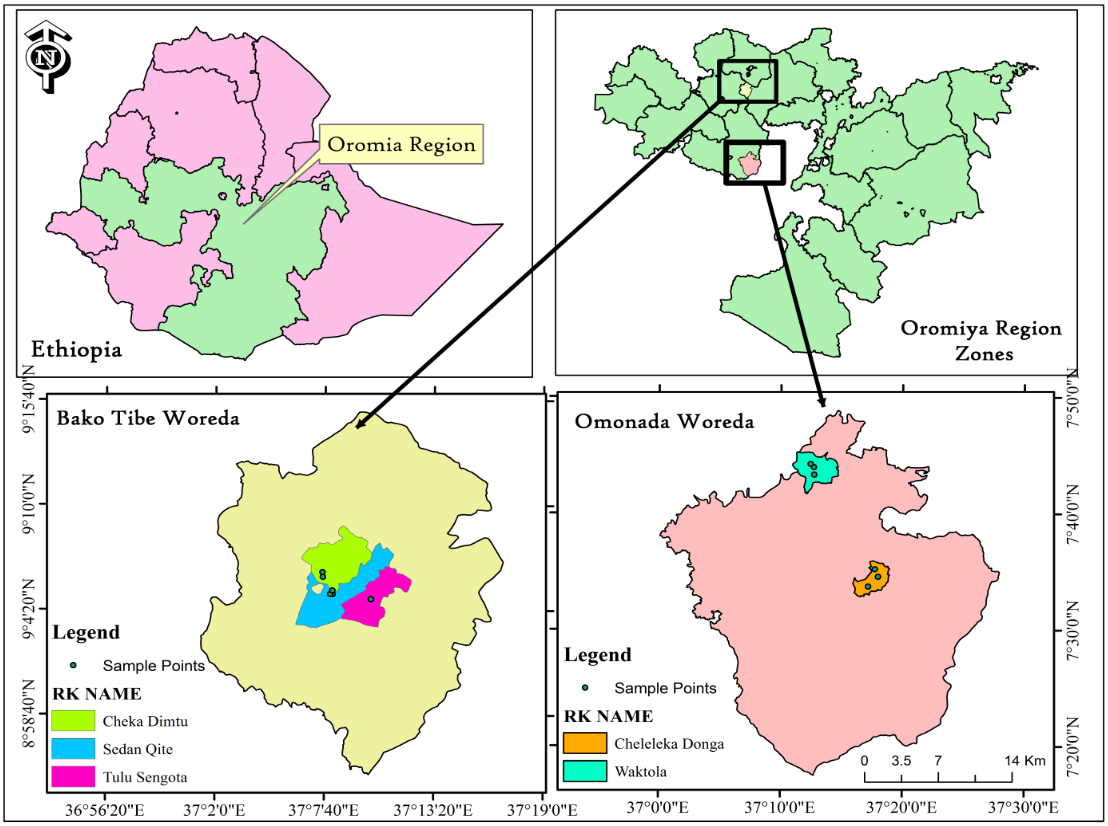

Figure 1.2 Location map and soil sampling sites of the study area

Note: Rk = Rural kebele (Peasant association)

The Omo Nada district is located in the Oromia region and Southwestern part of Ethiopia and lies between 7° 48' 25.236" to 7° 17' 5.6004" ’N and 37° 0' 4.464" to 37° 26' 53.7684" E. It is located at a distance of about 71 km from the zonal capital. It is bordered by the Dedo district in the West, Sokoru district in the North, Kersa district in the South, and Tiro Afata district in the East.

#### *1.4.1.2 Climate and topography*

Bako Tibe district is characterized by flat plains, high mountains, and hilly ridges. The altitude of the study area in the Bako Tibe district is in the range of 1674-2800 masl with an average elevation of 1732 m.a.s.l. The major agro-ecological zones of the Bako Tibe district are Tepid sub-humid mid-highlands, Tepid moist mid-highlands, Warm sub-humid lowlands, and Cool moist mid-highlands (Eyasu, 2016).

The rainfall data (unpublished data) obtained from the nearest weather station (Bako Agricultural Research Center) reveals that the rainy season covers April to October and the maximum rain is received in June, July, and August. The long-term (1976- 2017) mean annual rainfall is 1267 mm with an unimodal distribution. The area has a warm humid climate with the mean minimum, and mean maximum, air Temperatures of 13.9 $^0$C, and 28.1 $^0$C respectively (Figure 1.3).

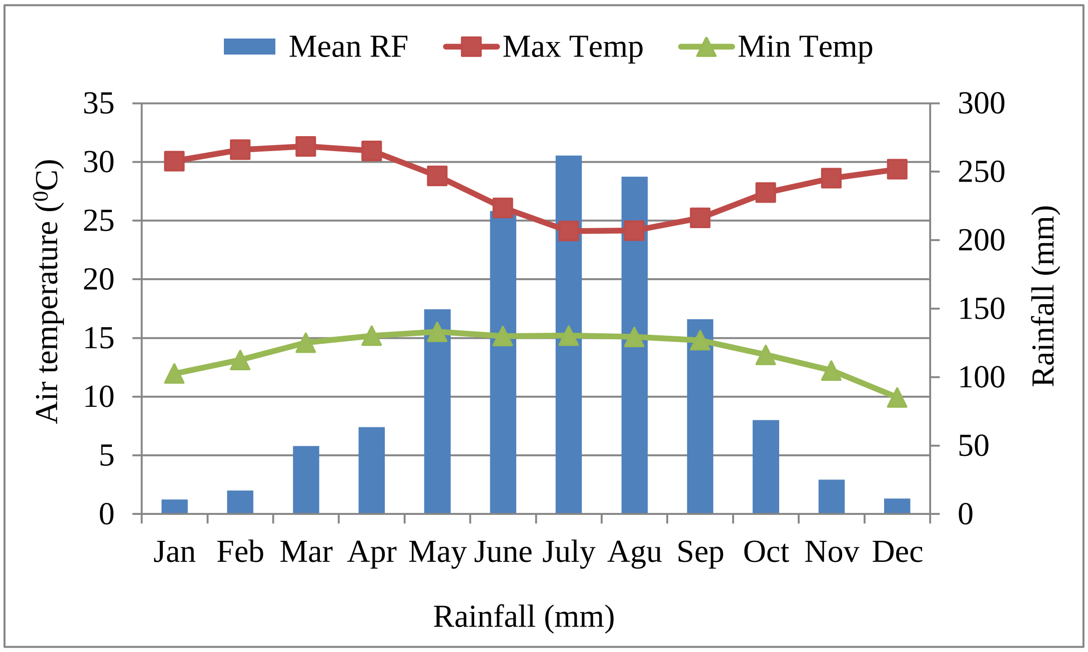

Figure 1.3: Long-term (1976-2017) mean monthly rainfall distribution and air temperature ($^0$C) of Bako Tibe district.

Source: BakoAgricultural Research Center (BARC), (unpublished data).

The major land topography of the Omo Nada district is high to mountainous relief hills, undulating to rolling high plateaus, major river gorges, canyons, and escarpments, and moderate to high relief hills. The major agroecological zones of the Omo Nada district are Tepid sub-humid mid-highlands, Warm sub-humid lowlands, and Cool sub-humid mid-highlands account for about 79%, 11%, and 10% of the area respectively (Eyasu, 2016). Based on the climatic data obtained from Jimma Agricultural Research Center (the nearest metrological station), the rainfall of the Omo Nada district is bimodal, with an erratic short rainy season from March to April and the main rainy season extends from June to September. The long-term thirty-year average rainfall is 1730 mm per year. The mean monthly minimum and maximal air temperatures are 12°C and 26 °C, respectively (Figure 1.4).

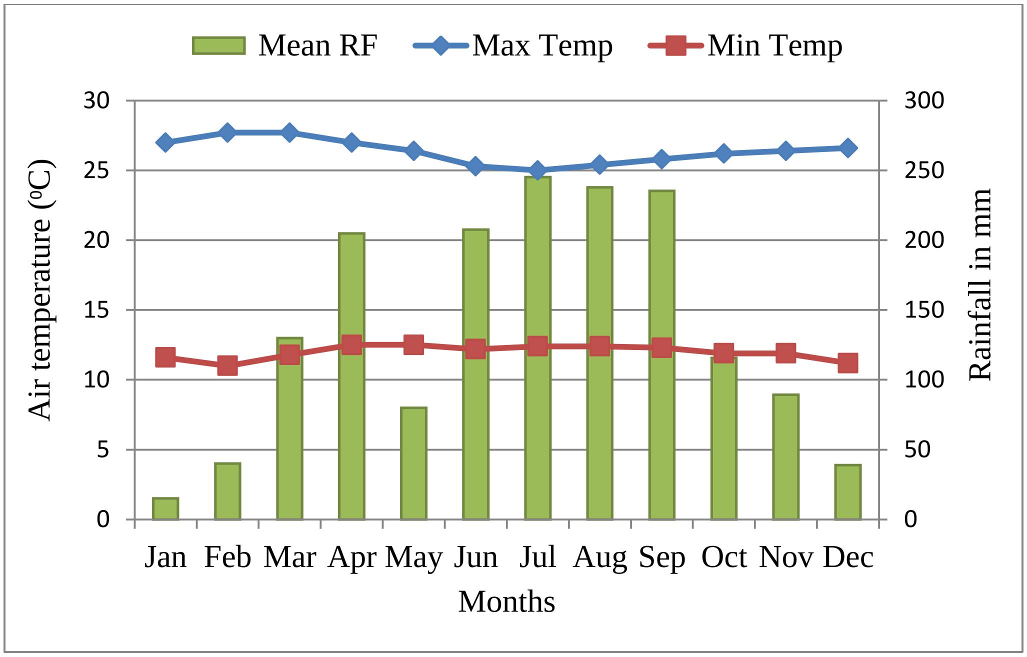

Figure 1.4: The thirty years (1988-2018) mean monthly rainfall distribution and air temperature ($^{0}$C) of Omo Nada district.

### *1.4.1.3 Soil and geology*

The geological feature of the Bako Tibe district is characterized by tertiary sediments of the Cenozoic era on the plain and basalt rocks in the High Mountain and hilly ridges (Billi, 2015; Eyasu, 2019). According to the IUSS Working Group WRB, (2015), the main soils identified in the BakoTibe district include Nitisols, Luvisols, Vertisols, Leptosols, and Fluvisols, and Nitisols is the most dominant soil type in the District. The mean pH value of the surface soil varies from 4.81 to 5.73. Thus, the topsoil is very strongly to moderately acidic in reaction (Table 4.1). The soils in Omo Nada are formed from volcanic parent materials (Sheleme et al., 2023). The most dominant soil types of the district include Nitisols, Luvisols, Andosols, Vertisols, Planosols, Acrisols, and Alisols (Eyasu, 2016). Alisols are strongly acidic in reaction while Andosols are slightelt acidic in reaction.

### *1.4.1.4 Land use and farming system*

As stated by different farmers, in Bako Tibe in the recent past, there has been a land use change, especially from forest land to cultivated fields and then to grazing lands. The reason for the change in land use was expansion of the farmland even towards the marginal and degraded areas, to feed the ever-increasing population number. The data from the agricultural development bureau of the area indicated that, currently, the cultivated land accounts for about 35,160 ha, grazing land for 12,670 ha, residences 19,720, shrub land 10, 380 ha, and the forest land (3,970 ha) almost gets nil except for small pouches of sparse small bushy trees along the river edges. The total land under natural forests before 2-3 decades was shifted to arable lands and few were replaced by exotic plantations. Mostly, grazing land was the land left as a narrow pouch around the homesteads, as the boundary of the fields or an abandoned land left out of production after the field was continuously cultivated for more than 15 years.

The farming system at and around Bako Tibe is of a subsistence nature involving a mixed crop-livestock production agricultural system. Rain-fed crop production is the dominant farming system in the study area. The most commonly grown annual and perennial crops in the study area include maize (*Zea mays*), sorghum (*Sorghum bicolor* L. Monch), *Teff* (*Eragrostis tef* (zucc.) Trotter), finger millet (*Eleusine coracana*), hot pepper (*Capsicum frutescence* L.), sugarcane (*Saccharum officinarum* L.), sweet potato (*Ipomoea batatas* Lam.), haricot bean (*Phaseolus vulgaris* L.), soybean (*Glycine max*), Niger seed (*Guziotia abyssinica*), mango (*Mangifera indica* L) and banana (*Musa spp*), *etc*.

In the Omo Nada district, the total area of land was categorized into different land uses such as communal grazing area (40,387 ha), dense forest (10,097 ha), Rain-fed cultivation (91,037 ha), settlement and homestead and irrigable lands (18,751 ha). In the Omo Nada district, the farming system is also a mixed crop-livestock agricultural activity. In the home garden, chat (*Catha edulis*) and ensete (*Ensete ventricosum*) are dominant. *Juniperus procera* is used as a live fence and a few remnants of *Hagenia abyssinica* are scattered around the homestead. There is abundant *Eucalyptus* *comandulensis* planted on the side slopes of the surrounding hills. Bamboo dominantly occurs along the banks of streams.

The major crops grown in the area are wheat (*Triticum spp.*) the most dominant field crop, fava bean (*Vicia faba*), field pea (*Pisum sativum*), maize (*Zea mays*) rapeseed (*Brassica spp.*) and barley (*Hordeum vulgare*). Most farmers rotate legumes with cereals as a soil fertility management practice. Farmers apply mainly 100 kg urea and 100 kg NPSB fertilizers for crop production. The homestead plots receive farmyard manure. Crop residues are used as livestock feed and fuel. Animals are allowed to graze free on cultivated land during the offseason.

### *1.4.2 Research Methodology*

The general methodology of the study described here was commonly used for the four major research objectives namely, (1) the characterization and classification of the acidic (low-pH) soils of the Bako Tibe and Omo Nada districts of Oromia, Ethiopia, (2) the Evaluation of the phosphorus sorption capacity, the determination of the external P and lime requirement of acidic soils in Bako Tibe and Omo Nada districts of Oromia, Ethiopia, (3) assessment of the integrated effects of lime and P fertilizer on maize yield parameters and selected soil chemical properties at Bako Tibe and Omo Nada Districts of Oromia, Ethiopia, and (4) evaluation of wheat response to different rates of P and fertilizer recommendation for optimum wheat production at Omo Nada in Southwestern Ethiopia.

Prior to establishing the experimental fields, a discussion was made with the farming community, the intention of the research work was explained and the farmers were convinced. Then the sites were selected based on the soil type (RSG), and their acidity problem. Potential for crop production (maize & Wheat) and the willingness of the farmers. Various methodologies used in this study such as the description of the study area, soil sampling methods, soil analysis procedures (physicochemical properties), and methods of statistical analysis, were designed to best fit the general study objectives (objectives 1-4). The environmental and soil profile description (objective 1), determination of the soil phosphorus sorption capacity and lime determination method (objective 2), experimental designs in field experiments, and economic analysis were used in conducting the individual research activities (objectives 3 and 4).

The data used in the study were obtained from qualitative data (field observation) and quantitative data such as soil lab analysis, and agronomic data from field experiments. The methods of data analysis employ models such as the Freundlich model, the general leaner model (GLM), and statistical analysis software (SAS). Different methodologies and data generated during the research work together gave a comprehensive insight into the research topic.

Previous soil surveys conducted in the CASCAPE project districts including Bako Tibe, and Omo Nada have identified the major agricultural soils and mapped their area extent at a 1:250,000 scale (Eyasu, 20016). The survey has shown that Nitisols, Luvisols, Alisols, and Andosols are among the widely distributed soils with strongly acidic properties. Based on this information, the current study was designed to characterize acidic soils, understand their properties, identify the factors contributing to soil acidity, and develop strategies to mitigate the adverse effects of soil acidity on agricultural productivity.

#### *1.4.2.1 Soil Sampling, and Sample Preparation*

Using the digital data and soil maps of Bako Tibe, and Omo Nada, sampling sites were delineated based on the soil types. Four low-pH soils (Nitisols, Luvisols, Alisols, and Andosols) were considered for the analysis of the physicochemical properties and phosphorus sorption capacity of the soils. From each soil type, 3 replicates of composite surface soil samples were collected at a depth of 0-30 cm based on procedures described by (Reeuwijk, 2002; Carter and Gregorich, 2007). A total of 12 composite surface soil samples were collected from the 2 districts. About ten sub-samples (per sampling unit) were collected in a zig-zag manner to form one kg composite soil sample. Also after crop harvesting, during 2017/18-2018/19, soil samples were collected from each plot that was treated with lime and chemical fertilizers for the evaluation of changes in the soil's chemical characteristics. The soil samples were collected in a clean polythene bag, labeled with the necessary information, and delivered to the lab for physical and chemical analysis. In the laboratory, the soil samples were dried in the air at room temperature, crushed in mortar and pestle, and then passed through a sieve of 2 mm openings, and the soil samples were stored in clean plastic bags that were sealed, labeled and kept in a safe, dry place until used.

#### *1.4.2.2 Laboratory analysis of soil physical and chemical properties*

The standard soil lab analysis procedures adopted by Waterworks and Design (Addis Ababa), Horticoops soil laboratory (Debre Zeit), and Ambo University Chemistry laboratory were followed for the determination of selected soil chemical and physical properties. Soil particle size determination was carried out by the Bouyoucos hydrometer method as described by Reeuwijk, (2002), while bulk density was measured using the core sampling method (Blake, 1965). The soil moisture contents at field capacity (FC) and permanent wilting point (PWP) were determined by the pressure plate apparatus technique. Available water holding capacity (AWHC) was obtained by deducting the value of PWP from the FC (AWHC = FC - PWP).

Soil pH was analyzed potentiometrically in $H_2O$ and 1 M KCl solution at the ratio of 1:2.5 for soil: $H_2O$ and soil: KCl solutions using a combined glass electrode pH meter (Okalebo et al., 2002). The change in pH was determined by subtracting soil pH (KCl) from soil pH ($H_2O$). The determination of soil organic carbon (OC) was carried out based on the Walkley-Black method standard operating procedure as described by FAO, (2020) and the percentage of organic matter was determined by multiplying the value of organic carbon by 1.724. Total N was determined by the Kjeldahl method using a micro-Kjeldahl distillation unit and Kjeldahl digestion stand (Jackson, M. L., 1958). Available P was extracted by the Olson procedure Olsen, (1965), the most commonly used for P extraction under a wide range of pH both in Ethiopia and elsewhere in the world (Landon, 1984; Mamo & Richter, 2002).

Cation exchange capacity (CEC) was determined by measuring $NH_4^+$ from the 1M ammonium acetate ($NH_4OAc$, pH 7.0) saturated soil samples (Chapman, 1965). The CEC of clay was computed by dividing CEC soil by the percentage of clay (x 100). All exchangeable macro elements and available microelements were determined by the Mehlich 3 method (Mehlich, 1985). Exchangeable acidity (Al and H) was determined by saturating the soil samples with 1N KCl solution and titrating them with sodium hydroxide (Mehlich, 1985). Percent base saturation was calculated as the percentage of the basic cations (Ca, Mg, K, and Na) to the CEC of the soil indicated as, PBS = $(Ca^{2+} + Mg^{2+} + K^+ + Na^+)/ECEC \times 100$.

Determination of $Fe_2O_3$ and $Al_2O_3$ was following the X-ray fluorescence (XRF) spectrometer (Towett et al., 2013). The citrate bicarbonate dithionite (CBD) procedure was used for the determination of total free iron oxides in soils (Fan et al., 2016).

### *1.4.2.3 Determination of the Lime Requirement*

The lime requirement was determined for the soil type (Nitisols, Luvisols, and Alisols) based on the exchangeable acidity (Exch.Ac) method (Reeuwijk, 2002; Getachew et al., 2019). The amount of lime applied at each level was calculated based on the mass of soil per 15 cm hectare-furrow-slice, soil sample density, and total exchangeable acidity of each site. It was assumed that 1.5 moles of Exch.Ac could be neutralized by the respective equivalent mole of $CaCO_3$. The equation is expressed as:

$$LR,\ CaCO_3\ (kg/ha) = \frac{cmolEA/kg\ of\ soil * 0.15\,m * 10^4\ m^2 * B.D.\,(Mg/m^3) * 1000}{2000} * 1.5$$

Where: LR- Lime requirement; Exch.Ac- Exchangeable acidity; B.D- Bulk density.

0.15 m = soil depth at which lime is incorporated

2000 = Conversion factor to convert exchangeable acidity from kg of soil to hectare.

### *1.4.2.3 Statistical Analysis*

The soil parameters and agronomic data were arranged in a Completely Randomized Design and Completely Randomized Block Design (CRBD) respectively and replicated three times. The data was subjected to analysis of variance (ANOVA) using the Statistical Analysis System (SAS) software version 9.4 (SAS Institute Inc., 2019). The Least Significance Difference test (LSD) at the 5% probability level was used for the mean comparison when the ANOVA showed significant differences. Also, a simple regression and correlation coefficient analysis was executed to assess the degrees and directions of the relationship between Kf and the various soil parameters.

## 1.5 Statement of the problem

The increase in the Ethiopian population places increasing demand on land resources (soils) leading to the clearing and use of land on steep slopes and tilling soils without proper land management practices. There is a need to identify soils and classify lands based on their limitation in use and productive capability. In Ethiopia, several studies were conducted on soil characterization but these are not disaggregated by soil type and rather missing (Assen & Yilma, 2010a). Still, such studies are uncommon for the most agriculturally potential areas of Ethiopia such as Bako Tibe and Omo Nada Districts. Soils vary both in their properties and, in turn, agricultural production is governed by major soil types and rainfall regimes.

Soil acidity has been reported as one of the major factors affecting crop production in the Southwestern and western regions of the country. Although studying soil acidity problems and lime requirement estimation have been done in some parts of the country, quantitative analysis using soil laboratory tests to come to solutions for this problem was very little. Due to this, the productive capacity of the land in the study area decreases from time to time. This is, therefore, necessitating a study on the extent of soil acidity, P sorption capacity of acid soils, and the level of lime requirement of the varies soils of the study area.

To determine the extent of the above-mentioned soil acidity problems in Bako Tibe and Omo Nada Districts of the Oromia Region, it is important to assess the situation deeply and evaluate the intervention through liming and the use of the optimum quantity of P fertilizer. The degree of soil acidity and phosphorus sorption capacity, external (solution) P requirement and lime requirement, and the response of maize to different rates of Phosphorus and lime is not specifically well known and documented for Nitisols, Luvisols, and Alisols of the study area. To this effect, to alleviate the P-fixation problem through soil-specific management (e.g., liming and targeted P-fertilization), it is necessary to estimate the degree of phosphorus sorption capacities of the dominant soil types.

For a long period, the blanket fertilizer recommendation has been practiced in Ethiopia and the growers have been using a similar rate of phosphorus fertilizer for crop production without considering the variation in the fertility status of their soils (Getachew et al., 2015). However, crops respond little to the previously recommended & applied rate of P fertilizer

There is no adequate information on the critical value of soil Olsen-P for wheat grown in volcanic soils (Andosols) of the Southwestern highlands of Ethiopia, where wheat is widely produced. The calculation of the optimal phosphorus fertilizer application rate is essential for better management of the soil Olsen phosphorus and phosphorus fertilizer use efficiency. Therefore, determining the optimum rates for P is crucial to ensure maximum crop yield and minimize negative impacts on the environment.

## 1.6. Research Questions/ Hypothesis

### 1.6.1 Research questions

1. What is the degree of soil acidity in the Bako Tibe and Omo Nada districts of Oromia, Ethiopia?
2. What is the extent of the phosphorus sorption capacity of acidic soils of the Bako Tibe and Omo Nada districts of Oromia, Ethiopia?
3. What amount of P-fertilizer and lime are required by different soils (Nitisols, Luvisols, Alisols, and Andosols) for sustainable crop production in the study area?

### 1.6.2 Hypothesis

- Hypothesis for characterization and classification of the Southwestern highland soils of Ethiopia;

∗ Null hypothesis: There are no differences in the soils and have the same extent of acidity.
∗ Alternative hypothesis: The soils differ in their characteristics and extent of acidity.

- Hypothesis for evaluation of the phosphorus sorption capacity of acidic soils of the Southwestern part of Ethiopia

∗ Null hypothesis: All the soils do not vary in their phosphorus sorption capacity.
∗ Alternative hypothesis: The soils differ in their phosphorus sorption capacity.

- Hypothesis for lime determination for different soils

∗ Null hypothesis: The soils do not vary in their lime requirement.
∗ Alternative hypothesis**:** The soils vary in their lime requirement.

- Hypothesis for the determination of the external P-fertilizer for acidic soils for the production of maize at Bako, and Omo Nada and wheat at Omo Nada.

∗ Null hypothesis: The soils do not vary in their external P requirement.
∗ Alternative hypothesis: The soils vary in their external P requirement.

## 1.7 Objectives

### *1.7.1 General objective*

The overall goal of the study was to characterize the soils and evaluate the degree of acidity of low pH soils, phosphorus sorption capacity, determine the lime requirement, and external P-fertilizer requirement of some acidic soils of the Ethiopian highlands including Nitisols, Luvisols, Alisols, and Andosols.

### *1.7.2 Specific Objectives*

The specific objectives of the study were:

- To characterize and classify some acidic (low-pH) soils of Bako Tibe and Omo Nada districts of Oromia, Ethiopia;
- To evaluate the phosphorus sorption capacity, determine the external P and lime requirement of acidic soils of Southwestern Ethiopia;
- To assess the integrated effects of lime and P fertilizer on maize yield parameters and selected soil chemical properties at Bako Tibe and Omo Nada Districts of Oromiya, Ethiopia and;
- To evaluate the wheat response to different P rates and P fertilizer recommendation for optimum wheat production at Omo Nada in Southwestern Ethiopia.

## 1.8 Significance of the Study

The relevance of the study is that it characterizes and classifies the soils in the study area based on the soil's morphological, physical, and chemical properties. It is also important to determine the amount of agricultural lime required by different soil types which helps to alleviate the soil acidity problems in the study areas and other locations with similar soil types and agroecology. Additionally, the current study addresses the problem related to the soil's P-fixing capacity and determines the quantity of phosphorus fertilizer required for Nitisols, Luvisols, Alisols, and Andosols that are optimum for crop (maize and wheat) production. Therefore, the study enhances maize yield in Bako Tibe and maize and wheat in the Omo Nada Districts of the Oromia region. With increasing the problems of soil acidity in the study area, soil characterization, investigation of the level and area extent of acidity of agricultural soils, and determination of the lime requirement for acidic soils and their reclamation are very crucial for designing effective land use planning and maximizing the crop yield that positively contributing to ward the nations' food self-sufficiency.

Any findings and data obtained from the study would provide reference information for the academic or scientific community, policymakers, resource managers, and more of the agrarian society. It is significant as it provides baseline data for acid soil management, fertilizer recommendation, and wise resource utilization that is achieved through effective land use planning (use the land according to its capability and limitation) that are appropriate for sustainable crop production at Bako Tibe and Omo Nada Districts.

## 1.9 Scope of the Study

The study of acidic soils is of great significance due to their detrimental effects on crop production and environmental sustainability. In the Southwest and western regions, acidic soils are particularly prevalent and pose a significant challenge to agricultural practices. Therefore, this study aims to investigate the causes of acidity in Southwest and western soils, assess its impact on crop yield, and propose sustainable management strategies to mitigate the negative effects of acidity on soil health and agricultural productivity. By addressing these research objectives, this study seeks to contribute to the development of effective soil management practices in the study area.

## 1.10 Limitations of the Study

The study has had some limitations. First, since there was a time and budget limitation, priority was given to the four major agricultural soils (Nitisols, Luvisols, Alisols, and Andosols) in the study districts. Soil characterization and classification, lime rate determination, and crop-soil-specific P recommendations were made only for the soils under this study. All the soil types in the districts were not assessed. Owing to this limitation, a more inclusive study needs to be conducted to cover each soil type in the region. For instance, as soil acidity is a major constraint for crop production in the highlands of Ethiopia, therefore, the external P-fertilizer requirement for individual crop grown and lime determination could be done on different soil types. Additionally, since soils are dynamic, feature studies could cope with the changing soil properties to generate the current and latest technology and recommendations.

Secondly, due to less accuracy in some soil laboratories, few of the soil analysis results were diverted from the scientific facts. Because of this, there were some difficulties in correctly assessing the soil properties and interpreting and reaching the right conclusion and recommendations. For example, results for the phosphorus sorption capacity of the soils, the BD values of Andosols, the values of available Fe, *etc.* Accurate lab analysis results are required to solve the above-mentioned limitations and to design the best soil management strategies.

## 1.11 Structure of the Dissertation

This dissertation is structured into six chapters. The General Introduction of the Topic, the Problems, Relevant Literature, the Research Gap, and the Methodologies are outlined in Chapter 1, Chapter 2 deals with the Characterization and Classification of Soils of Bako Tibe and Omo Nada Districts, in Southwestern Ethiopia, the part of this chapter Characterization and Classification of Soils of Bako Tibe is currently published as " **Berhanu Dinssa**, Eyasu Elias, (2021). Characterization and classification of soils of Bako Tibe District, West Shewa, Ethiopia. *Heliyon*, Vol. 7, Issue 11, e08279 https://doi.org/10.1016/j.heliyon.2021.e08279. Chapter 3 is currently published as "**Berhanu Dinssa**, Eyasu Elias, (2021). Evaluation of phosphate sorption capacity and external phosphorus requirement of some agricultural soils of the southwestern Ethiopian highlands. Sains Tanah Journal of Soil Science and Agroclimatology, 18 (2): 136-142. https://dx.doi.org/10.20961/stjssa.v18i2.51325. Chapter 4, Maize (*Zea Mays L.*) Yield Response to Lime and phosphorus Rates in Bako Tibe and Omo Nada Districts of Oromia Region, Southwestern Ethiopia is currently prepared to be submitted to the publishers, Chapter 5, evaluating wheat response to phosphorus application rates and fertilizer recommendation in Omo Nada district, on Andosoles of the Southwestern Ethiopian highlands is currently under revision (**Heliyon)** following reviewer's comment. The General Discussion/Conclusions and Recommendations were presented in the 6th chapter. The conclusion of this Ph.D. work summarizes the main results of the work and provides recommendations. Diagrammatically, the dissertation structures and layouts are presented in Figure 1.5 below.

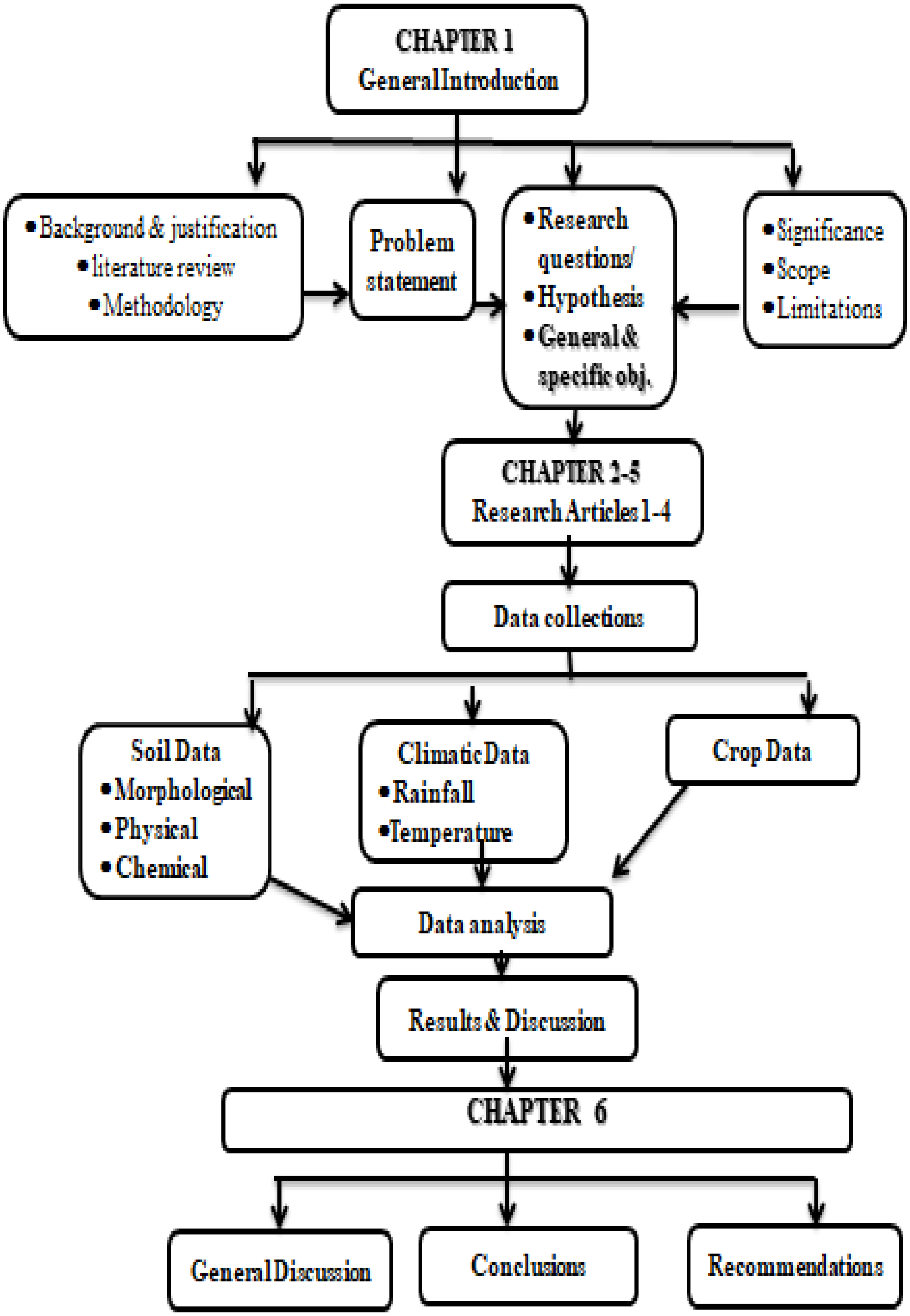

Figure 1.5: Diagrammatical representation of the dissertation structures and layouts

# CHAPTER 2: CHARACTERIZATION AND CLASSIFICATION OF ACID SOILS OF BAKO TIBE AND OMO NADA DISTRICTS, OF OROMIA, ETHIOPIA

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## ABSTRACT

*This study was conducted in the Bako Tibe and Omo Nada Districts of Oromia, Ethiopia, to characterize and classify agriculturally important acid soils. The study involved four soil types and twelve representative pedons. The soil samples were analyzed using standard lab procedures. Results revealed that the textural classes of most pedons were clay, followed by sandy clay and clay loam. The soils were slightly acidic to strongly acidic in reaction (pH 5.2-6.85). The organic carbon content was in the range of very low (0.19%) to very high (5.16%), and the available P content varied from very low (0.21 mg* $kg^{-1}$*) to low (8.45 mg* $kg^{-1}$*). The cation exchange capacity and percent base saturation ranged between medium (21* $cmol_{(+)}\ kg^{-1}$*) to very high (45* $cmol_{(+)}kg^{-1}$*) and very low (10%) to high (63%) respectively. The dominance of exchangeable bases was in the order of* $Ca^{2+}>Mg^{2+}>K^{+}>Na^{+}$*, and the soils were sufficient in available Fe, Mn, Zn, and B but deficient in Cu. The study identified various soil types, as Pedon 1 was Hyperdystric Nitisols (Humic); Pedons 2 and 3 were Umbric Nitisols; Pedon 4 was Rhodic Alisols (Hyperdystric); Pedon 5 was Rhodic Luvisols (Hypereutric); Pedon-6, Endoleptic Cambisols (Humic); Pedon 7 Chromic Alisols (Hyperdystric, Humic); Pedon 8 and 9 were Rhodic Alisols (Hyperdystric) and Chromic Alisols (Hyperdystric) respectively; Pedon 10 Mollic, Silandic Andosols (Clayic); Pedon 11, Dystric, Silandic Andosols (Clayic) and Pedon 12, Eutric, Silandic Andosols (Clayic). The study found that most soil physical and chemical characteristics were good quality indicators, suggesting potential for agricultural production. However, strong attention should be given to the reclamation of the acid soils through liming. Application of optimum rates of P, Cu, and B are essential in the study area.*

**Keywords:** *Pedon; reference soil groups, soil characterization, World Reference Base.*

## 2. 1. INTRODUCTION

In the Horn of Africa, Ethiopia has diverse topography, climatic conditions, and geology (Billi, 2015). The elevation ranges between two extremes from 125 m below sea level (bsl) Denakil Depression to 4620 m above sea level (asl) Ras Dashen peak. This wide range of topographic variation with its climatic diversity creates variations in the country's natural resources like soils and vegetation (B. Berhanu et al., 2013). Similarly, Wassie,(2020) reported that the country has abundant natural resources, proper land, fertile soil, favorable climate, water, wildlife, *etc*. However, many of its resources have not been properly identified, managed, and fully utilized.

Unwise utilization of these natural resources and intensive farming for thousands of years without protection degrades the soil, the natural reservoirs of essential plant nutrients, consecutively resulting in crop yield reduction. Amsalu & de Graaff, (2006) reported that agricultural land degradation is a major problem for current and potential food production in the Ethiopian highlands. To evaluate the quality of our natural resources and their potential to produce food, fodder, fiber, and fuel for the present and future generations, detailed information on soil properties is needed. Accurate land evaluation is a great concern to achieve sustainable agricultural production (Fadl & Sayed, 2020). Moreover, understanding soil properties and their distribution over an area is useful for sustainable soil management and the efficient use of limited land resources (Sanchez et al., 2003).

Pedological characterization and classification of soils of a given area are crucial for the determination of its potential and constraints for enhanced and sustained agricultural production (Alemu and Tadele, 2018). Soil characterization is carried out to classify soil and determine chemical and physical attributes (that can reflect the capacity of soil to function) not visible in field examination (Sanchez et al., 2003). Mohammed & Solomon (2010) indicated that soil classification helps to identify the most appropriate use of the land, estimate the production, and facilitate technology transfer, and information exchange between soil scientists, policymakers, planners, researchers, and agricultural extension consultants. It is required for maintaining soil productivity and realization of land use planning in most parts of the country. It is important to characterize and describe soil and land use to make recommendations for sustainable land use in Ethiopia (Zebire et al., 2019).

According to IUSS Working Group WRB, (2015) soil classification,  about 23 types of reference soil groups (RSG) are identified throughout the country. Vertisols, Luvisols, Cambisols, Leptosols, Fluvisols, and Nitisols represent about 90% of the RSG (Ashenafi et al., 2022). Nitisols, Cambisols, Luvisols, and Alisols are among the most extensive soil types accounting for 13.5, 11, 5.8, and 5 % of the agricultural landscapes of the Ethiopian highlands, respectively (Alemayehu, 2006). With appropriate management, they have medium to high potential for rain-fed agriculture. Alisols are particularly important in high rainfall upland farming systems of the Bako Tibe and Omonada districts. Based on the classification of IUSS Working Group WRB, (2015), the major soils identified in Bako Tibe District are Alic Nitisols, Haplic Nitisols, Luvic Nitisols, Litic Leptosols, Haplic Luvisols, Cutanic Luvisols, Vertic Luvisols, Nitic Luvisols, Leptic Luvisols, Haplic Regosols and Rhodic Alisols (Hyperdystric) and that of Omo Nada district are Alisols, Andosols, Leptosols, Luvisols, Nitisols, Planosols, and Vertisols (Eyasu, 2016).

However, these different soil types were not fully characterized and their properties were not well documented in the study area. Agricultural technologies and inputs were recommended at some specific areas in the country and extrapolated to other areas with different soil types that vary in morphological, physical, and chemical properties. This means the same inputs and technologies are recommended for different soil types with dissimilar properties, capabilities, and limitations, and the recommendations are not site and soil-specific (Soil Science Division Staff., 2016)

Previous studies conducted on soil characterization were not based on soil types (Assen & Yilma, 2010). Soils vary both in their properties and, in turn, agricultural production is governed by major soil types and rainfall regimes. Assen & Yilma, (2010) reported that considering differences in soil types can enhance agricultural productivity and sustainable land management practices in Ethiopia. Information on the soil types, and morphological, physical, and chemical characteristics of agricultural soils are essential in making decisions and sustaining land productivity (Eyasu, 2016). Soil characterization becomes fundamental to identifying the existing heterogeneity of the soil system and generates adequate information that determines soil potential and proper soil management practices. Hence, there is a need to characterize and classify the soils in the Bako Tibe and Omo Nada districts which is useful to come across the full production potentials of the area together with the identification of the factors which are likely to limit production. For that reason, the current study was intended:

1. To characterize some agriculturally important acid soils in Bako Tibe and Omo Nada Districts.
2. To study the major morphological, physical, and chemical characteristics and classify some agriculturally potential acid soils at Bako Tibe and Omo Nada Districts.

## 2.2 MATERIALS AND METHODS

The materials and methods section is the most crucial section that can determine the final results of the research work. This section includes a detailed description and the process by which the research was conducted. It starts with the description of the study area and materials that are used, the method and procedures employed to conduct the research, the sample size, the criteria used for sample collection, data analysis methods, and the statistical procedures used to analyze the data. The Methodology section can provide readers with details information so it helps them to replicate the studies. The experimental procedures which lead to the result are described in this part.

### *2.2.1 Description of the Study Area*

The sites considered in the present study are among the agriculturally important soils in the Bako Tibe District, Western Shoa Zone, and Omo Nada District of Jimma Zone of Ethiopia (Figure 2.1). The two sites were selected based on differences in soil type, their acidity problem, and P sorption capacities. Bako Tibe District is located 250 km West of Addis Ababa. Geographically the district is situated between 9°12'35"- 9°7’30’’N and 37°58’25’’- 37$^{o}$13’40’’E. The district is characterized by flat plains, high mountains, and rolling ridges. The geological feature of the district is characterized by Tertiary sediments from the Cenozoic era on the plain and basaltic rocks in the high mountains and rolling ridges (Billi, 2015).

BakoTibe district has three agro-climatic zones: Dega (highland), Woina Dega (midland), and Kolla (lowland). The rainfall data obtained from the nearest weather station (Bako Agricultural Research Center) reveals that the rainy season covers April to November and maximum rain is received in June, July, and August (Figure 2.2). The long period (1976-2017) average annual rainfall is 1267 mm with unimodal distribution. It has a warm humid climate with the mean minimum, mean maximum, and mean air Temperatures of 13.9 $^{0}$C, 28.1 $^{0}$C, and 21 $^{0}$C respectively and the altitudinal of the district is in the range of 1650 to 2800 masl. According to the Reference Base for Soil Resources IUSS

Working Group WRB, (2015), the major soils identified on the geomorphological map of the BakoTibe district (Figure 2.3) include Nitisols, Luvisols, Vertisols, Leptosols, and Fluvisols. The pH range of the surface and subsurface soils differs from 5.39 to 6.00 and 5.20 to 6.60 respectively (Gezu & Tekalign, 2019a). Based on the rating of Hazelton & Murphy, (2016) the topsoil is strongly acidic to moderately acidic while the subsurface soil is strongly acidic to slightly acidic.

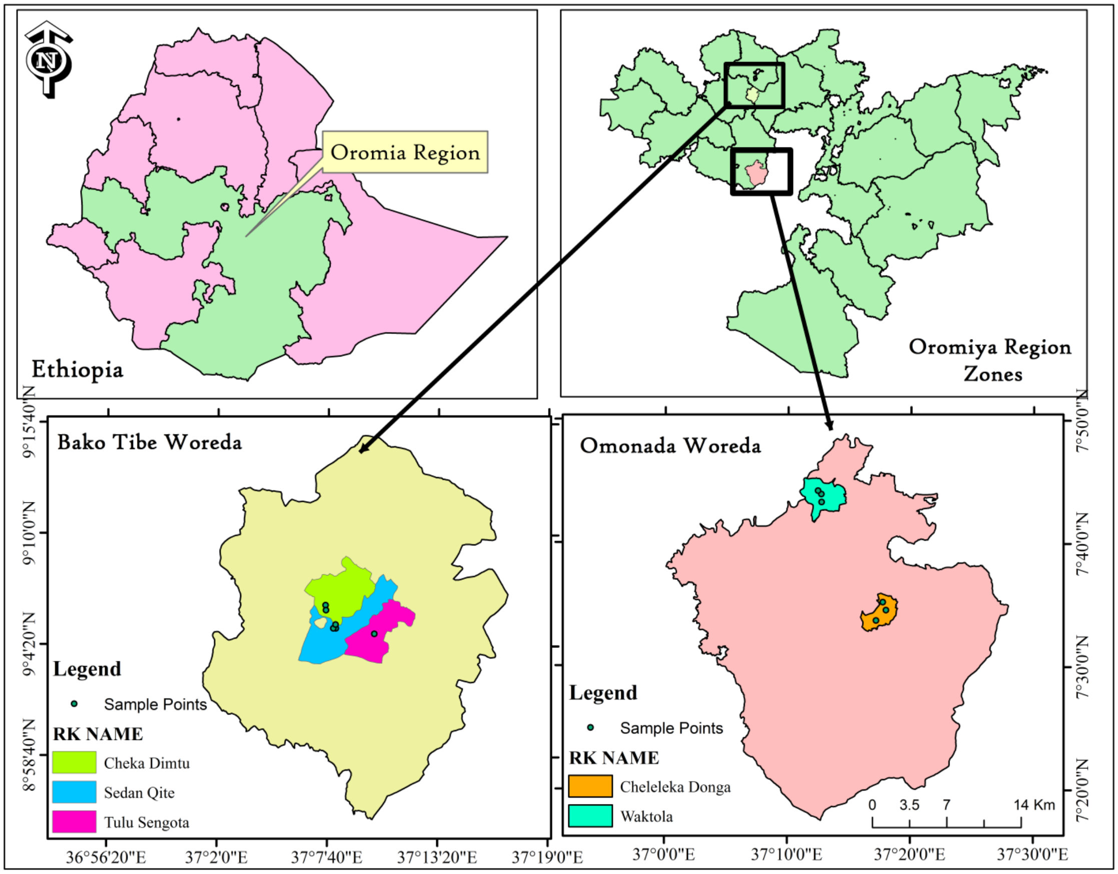

Figure 2.1. Location map of the study area (Bako Tibe District of West Shewa zone and Omo Nada District of Jimma zone).

Note: Rk = Rural Kebele (Peasent association)

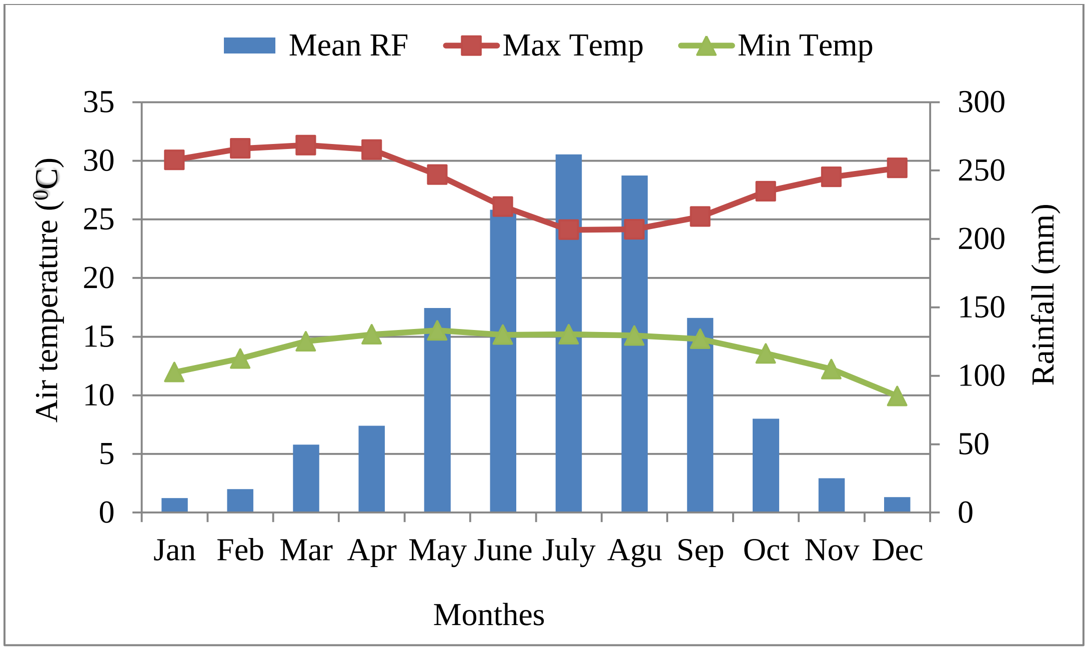

Figure 2.2: Long-term (1976-2017) mean monthly rainfall distribution and air temperature (0C) of Bako Tibe District. Source: BakoAgricultural Research Center (BARC), (unpublished data).

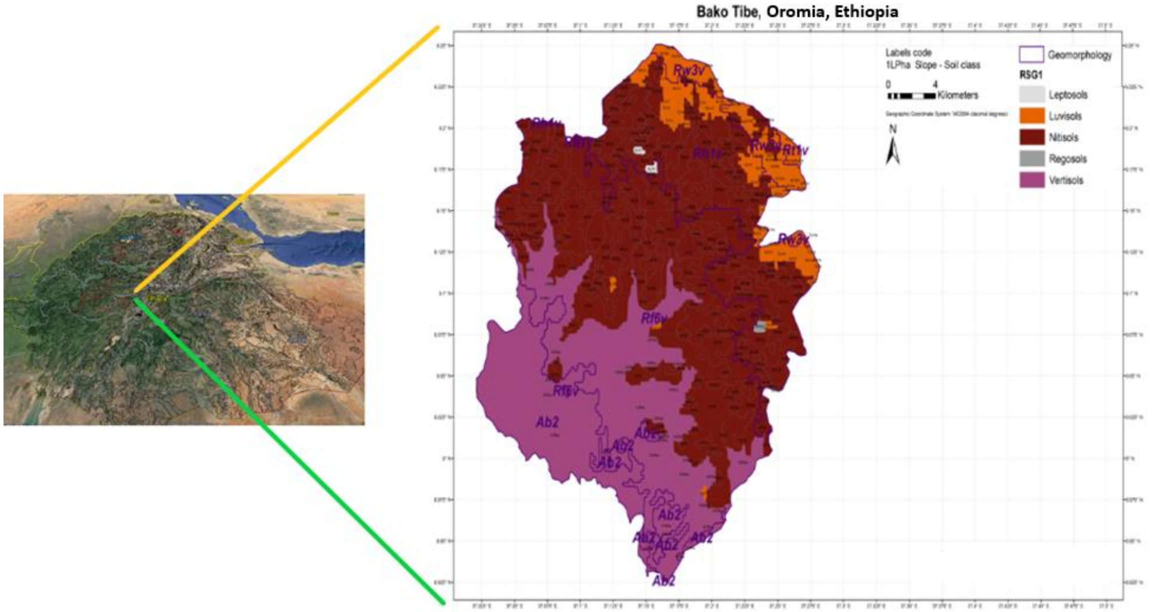

Figure 2.3. Geomorphological map of Bako Tibe District,
Source (Eyasu, 2016)

The Omo Nada district is located in the Oromia region and Southwestern part of Ethiopia and lies between 7° 48' 25.236" to 7° 17' 5.6004" ’N and 37° 0' 4.464" to 37° 26' 53.7684" E. It is located at a distance of about 71 km from the zonal capital. It is bordered by the Dedo district in the West, Sokoru district in the North, Kersa district in the South, and Tiro Afata district in the East (Figure 2.1). The rainfall of the district is bimodal, with an erratic short rainy season from March to April and the main rainy season extends from June to September. The long-term thirty-year average rainfall is 1730 mm per year. The mean monthly minimum and maximal air temperatures are 12°C and 26 °C, respectively (Figure 2.4).

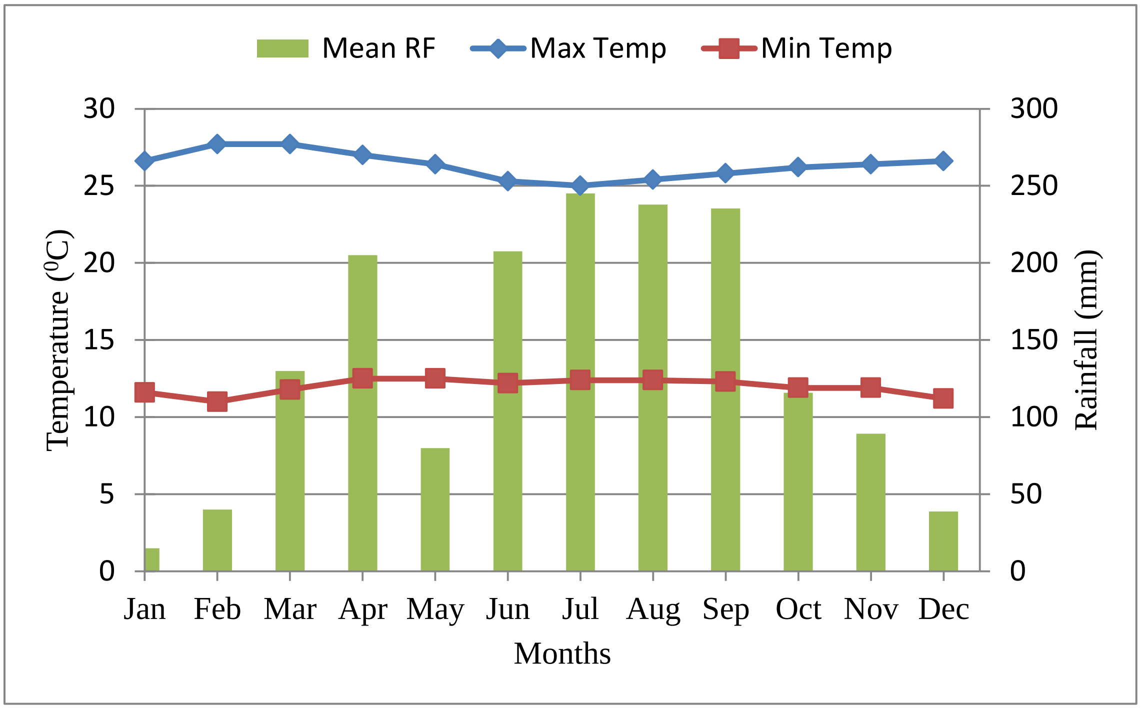

Figure 2.4. The thirty years (1988-2018) mean monthly rainfall distribution and air temperature ($^0$C) of the Jimma Zone

Omo Nada district has three major agro-ecological zones of which Tepid sub-humid highlands, Warm sub-humid lowlands, and Cool sub-humid mid-highlands account for about 79%, 11%, and 10% of the area respectively (Eyasu, 2016). The area is characterized by gentle, flat, and undulating terrain within the 1650 – 2670 m.a.s.l altitude range. The most dominant soil types of the trial sites are Chromic Alisols (Hyperdystric). Other soils of the district landmass include Andosols, Cambisols, Planosols, Regosols, and Acrisols (Eyasu, 2016). The soils are made up of volcanic parent materials (basalts and rhyolites).

### *2.2.2. Soil Profile Description, Sampling, and Sample Preparation*

Soil characterization was done using soil profile pits which were excavated at the representative sites (Table 2.1). The representative sites were selected for Nitisols, Luvisols, Alisols, and Andosols and 3 pits were opened for each soil type (a total of 12 pits opened) to a depth of 2 m with 1m width and 2m length. The opened soil profiles were described *in situ* for morphological characteristics based on the Guidelines for Soil Description (FAO, 2006).

The soil color was described using soil color charts (Munsell, 2000). Texture and consistency were described by the feel methods. The soil consistency was identified at dry, moist, and wet moisture conditions. Visual observation was used to determine soil structure in terms of type (shape), class (size), and grade (strength) of aggregates whereas horizon boundaries were described in terms of depth, distinctness, and topography. Undisturbed core samples were collected at different points across each horizon for the determination of bulk density. A cylindrical metal core with a volume of 100 $cm^3$ was pressed into the soil until it was filled. The soil was trimmed at both ends with a knife covered with a cap, labeled, and packed in a box.

Table 2.1 Selected environmental information of representative profiles at Bako and Omo Nada Districts

| Profile No. | Location | | Altitude (m.a.s.l) | Slope (%) | Drainage class | Position | Erosion/ Deposition | Land use | Parent material |
|---|---|---|---|---|---|---|---|---|---|
| | Latitude (N) | Longitude (E) | | | | | | | |
| P-1 | $9^0$ 05.196N | $37^0$08.196 E | 1724 | 8 | WD | UpS | Sheet & rill | An. FC | Basalt |
| P-2 | $9^0$ 05.198 N | $37^0$08.161 E | 1674 | 6 | WD | MdS | Sheet & rill | An. FC | Basalt |
| P-3 | $9^0$ 05.391N | $37^0$08.079 E | 1710 | 9 | WD | MdS | Sheet & rill | An. FC | Basalt |
| P-4 | $9^0$05.199 N | $37^0$9.549 E | 1716 | 3 | WD | MdS | Sheet & rill | An. FC | Basalt |
| P-5 | $9^0$ 06.23.4N | $37^0$ 07.334 E | 1735 | 10 | WD | UpS | Sheet & rill | An. FC | Basalt |
| P-6 | $9^0$ 05.074'N | $37^0$ 07.70 E | 1790 | 19 | WD | UpS | Sheet & rill | An. FC | Basalt |
| P-7 | $7^0$ 43.808 N | $37^0$ 12.153 E | 1760 | 13 | WD | LoS | Sev.Sh. & MoR | An. FC | Volcanic |
| P-8 | $7^0$ 42.970 N | $37^0$ 12.506 E | 1762 | 10 | WD | MdS | Sev.Sh. & MoR | An. FC | Volcanic |
| P-9 | $7^0$ 44.248 N | $37^0$ 12.442 E | 1750 | 15 | WD | MdS | Sev.Sh. & MoR | An. FC | Volcanic |
| P-10 | $7^0$ 17.739 N | $37^0$37.·739E | 2406 | 13 | WD | MdS | Sev.Sh. & MoR | An. FC | Volcanic |
| P-11 | $7^0$ 17.997 N | $37^0$ 34.571 E | 2530 | 10 | WD | UpS | Sev.Sh. & MoR | An. FC | Volcanic |
| P-12 | $7^0$ 17.723 N | $37^0$ 17.195 E | 2670 | 7 | WD | UpS | Sev.Sh. & MoR | An. FC | Volcanic |

Note: WD = well-drained, UpS = upper slope, MdS = middle slope, LoS = lower slope, Sev. MoR = moderate rill, Sh. & Mo. Rill = Sever sheet erosion and moderate rill erosion, An. FC = Annual field crop

About 1 kilogram of disturbed soil sample which contains an equal proportion from all of the horizons within the described profile (excluding the boundary of the horizon) was taken. A total of 97 (45 undisturbed and 52 disturbed) soil samples were collected from the pits. The samples were placed in a clean plastic bag labeled with the necessary information and transported to the laboratory. In the laboratory, the samples were spread on clean polythene sheets to dry in the air at room temperature. After drying, the samples were crushed in mortar and pestle and then passed through a sieve of 2 mm openings. The sieved soil samples were transferred into clean plastic bags. The plastic bags were sealed and labeled in the same way that they were labeled in the field. The samples were stored in a safe, dry place until they were used. Standard laboratory procedures were followed for soil laboratory analysis.

### *2.2.3 Laboratory Analysis of Soil Physical and Chemical Properties*

The standard soil lab analysis procedures adopted by Waterworks and Design (Addis Ababa), Horticoops soil laboratory (Debre Zeit), and Ambo University Chemistry laboratory were followed for the determination of selected soil chemical and physical properties. Soil particle size determination was carried out by the Bouyoucos hydrometer method as described by Reeuwijk, (2002), while bulk density was measured using the core sampling method (Blake, 1965). The soil moisture contents at field capacity (FC) and permanent wilting point (PWP) were determined by the pressure plate apparatus technique. Available water holding capacity (AWHC) was obtained by deducting the value of PWP from the FC (AWHC = FC - PWP).

Soil pH was analyzed potentiometrically in $H_2O$ and 1 M KCl solution at the ratio of 1:2.5 for soil: $H_2O$ and soil: KCl solutions using a combined glass electrode pH meter (Okalebo et al., 2002). The change in pH was determined by subtracting soil pH (KCl) from soil pH ($H_2O$). The determination of soil organic carbon **(**OC**)** was carried out based on the Walkley-Black method standard operating procedure as described by (FAO, 2020).

Total N was determined by the Kjeldahl method using a micro-Kjeldahl distillation unit and Kjeldahl digestion stand as described by (Jackson, M. L., 1958). Available P was extracted by the Olson procedure Olsen, (1965)**,** the most commonly used for P extraction under a wide range of pH both in Ethiopia and elsewhere in the world (Landon, 1984; Mamo & Richter, 2002). Cation exchange capacity (CEC) was determined by measuring $NH_4^+$ from the 1M ammonium acetate (NH4OAc, pH 7.0) saturated soil samples (Chapman, 1965). The CEC of clay was computed by dividing CEC soil by the percentage of clay (x 100).

All exchangeable macro elements and available microelements were determined by the Mehlich 3 method (Mehlich, 1985). Exchangeable acidity (Al and H) was determined by saturating the soil samples with 1M KCl solution and titrating them with sodium hydroxide as described by (Mehlich, 1985). Percent base saturation was calculated as the percentage of the basic cations (Ca, Mg, K, and Na) to the CEC of the soil. Determination of $Fe_2O_3$ and $Al_2O_3$ was following the X-ray fluorescence (XRF) spectrometer (Towett et al., 2013). Finally, based on the absence or presence of particular diagnostic horizons, properties, materials, and qualifiers, the soils were categorized into their respective reference soil groups following the World Reference Base for soil resource (IUSS Working Group WRB, 2015). The land capability classification was made based on the USDA (2007) land capability classification.

P-1: BA/SK1/NT

P-2: BA/SK2/NT

P3: BA/CD1/NT

P-4: BA/TS1/LV

P-5: BA/CD2/LV

P-6: BA/CD3/CM

P-7: ON/Wak1/AL

P-8: ON/Wak2/AL

P-9: ON/Wak3/AL

P-10: ON/CD1/AN

P-11: ON/CD2/AN

P-12: ON/CD3/AN

Figure 2.5. The Pedons 1-12, that opened for different soil types at the study sites

## 2.3. RESULTS

### *2.3.1 Selected Soil Morphological Characteristics*

#### *2.3.1.1. Soil color*

Some important soil morphological properties of the studied profiles are presented in Tables 2.2a and 2.2b. The moist soil color for all the surface layers of Nitisols (Pedon 1, 2, and 3) was dark reddish-brown (2.5YR 2.5/3 to 2.5YR 2.5/4) in color while the surface layers of Luvisols were dark brown (7YR 3/2) for pedon 5 and the surface color of Peon 6 (Cambisols) was dark reddish brown (2.5YR 2.5/3) in color. The moist soil color of surface horizons for Alisols (pedon 4) was very dark brown (5YR 2.5/3), dark reddish brown (2.5YR 2.5/3 for pedon 7 and 9, and 5YR 3/2 for pedon 8). The moist surface soil color of Andosols differs from dark (5YR 2.5/1) pedon 10 to Dusk reddish gray (2.5 YR 3/1) pedon 11 and 12.

The subsurface soil color (mois) of Nitisols (pedon 1, 2, and 3) differs from dark reddish-brown (2.5YR 2.5/4) to Dusky red (7.5R 3/4), and the subsurface moist soil colors of Luvisols (pedons 5) very dark brown (7.5YR 2.5/3) and that of Cambisols (pedon 6) was dark brown (7.5YR 3/3). The subsurface soil color (mois) for Alisols (pedons 4, 7, 8, and 9) differs from dark reddish brown (2.5YR 3/4) to red (2.5YR 4/6). For Andosols (pedons 10, 11, and 12), the subsurface soil color (mois) differs between black (5YR 2.5/1) and dark reddish-brown (5YR3/4).

#### *2.3.1.2. Soil structure and consistency*

In Nitisols (pedons 1, 2, and 3) the surface soils had strong coarse subangular blocky structure (ST CO SAB) and the subsurface soil layers had strong coarse angular blocky (ST CO AB) structure. In pedon 4, the surface soil layer (Ap) and the subsurface soil layer, the Bt1 and Bt2 had a strong coarse subangular blocky (ST CO SAB) structure while the Bt3 and Bt4 had moderate medium subangular blocky (MO ME SAB) structure. In pedon 5, the surface soil (AP) and subsurface Bt1 had a strong coarse subangular blocky (ST CO SAB) structure and the B horizon had a strong coarse angular blocky (ST CO AB) structure. In the surface soil of Cambisols (pedon 6), the surface soils (Ap) had a strong medium subangular blocky (ST ME SAB) structure and the subsurface soil layers (B) had a strong coarse subangular blocky (ST CO SAB) structure. For Alisols (pedons 7, 8, and 9)  the surface soil structures were moderate, medium, and granular structures and gradually changed into weak to strong, coarse, angular blocky structures in subsurface soil horizons. In Andosols (pedons 10, 11, and 12), the surface soil had weak, medium granular structures while the subsurface soil structures were moderate, medium, and subangular to angular blocky structures.

The dry consistency varied from slightly hard to hard in general and both the surface and subsurface horizons of Nitisols, Luvisols, and Cambisols (pedons 1-6) were hard while the surface horizon of Aliaolas and Andosols (pedon 7-12) were slightly hard but the subsurface horizons were hard. The moist Constance for all the surface and subsurface layers of all the pedons studied were friable. On the other hand, the wet consistency ranged from slightly sticky/slightly plastic in the surface layers to very sticky/very plastic in the subsurface soil layers (Tables 2.2a and 2.2b).

#### *2.3.1.3 Soil depth and horizon boundaries*

Based on the soil depth class described by USDA, (2017), all the pedons were very deep (> 150 cm) except Pedon 5 which was deep (102 cm), and Pedon 6, which was moderately deep (0-55 cm) and limited by massive basalt. The amount of plant nutrients and water available to plant roots is determined by the rooting depth of the soil. The lower boundaries of surface and subsurface horizons in Nitisols (Pedons 1) were gradual and smooth; the lower boundary surface horizon of Pedon 2 was clear and smooth which changed to gradual and smooth at subsurface horizons. The lower boundary of the surface horizon of pedon 3 was gradual and smooth up to the depth of 60 cm and below 60-140 cm the subsurface boundaries were diffuse and smooth. For Pedon 4, 5, and 6, all the lower boundaries of the surface soils were clear and smooth while the lower boundaries of Pedon 4 were gradual and smooth but the lower boundaries of the subsurface horizons of both Pedon 5 and 6 were clear, and smooth (Table 2.2a).

On the other hand, the lower boundaries of both surface and subsurface soils of (pedons 7, 8, and 9) were abrupt and smooth which shows the soils are formed from different parent materials. Andosols (pedons 10, 11, and 12) all had abrupt and smooth lower boundaries of the surface horizons while those of the subsurface horizons were changed into clear and smooth (Table 2.2b).

Table 2.2a. Soil morphological data for Nitisols, Alisols, Luvisols, and Cambisols

| Depth | Horizon | Color (Moist) | Structure Grade/class/ty | Consistency Dry/moist/wet | Roots Abund | Boundary |
|---|---|---|---|---|---|---|
| Pedon 1, BA/SK1/NT | | | | | | |
| 0-20 | Ap | 2.5YR 2.5/4 | ST, CO, SAB, | HA, FR, ST, PL | C, F | G, S |
| 20-50 | Bt1 | 2.5YR 2.5/4 | ST, CO, AB | HA, FR, ST, PL | C, F | G, S |
| 50-80 | Bt2 | 10R ¾ | ST, CO, AB | HA, FR, ST, PL | F, F | C, S |
| 80-125 | Bt3 | 10R 3/3 | ST, CO, SAB | HA, FR, ST, PL | F, F | G S |
| 125-145 | Bt4 | 10R 3/3 | ST, CO, AB | HA, FR, ST, PL | F, F | G, S |
| 145- | Bt5 | 10R 3/6 | ST, CO, AB | HA, FR, ST, PL | F, F | —– |
| | Pedon 2, BA/SK2/NT | | | | | |
| 0-20 | Ap | 2.5YR 3/3 | ST, CO, SAB | HA FR, ST, PL | C, F | C, S |
| 20-62 | A | 2.5YR 2.5/4 | ST, CO, AB | HA, FR, ST, PL | F, F | G, S |
| 62-110 | B | 10R 3/3 | ST, CO, AB | HA, FR, ST, PL | F, F | G, S |
| 110-190$^+$ | Bt1 | 7.5R 2.5/4 | ST, CO, SAB | HA, FR, ST, PL | --- | — |
| | Pedon 3, BA/CD1/NT | | | | | |
| 0-15 | Ap | 2.5YR 2.5/3 | ST, CO, SAB | HA, FR, ST, PL | C, F | G, S |
| 15-28 | A | 2.5YR ¾ | ST, CO, AB | HA, FR, ST, PL | F, F | G, S |
| 28-60 | Bt1 | 10R 3/3 | ST, CO, AB | HA, FR, ST, PL | F, F | D, S |
| 60-140 | Bt2 | 10R ¾ | ST, CO, AB | HA, FR, ST, PL | F, F | D, S |
| 140-200$^+$ | Bt3 | 7.5R ¾ | ST, ME, AB | HA, FR, ST, PL | --- | — |
| | Pedon 4, BA/TS1/ LV | | | | | |
| 0-20 | Ap | 7.5YR 2.5/3 | ST, CO, SAB | SHA, FR, ST,PL | C, M | C, S |
| 20-50 | AB | 7.5YR 2.5/3 | ST, CO, AB | SHA, FR, ST, PL | C, F | G, S |
| 50-80 | Bt1 | 7.5YR 3/3 | ST, CO, SAB | HA, FR, ST, PL | C, F | G, S |
| 80-110 | Bt2 | 5YR 3/2 | ST, CO, SAB | HA, FR, ST, PL | F, F | C, S |
| 110-153 | Bt3 | 5YR 3/3 | MO, Me, SAB | SHA, FR, ST, PL | C, F | A, S |
| 153-200$^+$ | Bt4 | 2.5YR 3/3 | MO, Me, SAB | HA, FR, ST, PL | F, F | —– |
| | Pedon 5, BA/CD2/LV | | | | | |
| 0-18 | Ap | 7.5YR 3/2 | ST, CO, SAB | HA, FR, ST, PL | M, F | C, S |
| 18-50 | Bt1 | 2.5YR 2.5/2 | ST, CO, SAB, | HA, FR, ST, PL | C, F | C, S |
| 50-102 | B | 5YR ¾ | ST, CO, AB | HA, FR, ST, PL | F, F | --- |
| | Pedon 6, BA/CD3/CM | | | | | |
| 0-10 | Ap | 2.5YR2.5/3 | ST, ME, SAB | HA, FR, ST, PL | M, M | C, S |
| 10-28 | B | 7.5YR 3/1 | ST, CO, SAB | HA, FR, ST, PL | C, F | C, S |
| 28-55 | BC | 7.5YR3/3 | ST, ME, AB | HA, FR, ST, PL | F, F | --- |

A=abundance; G=grade; Na=nature; ST=stickiness; C=contrast; Cn=continuity; Moi=moist condition; H=horizons; S=structure; Sh=shape; Ty=type; T=topography; Co=color; K=kind; Si=size; FR=Friable; PL=plasticity; D=distinctness; De=degree; F=form; L=location; Fa=fabric; B=boubdry;W=weathering; HA=hard; C, Clear boundary; S, Smooth topography of the boundary.

Table 2.2b Soil morphological data 0-200 cm for Alisols, and Andosols

| | Horizon | Color | Structure | Consistency | Roots | Bounda |
|---|---|---|---|---|---|---|
| Depth | | (Moist) | Grade/class/ | Dry/moist/w | Abunda | ry |
| Pedon 7, ON/Wak1/AL | | | | | | |
| 0-10 | Ap | 2.5YR 2.5/3 | MO, ME, GR | SHA, FR, ST, PL | M, M | A, S |
| 10-30 | AB | 2.5YR ¾ | MO, ME, AB | HA, FR, ST, PL | C, F | A, S |
| 30-110 | Bt1 | 2.5YR 4/6 | MO, ME, AB | HA, FR, ST, PL | F, F | G, S |
| 110- | BC | 2.5YR ¾ | MO, CO, AB | SHA,FR,ST,VPL | F, F | — |
| Pedon 8, ON/Wak2/AL | | | | | | |
| 0-15 | Ap | 5YR 3/2 | MO, ME, GR | SHA, FR, SST, | C, M | A, S |
| 15-80 | A | 2.5YR ¾ | MO, CO, SAB | HA, FR, ST, PL | M, F | A, S |
| 80-120 | Bt1 | 2.5YR ¾ | WE, ME, AB | SHA, FR, ST, PL | C, F | A, S |
| 120- | Bt2 | 2.5YR 3/3 | WE, ME, AB | SHA, FR, ST, PL | VF, F | — |
| Pedon 9, ON/Wak3/AL | | | | | | |
| 0-16 | Ap | 2.5YR 3/3 | MO, ME, GR | HA, FR, ST, PL | M, M | A, S |
| 16-40 | A | 2.5YR ¾ | ST, ME, SAB | HA, FR, ST, PL | F, F | A, S |
| 40-120 | Bt1 | 2.5YR 4/6 | ST, ME, SAB | VHA,FR, ST, PL | F,F | A,S |
| 120- | Bt2 | 2.5YR 3/6 | ST, CO, AB | SHA, FR, ST, PL | F, VF | — |
| Pedon 10, ON/CD1/AN | | | | | | |
| 0-20 | Ap | 5YR 2.5/1 | WE, ME, GR | SHA, FR, NST, | C, M | A, S |
| 20-60 | Bt1 | 5YR 2.5/1 | MO, ME, AB | SHA, FR, NST, | C, F | C, S |
| 60-120 | Bt2 | 5YR 2.5/2 | MO, ME, SAB | HA, FR, VST, PL | F, F | G, S |
| 120- | BC | 2.5YR 2.5/3 | MO,CO,AB | HA,FR,VST,PL | VF,F | — |
| Pedon 11, ON/CD2/AN | | | | | | |
| 0-15 | Ap | 2.5YR 3/1 | WE, ME, GR | SHA, FR, ST, PL | M, M | A, S |
| 15-60 | A | 2.5YR 3/1 | MO, ME, GR, | SHA, FR, ST, PL | F, F | C, S |
| 60-100 | Bt1 | 5YR 2.5/1 | MO, CO, SAB | SHA,FR, VST, PL | F, F | A,S |
| 100- | Bt2 | 5YR ¾ | MO, CO, AB | HA,FR, VST, PL | VF, F | — |
| Pedon 12, ON/CD3/AN | | | | | | |
| 0-17 | Ap | 2.5YR 2.5/2 | WE, ME, GR | SHA, FR, ST, PL | M, M | A, S |
| 17-23 | Bt1 | 2.5YR 2.5/1 | MO, ME,AB | VHA, FR, ST, PL | C, F | C,S |
| 23-65 | Bt2 | 2.5YR 2.5/1 | ST,ME, AB | VHA, FR, ST, PL | F, F | A,S |
| 65-105 | Bt3 | 2.5YR 2.5/2 | ST, ME, SAB | SHA,FR, VST, | F, F | A,S |
| 105- | Bt4 | 5YR 3/3 | MO, CO, SAB | SHA, FR, ST, PL | F, F | — |

A=abundance; G=grade; Na=nature; ST=stickiness; C=contrast; Cn=continuity; Moi=moist condition; H=horizons; S=structure; Sh=shape; Ty=type; T=topography; Co=color; K=kind; Si=size; FR=Friable; PL=plasticity; D=distinctness; De=degree; F=form; L=location; Fa=fabric; B=boubdry;W=weathering; HA= Hard.

### *2.3.2 Soil Physical Characteristics*

#### *2.3.2.1. Soil particle size distribution*

The soil textural class was determined in the field by the feel method and laboratory (Tables 2.3a and 3b). Results on the particle-size distribution for all pedons indicated that the clay content slightly increased with the depth of the soil profiles that revealed most subsoil horizons as argic (Bt) and then decreased with the depth except for pedon 6 in which the clay content decreased as the soil depth increased. The sand and silt particle size distribution in most of the studied pedons shows a decreasing trend with soil depth (Table 2.3a and 2.3b). Across the profiles, the highest (64%) and lowest (36%) clay contents were recorded in Pedon 7. For argic horizons, the clay skins (cutans) were found on the sides of ped faces, implying that clay illuviation occurred.

#### *2.3.2.2. Silt/clay ratio*

The silt/clay ratio is an indicator used to evaluate the degree of soil weathering and establish the stage of soil development. The silt/clay ratio of the surface soils of the studied pedons was in the range of 0.09 (Pedon 1) to 0.69 (pedons 10 and 11) (Tables 2.3a and b). There was no clear trend of decrease or increase of silt /clay ratio within soil types and depth in the pedons 1-9 (Nitisols, Luvisols, Cambisols, and Alisols) but for Andosols (pedons 10, 11, and 12) the silt/clay ratio decreased with increasing soil depth, that followed the opposite pattern of variation with clay particles (Table 2.3b). This indicates in Andosols there is an upward soil development (upward pedogenesis) as the new tephra accumulated on the older tephra. According to VanWambeke, (1962), soils with a silt/clay ratio < 0.15 are considered to be highly weathered soils whereas soils with a silt/clay ratio value > 0.15 are young and contain readily weatherable minerals. The soil lab analysis data revealed that Nitisols are weathered soils and Andosols are young soils (Si/C >0.15) especially the younger soils are found at the surface layer of the Andosols. This finding is in line with that of McDaniel, *et al*, (2012) stated that unlike many other soils, Andisol profiles commonly undergo “upbuilding pedogenesis” as younger tephra materials are deposited on the upper surface.

### *2.3.2.3. Bulk density*

The bulk density (BD) of the surface and subsurface layers of all pedons were in the optimum range (0.92-1.30 g/ $cm^3$) for agricultural crop production. The highest BD was observed at the soil layers below 60 cm soil depth. Surface horizon bulk density ranges from 0.92 g $cm^{-3}$ to 1.15 g $cm^{-3}$; being minimum in profile 10 and maximum in profile 5. The subsurface horizon bulk density ranges from 0.93 g $cm^{-3}$ to 1.21 g $cm^{-3}$ being minimum in the subsurface layer of pedon 10 and maximum in the subsurface layer of pedon 5 respectively (Table 2.3a and 2.3b).

As rated by Hazelton and Murphy, (2016), the bulk densities of surface horizons were in the optimum range (1.3-1.6 g /$cm^{-3}$) for mineral soils. Naturally, Andosols had a low bulk density value (0.9 g $cm^{-3}$ or less) compared to the other soil types. In most of the profiles, the bulk density increases irregularly with depth which could be because of the weight of the overlying soil, low porosity, and the relatively low amount of OM in the subsurface soil layers. The low bulk density of profile 10 (Andosols) was attributed to the high amount of OM content and well-structured characteristics of the soils. Hence, the non-systematic increasing pattern in bulk densities with depth of profiles could be related to a decrease in the contents of OM.

### *2.3.2.4 Soil moisture characteristics of the surface soils*

The soil moisture content at FC ranged from 36 to 44% for the surface horizons (Table 2.3a and 2.3b); being the lowest (36%) in the pedon 7 surface horizon with 55% clay content and the highest FC (44%) in the pedon 2 surface horizon with the lowest clay content (36%). The available water holding capacity (AWHC) was lowest (11%) for pedons 1, 4, and 5 and the highest was in pedon 2 (16%) following a similar trend with FC.

Hazelton and Murphy, (2016) rated the AWHC of the soil with <10%, 10–20%, and >20% as low, medium, and high respectively. Accordingly, the mean AWHC of the soils under study was in the medium range (11–16% AWHC) which is suitable for crop production. The highest AWHC (16%) for pedon 2 was most probably due to its lowest sand percentage (23%) and the highest silt (23%) and clay (55%) content and low bulk density (1.07 g cm3). Similarly, Reichert et al., (2009) reported that the amount of plant-available water capacity was lowest in the sand textural class due to low specific surface area, while the greatest AWHC was detected in the textural classes with higher silt content and clay. In line with this, various reports indicated that clay content had a positive relationship with the quantity of water retained at FC and PWP (Nagaraju & Gajbhiye, 2014). The water retention at PWP (1500 kPa) is roughly 0.4 times the clay percentage. The water content at air dryness is about 10 percent of the clay percentage, assuming complete dispersion of clay (USDA, 2017).

Table 2.3a: Selected soil physical characteristics of the soil profile at Bako Tibe District

| Depth (cm) | Horizon | Particle size analysis (%) | | | | Si/C | BD (g cm-3) | FC (%) | PWP (%) | AWC (%) |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Sa | Si | C | Class | | | | | |
| Pedon 1, BA/SK1/NT | | | | | | | | | | |
| 0-20 | Ap | 41 | 5 | 54 | Clay | 0.09 | 1.10 | 40 | 29 | 11 |
| 20-50 | Bt1 | 44 | 5 | 51 | Clay | 0.10 | 1.20 | - | - | - |
| 50-80 | Bt2 | 39 | 5 | 56 | Clay | 0.09 | 1.05 | - | - | - |
| 80-125 | Bt3 | 29 | 8 | 64 | Heavy Clay | 0.12 | 1.02 | - | - | - |
| 125-145 | Bt4 | 41 | 5 | 54 | Clay | 0.09 | - | - | - | - |
| 145-200+ | Bt5 | 34 | 10 | 56 | Clay | 0.18 | - | - | - | - |
| Pedon 2, BA/SK2/NT | | | | | | | | | | |
| 0-20 | Ap | 23 | 23 | 55 | Clay | 0.38 | 1.07 | 44 | 28 | 16 |
| 20-62 | A | 40 | 1 | 59 | Clay | 0.38 | 1.16 | - | - | - |
| 62-110 | B | 36 | 8 | 56 | Clay | 0.09 | 0.96 | - | - | - |
| 110-190$^{+}$ | Bt1 | 29 | 8 | 64 | Heavy Clay | 0.15 | - | - | - | - |
| | Pedon 3, BA/CD1/NT | | | | | | | | | |
| 0-15 | Ap | 36 | 18 | 46 | Clay | 0.38 | 1.00 | 40 | 26 | 14 |
| 15-28 | A | 41 | 16 | 43 | Clay | 0.38 | 1.00 | - | - | - |
| 28-60 | Bt1 | 39 | 5 | 56 | Clay | 0.09 | 1.09 | - | - | - |
| 60-140 | Bt2 | 41 | 8 | 51 | Clay | 0.15 | 1.14 | - | - | - |
| 140-200$^{+}$ | Bt3 | 35 | 4 | 61 | Heavy Clay | 0.06 | - | - | - | - |
| Pedon 4, BA/TS1/LV | | | | | | | | | | |
| 0-20 | Ap | 29 | 15 | 56 | Clay | 0.27 | 1.04 | 39 | 28 | 11 |
| 20-50 | AB | 41 | 18 | 41 | Clay | 0.42 | 1.05 | - | - | - |
| 50-80 | Bt1 | 30 | 18 | 53 | Clay | 0.33 | 1.20 | - | - | - |
| 80-110 | Bt2 | 39 | 8 | 54 | Clay | 0.14 | 1.09 | - | - | - |
| 110-153 | Bt3 | 31 | 16 | 53 | Clay | 0.31 | - | - | - | - |
| 153-200$^{+}$ | Bt4 | 26 | 8 | 66 | Heavy Clay | 0.11 | - | - | - | - |
| Pedon 5, BA/CD2/LV | | | | | | | | | | |
| 0-18 | Ap | 41 | 13 | 46 | Clay | 0.27 | 1.15 | 42 | 31 | 11 |
| 18-50 | Bt1 | 34 | 10 | 56 | Clay | 0.18 | 1.21 | - | - | - |
| 50-102 | B | 40 | 16 | 44 | Clay | 0.37 | 1.15 | - | - | - |
| Pedon 6, BA/CD3/LV | | | | | | | | | | |
| 0-10 | Ap | 41 | 15 | 44 | Clay | 0.34 | 1.07 | 41 | 27 | 14 |
| 10-28 | B | 46 | 13 | 41 | Sandy Clay | 0.30 | 1.15 | - | - | - |
| 28-55 | BC | 45 | 18 | 38 | Sandy Clay | 0.47 | - | - | - | - |

Note: Sa = sand; Si = silt; C = clay; Si/C = silt to clay ratio; BD = bulk density; FC = water content at field capacity; PWP = water content at field capacity; AWC = available water content.

Table 2.3b: Selected soil physical characteristics for the soil profile at Omo Nada District

| Depth |  | Particle size analysis (%) |  |  |  | Si/C | BD | FC | PWP | AWC |
|---|---|---|---|---|---|---|---|---|---|---|
| (cm) | Horizon | Sa | Si | C | Class |  | (g cm-3) | (%) | (%) | (%) |
| Pedon 7, ON/Wak1/AL |  |  |  |  |  |  |  |  |  |  |
| 0-10 | Ap | 41 | 23 | 36 | Clay | 0.63 | 0.97 | 36 | 24 | 12 |
| 10-30 | AB | 34 | 10 | 56 | Clay | 0.17 | 1.01 | - | - | - |
| 30-110 | Bt1 | 29 | 8 | 64 | Clay | 0.34 | 0.97 | - | - | - |
| 110-200$^{+}$ | BC | 31 | 18 | 52 | Clay | 0.12 | 1.08 | - | - | - |
| Pedon 8, ON/Wak2/AL |  |  |  |  |  |  |  |  |  |  |
| 0-15 | Ap | 31 | 15 | 44 | Clay | 0.34 | 1.05 | 38 | 24 | 14 |
| 15-80 | A | 39 | 8 | 54 | Clay | 0.14 | 1.13 | - | - | - |
| 80-120 | Bt1 | 39 | 8 | 54 | Clay | 0.14 | 1.13 | - | - | - |
| 120-200$^{+}$ | Bt2 | 34 | 13 | 54 | Clay | 0.23 | 1.13 | - | - | - |
| Pedon 9, ON/Wak3/AL |  |  |  |  |  |  |  |  |  |  |
| 0-16 | Ap | 39 | 18 | 44 | Clay | 0.40 | 1.01 | 41 | 27 | 14 |
| 16-40 | A | 31 | 10 | 59 | Clay | 0.17 | 1.09 | - | - | - |
| 40-120 | Bt1 | 34 | 10 | 56 | Clay | 0.18 | 1.16 | - | - | - |
| 120-200$^{+}$ | Bt2 | 41 | 8 | 51 | Clay | 0.15 | 1.28 | - | - | - |
| Pedon 10, ON/CD1/AN |  |  |  |  |  |  |  |  |  |  |
| 0-20 | Ap | 43 | 23 | 34 | clay Loam | 0.69 | 0.92 | 37 | 24 | 12 |
| 20-60 | Bt1 | 41 | 23 | 38 | Clay | 0.60 | 0.93 | - | - | - |
| 60-120 | Bt2 | 36 | 20 | 44 | Clay | 0.46 | 0.94 | - | - | - |
| 120-200$^{+}$ | BC | 30 | 15 | 55 | Clay | 0.27 | 1.18 | - | - | - |
| Pedon 11, ON/CD2/AN |  |  |  |  |  |  |  |  |  |  |
| 0-15 | Ap | 45 | 22 | 33 | Clay Loam | 0.69 | 0.94 | 37 | 24 | 13 |
| 15-60 | A | 41 | 23 | 36 | Clay | 0.62 | 0.94 | - | - | - |
| 60-100 | Bt1 | 31 | 15 | 54 | Clay | 0.27 | 0.95 | - | - | - |
| 100-200$^{+}$ | Bt2 | 36 | 8 | 56 | Clay | 0.13 | 1.14 | - | - | - |
| Pedon 12, ON/CD3/AN |  |  |  |  |  |  |  |  |  |  |
| 0-17 | Ap | 44 | 15 | 41 | Clay | 0.37 | 0.98 | 40 | 25 | 15 |
| 17-23 | Bt1 | 35 | 10 | 55 | Clay | 0.18 | 0.99 | - | - | - |
| 23-65 | Bt2 | 44 | 6 | 50 | Clay | 0.12 | 0.99 | - | - | - |
| 65-105 | Bt3 | 36 | 10 | 54 | Clay | 0.19 | 0.90 | - | - | - |
| 105-200$^{+}$ | Bt4 | 36 | 10 | 54 | Clay | 0.19 | 1.11 | - | - | - |

Note: Sa = sand; Si = silt; C = clay; Si/C = silt to clay ratio; BD = bulk density; FC = water content at field capacity; PWP = water content at field capacity; AWC = available water content.

### *2.3.3. Soil Chemical Characteristics*

The soil laboratory analysis results of some selected soil chemical characteristics of the studied pedons are presented in Tables 2.4a, 2.4b, 2.5a, and 2.5b. These soil properties were used for soil characterization, classification, and land capability classification and their management strategies were devised based on these properties in combination with some soil physical characteristics.

#### *2.3.3.1 Soil pH*

The value of soil pH ($H_2O$) was slightly increased with the increasing soil depth. The pH of all the surface and subsurface soil horizons was < 7. In the surface horizons, it ranges from 5.2 on the surface horizon of pedon 1 (Table 2.4a) to 6.44 on the surface horizon of pedon 12 (Table 2.4b). In subsoil horizons, the minimum pH ($H_2O$) was 5.23 for pedon 7 and the maximum pH was 6.85 for pedon 10. The increasing trend of soil pH across soil depth could be due to the washing down of basic cations from the surface to subsurface soil and the decrease in OM content in the subsurface soil. The low pH of surface soil could be due to the effect of leaching of basic cations as a result of the high rainfall in the study area and the release of a proton ($H^+$) upon the decomposition of OM at the surface soil layers. The pH ($H_2O$) values (< 6.5) of the current study are generally considered as non-calcareous. Soil pH of < 5.5 indicates the presence of exch. $Al^{3+}$ and removal of exchangeable cations, revealing low phosphorus availability due to the binding effects of $Al^{3+}$ and $Fe^{3+}$. As rated by Jones (2003), the pH ($H_2O$) values throughout the horizons of most pedons were within the neutral to slightly acidic range which is the preferred range for most crops except for Alisols which was strongly to moderately acidic in reaction.

#### *2.3.3.2. Soil organic carbon, and total nitrogen*

Variation was observed in OC (%) content of the surface soil horizons of the studied pedons (Tables 2.4a and 2.4b). For surface soil, the lowest value of OC content (1.89%) was observed in the surface soil layer of pedon 9 and the highest (5.16%) was recorded at the surface soil layer of pedon 11. For Alisols, the highest and lowest values of OC content of 1.89% and 0.19 % were recorded for pedon 9 at both surface and subsurface soil layers respectively. For Andosols, the highest (5.16%) and the lowest (0.97%) OC content was recorded in the surface soil of pedon 11 and the subsurface soil layers of pedon 10 respectively. In general, the soil OC content was in a decreasing trend across the increasing depth of all pedons (Tables 2.4a and 2.4b).

Based on the ratings of Hazelton and Murphy (2016), the OC content of the surface soil was in the range of medium (1.89% OC in Pedon 9) to very high (5.16% OC in Pedon 11). The variation of OC across the surface soil could be due to relatively low biomass production due to continued pepper moncroping, a faster rate of organic matter decomposition at warmer climates, complete removal of the crop residue from the field, and frequent burning of crop residues while the highest OC content for Andosols was because high amount of rainfall that favors high organic matter production, the cool climate at such a higher elevation (2530 m) causes the slow rate of decomposition of OM and favors more accumulation of OM in the soil. Similarly, Abayneh et al., (2006) stated that in soils located at elevations higher than 1850 m, the relatively lower temperatures may facilitate the OC accumulation. The decreasing trend of OM across the increasing depth of all pedons suggests a comparatively greater addition of decomposable organic materials on the surface horizons than in the subsurface soil horizon.

For the surface soil horizons, the lowest and the highest values of total nitrogen (TN) content were 0.15% in pedon 7 and 0.35% in pedon 11 respectively. In the subsurface horizon, the lowest and the highest values were 0.05% in Pedon 1 and 0.28% in Pedon 12 respectively. The TN content of the surface horizons was higher as compared to the subsurface soil horizons and it followed similar trends with the values of OC in all the studied pedons. For this particular study, the OC, TN, and AP content of the soil decreased together down the soil depth (Table 2.4a and 2.4b). This implies a strong relationship between TN and AP with the OC content of the soils. This study was in agreement with the study of Meysner *et al*. (2006) stated that nearly 93-97% of total nitrogen in the soil is related to OC. Similarly, Cheng et al., (2016) reported that there is a significant direct relationship between soil OC and TN. Based on the rating set by FAO

(2006), the total N contents of the surface layers of the pedons were in the medium range (0.15- 0.35%) and it was optimum for agricultural soils if maintained with good management practices.

#### *2.3.3.3. Available phosphorus*

The soil laboratory analysis results of available P for all pedons are displayed in Tables 2.4a and 2.4b. The maximum Olsen available phosphorus (P) contents of the surface horizons were in pedon 2 (7.85 mg kg$^{-1}$) followed by pedon 3 (7.84 mg kg$^{-1}$) and pedon 4 (7.66 mg kg$^{-1}$) while the minimum (4.0 mg P kg$^{-1}$) was recorded in the pedon 12). In the subsurface soil layers, the minimum available P (0.21 mg kg$^{-1}$) was recorded in pedon 7 followed by 0.47 mg kg$^{-1}$in pedon 12, and the maximum value (8.45 mg kg$^{-1}$) was recorded under the subsurface layer of pedon 2. In all pedons, the values of available P were in a decreasing trend with increasing pedon depth which is attributed to the decrease in soil OM content and low external inputs of P sources at subsoil horizons.

Based on the rating of FAO, (2006), the available P content of the surface soils was categorized in the deficient range (5-9 mg kg$^{-1}$) because of the acidic nature of the soils and the types of clay mineralogy of the soils. Therefore, P deficiency is one of the bottleneck problems for crop production in the study area. This study is in agreement with the findings of Melese *et al.,* (2015; Daniel and Tefera,( 2016); Kebede *et al*., (2017) who stated that phosphorus is the most commonly deficient plant nutrient in Ethiopian soils. This is because of the slow diffusion of P in the soil, the high P-fixation capacity of the soils, and poor P management practices such as low external inputs of P into the soil (Johan et al., 2021). For this particular study, the soil's available P content shows a decreasing trend along the soil depth for all the soil.

Table 2.4a. Soil pH, OC, TN, and Available phosphorus in Nitisols, Alisols Luvisols, and Cambisols profile

| Depth<br>(cm | Horizon | pH<br>($H_2O$) | OC<br>(%) | TN<br>(%) | AP<br>(mg $kg^{-1}$) |
|---|---|---|---|---|---|
| Pedon 1, BA/SK1/NT | | | | | |
| 0-20 | Ap | 5.25 | 2.35 | 0.17 | 6.66 |
| 20-50 | Bt1 | 5.50 | 1.19 | 0.10 | 4.48 |
| 50-80 | Bt2 | 5.72 | 0.84 | 0.08 | 6.72 |
| 80-125 | Bt3 | 5.56 | 0.63 | 0.07 | 4.37 |
| 125-145 | Bt4 | 5.7 | 0.53 | 0.05 | 4.74 |
| 145-200+ | Bt5 | 5.66 | 0.5 | 0.06 | 3.95 |
| Pedon 2, BA/SK2/NT | | | | | |
| 0-20 | Ap | 6.00 | 2.59 | 0.18 | 7.84 |
| 20-62 | A | 6.15 | 0.89 | 0.08 | 7.28 |
| 62-110 | B | 6.32 | 0.63 | 0.07 | 3.09 |
| 110-190$^+$ | Bt1 | 6.27 | 0.45 | 0.06 | 8.45 |
| Pedon 3, BA/CD1/NT | | | | | |
| 0-15 | Ap | 5.47 | 2.59 | 0.19 | 7.85 |
| 15-28 | A | 5.60 | 2.26 | 0.17 | 7.68 |
| 28-60 | Bt1 | 5.93 | 0.97 | 0.08 | 4.11 |
| 60-140 | Bt2 | 5.73 | 0.73 | 0.07 | 2.70 |
| 140-200$^+$ | Bt3 | 5.46 | 0.44 | 0.06 | 3.60 |
| Pedon 4, BA/TS1/AL | | | | | |
| 0-20 | Ap | 5.39 | 3.08 | 0.22 | 7.66 |
| 20-50 | AB | 5.40 | 2.60 | 0.20 | 2.96 |
| 50-80 | Bt1 | 5.52 | 2.26 | 0.14 | 2.31 |
| 80-110 | Bt2 | 5.75 | 2.19 | 0.12 | 3.09 |
| 110-153 | Bt3 | 5.25 | 2.11 | 0.12 | 2.46 |
| 153-200$^+$ | Bt4 | 5.40 | 0.94 | 0.08 | 2.10 |
| Pedon 5, BA/CD2/LV | | | | | |
| 0-18 | Ap | 5.93 | 2.14 | 0.19 | 6.49 |
| 18-50 | Bt1 | 6.60 | 1.22 | 0.11 | 3.64 |
| 50-102 | B | 6.62 | 0.88 | 0.08 | 3.02 |
| Pedon 6, BA/CD3/CM | | | | | |
| 0-10 | Ap | 5.72 | 2.26 | 0.20 | 5.99 |
| 10-28 | B | 6.35 | 1.33 | 0.13 | 8.61 |
| 28-55 | BC | 6.63 | 0.90 | 0.08 | 5.83 |

Note: OC, organic carbon; TN, total nitrogen; AP, available phosphorus

Table 2.4b. Soil pH, OC, TN, and Available phosphorus in Alisols and andAndosols profiles

| Depth (cm | Horizon | pH ($H_2O$) | OC (%) | TN (%) | AP (mg kg$^{-1}$) |
|---|---|---|---|---|---|
| Pedon 7, ON/Wak1/AL | | | | | |
| 0-10 | Ap | 5.23 | 1.91 | 0.15 | 5.44 |
| 10-30 | AB | 5.57 | 1.40 | 0.12 | 1.51 |
| 30-110 | Bt1 | 5.60 | 0.67 | 0.10 | 0.46 |
| 110-200$^{+}$ | BC | 5.57 | 0.55 | 0.09 | 0.21 |
| Pedon 8, ON/Wak2/AL | | | | | |
| 0-15 | Ap | 5.48 | 2.06 | 0.16 | 5.06 |
| 15-80 | A | 6.12 | 0.82 | 0.09 | 2.08 |
| 80-120 | Bt1 | 5.76 | 0.59 | 0.09 | 1.70 |
| 120-200$^{+}$ | Bt2 | 5.66 | 0.54 | 0.08 | 1.46 |
| Pedon 9, ON/Wak3/AL | | | | | |
| 0-16 | Ap | 5.35 | 1.89 | 0.16 | 5.31 |
| 16-40 | A | 5.90 | 0.45 | 0.07 | 2.17 |
| 40-120 | Bt1 | 5.75 | 0.64 | 0.09 | 2.29 |
| 120-200$^{+}$ | Bt2 | 5.73 | 0.19 | 0.12 | 2.24 |
| Pedon 10, ON/CD1/AN | | | | | |
| 0-20 | Ap | 6.20 | 3.78 | 0.29 | 7.78 |
| 20-60 | Bt1 | 6.75 | 3.33 | 0.23 | 5.31 |
| 60-120 | Bt2 | 6.85 | 1.72 | 0.15 | 3.62 |
| 120-200$^{+}$ | BC | 6.62 | 0.97 | 0.12 | 2.77 |
| Pedon 11, ON/CD2/AN | | | | | |
| 0-15 | Ap | 6.26 | 5.16 | 0.35 | 6.84 |
| 15-60 | A | 6.22 | 3.35 | 0.26 | 4.16 |
| 60-100 | Bt1 | 6.03 | 1.29 | 0.11 | 2.96 |
| 100-200$^{+}$ | Bt2 | 6.30 | 0.61 | 0.12 | 2.61 |
| Pedon 12, ON/CD3/AN | | | | | |
| 0-17 | Ap | 6.44 | 4.16 | 0.31 | 4.00 |
| 17-23 | Bt1 | 6.57 | 3.71 | 0.28 | 3.71 |
| 23-65 | Bt2 | 6.67 | 2.06 | 0.15 | 3.09 |
| 65-105 | Bt3 | 6.75 | 0.80 | 0.10 | 2.25 |
| 105-200$^{+}$ | Bt4 | 6.33 | 0.43 | 0.10 | 0.47 |

OC, organic carbon; TN, total nitrogen; AP, available phosphorus

### *2.3.3.4 Exchangeable bases, cation exchange capacity (CEC), and base saturation (BS)*

The major cations occupying the exchange sites listed in increasing order were $Na^+ < K^+ < Mg^{2+} < Ca^{2+}$. The concentration of $Ca^{2+}$ decreased consistently with increasing the pedon depth (Table 2.5a & 2.5b). In the surface soil, the highest value of exchange $Ca^{2+}$ (15.93 $cmol_{(+)}kg^{-1}$) was recorded in Pedon 10 (Andosols), and the lowest value (4.97 $cmol_{(+)}kg^{-1}$) was in Pedon 7 (Alisols). This highest concentration of $Ca^{2+}$ indicates low leaching condition of $Ca^{2+}$ Hazelton and Murphy, (2016), and the Andosols under this study were the young soils with high $Ca^{2+}$ content. According to Hazelton and Murphy's (2016) rating of exchangeable $Ca^{2+}$, the soils were in the medium to high range in $Ca^{2+}$ content which is indicative of the soils varying in their weathering stage from well-developed Nitisols to the younger Andosols. Exchangeable Mg contents varied from 2 $cmol_{(+)}kg^{-1}$in Pedon 4 to 4.64 $cmol_{(+)}kg^{-1}$in Pedon 6 of the surface horizons and 0.89 $cmol_{(+)}kg^{-1}$ in Pedon 4 to 6.13 $cmol_{(+)}kg^{-1}$of Pedon 5 in the subsoil horizons. Generally, the Mg content was rated as low to high in the exchange site of the soil pedons (Hazelton and Murphy, 2016).

The highest exchangeable $K^+$ (2.15 $cmol_{(+)}kg^{-1}$) was recorded in the surface horizon of pedon 5 (luvisols), and the lowest (0.38 $cmol_{(+)}kg^{-1}$) was recorded in pedon 4 (Alisols). In the subsoil horizon, the lowest $K^+$ content (0.12 $cmol_{(+)}kg^{-1}$) was recorded under pedon 1 (Nitisols), and the highest (2.23 $cmol_{(+)}kg^{-1}$) was recorded under pedon 12 (Andosols) and was not consistent with soil depth. As rated by Hazelton and Murphy, (2016), the exchangeable $K^+$ varied from very high to moderate in surface soils and very low to very high in subsurface soils. Therefore, currently, the exchangeable $K^+$ was not the limiting element for crop production in the study area.

The exchangeable sodium is low throughout the profiles of the studied soils (Table 2.5a & b). It shows an irregular pattern of variation with the depth of the pedons. The reason for low exchangeable Na was that a high amount of rainfall leaches the base and as a result, adverse effects of Na would not be expected in the study area (Bako Tibe and Omo Nada districts). The quantity of exchangeable Na varied from 0.06 $cmol_{(+)}kg^{-1}$soils (pedon 9) to 0.21 $cmol_{(+)}kg^{-1}$ soil (pedon 10) in the surface horizon and 0.07 $cmol_{(+)}kg^{-1}$ (pedon 9) to 0.28 $cmol_{(+)}kg^{-1}$soils (pedon 4) in the subsoil horizons.

As there is a strong relationship between CEC and OM, the CEC of surface horizons was higher than that of subsoil horizons. In the surface horizons, CEC varies from 23 $cmol_{(+)}kg^{-1}$ soil (pedon 7) to 45 $cmol_{(+)}kg^{-1}$ soil (pedon 6). CEC values generally show a systematic variation (decrease) with depth in pedons 6 and 10 and vary non-systematically with depth in other pedons. In the subsoil horizons, CEC varies between 21 $cmol_{(+)}$ $kg^{-1}$ soil (pedon 7) and 44 $cmol_{(+)}kg^{-1}$soil (pedon 6). For this particular study, Alisols had the lowest CEC values and Luvisols had the highest CEC values followed by Andisols and Nitisols (contains high activity clays) both at surface and subsurface soil horizons which is very crucial for soil classification (Table 2.5a and 2.5b).

### *2.3.3.5 The Ca/Mg ratio in the studied pedons*

The Ca: Mg ratio of surface horizons varied from 2.3:1, pedon 7 (Alisols) to 5.2:1, pedon 10 (Andosols). Across the soil depth, the Ca: Mg ratio was regularly decreased for some of the pedons (1, 3, 4, 6, 10, 11, and 12) and irregularly distributed for other pedons (2,5,7,8, and 9). For the subsurface horizons, the lowest Ca: Mg ratio (1.76:1) was recorded for pedon 9 and the highest (5.1:1) was recorded under pedon 10 (Table 2.5a and 2.5b). Generally, Andosols had the highest Ca: Mg ratio and Alisols had the lowest Ca: Mg ratio for this particular study (Table 2.5b).

### *2.3.3.6 Percent base saturation (PBS) and Exchangeable sodium percentage (ESP)*

The percent base saturation of the soils decreased with increasing soil depth in Pedons 7, 8, and 12, while it was inconsistent in the other pedons, (Table 2.5a and 2.5b). Percent base saturation of surface soil horizons ranged from 28% (in Pedon 4) to 54% (in Pedons 10 and 11). In the subsurface soils, PBS varied from 10% in the Bt3 horizon of Pedon 4 (Alisols) to 63% in the bottom layer (BC horizon) of Pedon 6. Hazelton and Murphy (2016) described PBS rating as PBS of 0-20 = very low, 20-40 = low, 40-60 = moderate, 60-80 = high, and > 80 = very high. Based on this rating, pedon 4 was very low, pedons 10 and 11 were moderate and pedon 6 was high in PBS.

Exchangeable sodium is low throughout the profiles of all the studied soils (Tables 2.5a and 2.5b). It shows an irregular pattern of variation with the depth of the profiles. High exchangeable Na would not be expected in the high rainfall areas such as the Southwestern region of the country. As a result, adverse effects of exchangeable Na would not be expected in the study area and similar environments of the Bako and Jimma in general. In pedons 1, 4, and 6, the magnitude of exchangeable Na shows a general increasing trend with depth while it had irregular distribution with depth in other pedons. The amount of exchangeable Na varied from 0.25 $cmol_{(+)}kg^{-1}$ soil to 0.58 $cmol_{(+)}kg^{-1}$ soil on the surface and 0.27 $cmol_{(+)}$ $kg^{-1}$ to 1.13 $cmol_{(+)}kg^{-1}$ soil in the subsoil horizons. The highest amount of exchangeable Na for surface and subsurface horizons was recorded in pedon 4.

Table 2.5a. CEC, exchangeable bases, and base saturation of Nitisols and Luvisols profiles

| Depth | Horizon | Cmol(+)/kg | | | | | | Ca/mg | BS | ESP |
|---|---|---|---|---|---|---|---|---|---|---|
| | | CEC | Ca$^{2+}$ | Mg$^{2+}$ | K$^{+}$ | Na$^{+}$ | Sum | Ratio | (%) | (%) |
| Pedon 1, BA/SK1/NT | | | | | | | | | | |
| 0-20 | Ap | 33 | 6.93 | 2.27 | 0.54 | 0.14 | 9.88 | 3.05 | 30 | 0.43 |
| 20-50 | Bt1 | 34 | 6.79 | 2.53 | 0.19 | 0.18 | 9.69 | 2.68 | 28 | 0.53 |
| 50-80 | Bt2 | 29 | 7.07 | 2.71 | 0.15 | 0.14 | 10.07 | 2.61 | 37 | 0.48 |
| 80-125 | Bt3 | 28 | 5.4 | 2.12 | 0.12 | 0.15 | 7.79 | 2.55 | 28 | 0.54 |
| 125-145 | Bt4 | 27 | 5.73 | 2.5 | 0.12 | 0.15 | 8.5 | 2.29 | 32 | 0.56 |
| 145-200$^{+}$ | | 26 | 5.47 | 2.75 | 0.12 | 0.14 | 8.48 | 1.99 | 33 | 0.54 |
| Pedon 2, BA/SK2/NT | | | | | | | | | | |
| 0-20 | Ap | 34 | 10.03 | 2.99 | 1.08 | 0.19 | 14.29 | 3.35 | 42 | 0.56 |
| 20-62 | A | 29 | 7.39 | 3.04 | 0.52 | 0.15 | 11.10 | 2.43 | 38 | 0.52 |
| 62-110 | B | 23 | 6.46 | 2.33 | 0.22 | 0.14 | 9.15 | 2.77 | 40 | 0.62 |
| 110-190$^{+}$ | Bt1 | 27 | 5.87 | 1.94 | 0.19 | 0.22 | 8.22 | 3.03 | 31 | 0.83 |
| Pedon 3, BA/CD1/NT | | | | | | | | | | |
| 0-15 | Ap | 36 | 8.92 | 2.44 | 1.27 | 0.15 | 12.7 | 3.66 | 36 | 0.42 |
| 15-28 | A | 38 | 8.50 | 2.18 | 0.44 | 0.11 | 11.2 | 3.90 | 29 | 0.29 |
| 28-60 | Bt1 | 25 | 5.47 | 2.16 | 0.28 | 0.12 | 8.03 | 2.53 | 32 | 0.48 |
| 60-140 | Bt2 | 21 | 4.89 | 1.98 | 0.79 | 0.13 | 7.79 | 2.47 | 38 | 0.63 |
| 140-200$^{+}$ | Bt3 | 29 | 5.09 | 2.21 | 0.62 | 0.14 | 8.06 | 2.30 | 28 | 0.49 |
| Pedon 4, BA/TS1/LV | | | | | | | | | | |
| 0-20 | Ap | 35 | 7.27 | 2.00 | 0.38 | 0.20 | 9.85 | 3.64 | 28 | 0.58 |
| 20-50 | AB | 36 | 6.72 | 2.25 | 0.19 | 0.21 | 9.37 | 2.99 | 26 | 0.58 |
| 50-80 | Bt1 | 38 | 8.41 | 2.26 | 0.18 | 0.24 | 11.0 | 3.72 | 29 | 0.62 |
| 80-110 | Bt2 | 37 | 7.13 | 2.00 | 0.17 | 0.28 | 9.58 | 3.57 | 26 | 0.76 |
| 110-153 | Bt3 | 41 | 2.69 | 0.89 | 0.12 | 0.27 | 3.97 | 3.02 | 10 | 0.67 |
| 153-200$^{+}$ | Bt4 | 23 | 4.14 | 1.25 | 0.14 | 0.26 | 5.79 | 3.31 | 25 | 1.13 |
| Pedon 5, BA/CD2/LV | | | | | | | | | | |
| 0-18 | Ap | 44 | 12.74 | 4.21 | 2.15 | 0.13 | 19.23 | 3.03 | 44 | 0.29 |
| 18-50 | Bt1 | 40 | 13.45 | 4.89 | 2.01 | 0.17 | 20.52 | 2.75 | 52 | 0.43 |
| 50-102 | B | 43 | 13.84 | 6.13 | 1.95 | 0.15 | 22.07 | 2.26 | 51 | 0.35 |
| Pedon 6, BA/CD3/CM | | | | | | | | | | |
| 0-10 | Ap | 45 | 15.31 | 4.64 | 2.04 | 0.13 | 22.12 | 3.30 | 49 | 0.29 |
| 10-28 | B | 44 | 14.94 | 4.78 | 1.39 | 0.13 | 21.24 | 3.13 | 48 | 0.30 |
| 28-55 | BC | 41 | 18.64 | 6.22 | 0.81 | 0.20 | 25.87 | 3.00 | 63 | 0.48 |

*Note:* BA = Bako Tibe; NT = Nitisols; Lv = Luvisols; CD1, CD2, CD3= Cheka Dimtu kebele field (pit) 3,5and 6 respectively;

Table 2.5b. CEC, exchangeable bases, and base saturation of Alisols and Adosols profiles

| Depth | Horizon | Cmol(+)/kg | | | | | | Ca/Mg | BS | ESP |
|---|---|---|---|---|---|---|---|---|---|---|
| | | CEC | $Ca^{2+}$ | $Mg^{2+}$ | $K^+$ | $Na^+$ | Sum | Ratio | (%) | (%) |
| Pedon 7, ON/Wak1/AL | | | | | | | | | | |
| 0-10 | Ap | 25 | 4.76 | 2.11 | 0.70 | 0.07 | 7.6 | 2.25 | 33 | 0.31 |
| 10-30 | AB | 27 | 4.44 | 2.11 | 0.42 | 0.08 | 7.0 | 2.11 | 25 | 0.27 |
| 30-110 | Bt1 | 21 | 2.63 | 1.45 | 0.35 | 0.13 | 4.5 | 1.81 | 21 | 0.59 |
| 110- | BC | 21 | 1.17 | 0.49 | 0.33 | 0.11 | 2.1 | 2.39 | 10 | 0.54 |
| Pedon 8, ON/Wak2/AL | | | | | | | | | | |
| 0-15 | Ap | 28 | 8.36 | 3.45 | 1.27 | 0.15 | 13.23 | 2.43 | 47 | 0.54 |
| 15-80 | A | 33 | 8.41 | 4.19 | 0.56 | 0.11 | 13.27 | 2.01 | 41 | 0.33 |
| 80-120 | Bt1 | 27 | 6.75 | 3.58 | 0.60 | 0.13 | 11.07 | 1.89 | 41 | 0.50 |
| 120-200$^+$ | Bt2 | 31 | 4.48 | 2.08 | 0.64 | 0.15 | 7.35 | 2.16 | 23 | 0.47 |
| Pedon 9, ON/Wak3/AL | | | | | | | | | | |
| 0-16 | Ap | 24 | 5.55 | 2.42 | 1.34 | 0.06 | 9.37 | 2.30 | 39 | 0.25 |
| 16-40 | A | 25 | 5.32 | 3.01 | 0.70 | 0.10 | 9.13 | 1.76 | 37 | 0.40 |
| 40-120 | Bt1 | 24 | 5.71 | 2.65 | 0.88 | 0.08 | 9.32 | 2.15 | 39 | 0.31 |
| 120-200$^+$ | Bt2 | 20 | 5.96 | 3.18 | 1.22 | 0.07 | 10.4 | 1.88 | 51 | 0.33 |
| Pedon 10, ON/CD1/AN | | | | | | | | | | |
| 0-20 | Ap | 38 | 15.93 | 3.07 | 1.37 | 0.21 | 20.59 | 5.19 | 54 | 0.57 |
| 20-60 | Bt1 | 36 | 17.67 | 3.47 | 1.13 | 0.14 | 22.41 | 5.10 | 62 | 0.39 |
| 60-120 | Bt2 | 32 | 12.50 | 3.58 | 1.26 | 0.17 | 17.52 | 3.49 | 55 | 0.55 |
| 120- | BC | 29 | 9.50 | 4.23 | 0.90 | 0.18 | 14.80 | 2.25 | 51 | 0.62 |
| Pedon 11, ON/CD2/AN | | | | | | | | | | |
| 0-15 | Ap | 34 | 11.44 | 3.10 | 1.58 | 0.18 | 16.30 | 3.69 | 48 | 0.53 |
| 15-60 | A | 34 | 11.09 | 3.28 | 1.23 | 0.29 | 15.89 | 3.38 | 46 | 0.86 |
| 60-100 | Bt1 | 29 | 6.87 | 3.89 | 1.29 | 0.18 | 12.23 | 1.76 | 43 | 0.63 |
| 100-200$^+$ | Bt2 | 25 | 4.05 | 2.51 | 2.21 | 0.17 | 8.94 | 1.61 | 36 | 0.68 |
| Pedon 12, ON/CD3/AN | | | | | | | | | | |
| 0-17 | Ap | 37 | 14.49 | 3.22 | 2.06 | 0.11 | 19.88 | 4.50 | 54 | 0.29 |
| 17-23 | Bt1 | 39 | 14.47 | 3.40 | 1.56 | 0.11 | 19.53 | 4.26 | 50 | 0.27 |
| 23-65 | Bt2 | 33 | 10.16 | 4.13 | 2.20 | 0.10 | 16.60 | 2.46 | 50 | 0.31 |
| 65-105 | Bt3 | 29 | 5.84 | 2.79 | 3.44 | 0.10 | 12.17 | 2.09 | 42 | 0.36 |
| 105-200$^+$ | Bt4 | 26 | 5.34 | 2.64 | 2.23 | 0.09 | 10.30 | 2.03 | 39 | 0.33 |

*Note:* ON = Omo Nada; AN = Andosols; AL = Alisols; CD1, CD2, CD3= Chalalaka Donga kebele field (pit) 1,2 and 3 respectively; Wak1, Wak2, and wak3 = Waktola kebele field (pit) 1,2 and 3 respectively;

### *2.3.3.7. Available Micronutrients (Fe, Mn, Zn, Cu, and B)*

The available micronutrients (Fe, Mn, Zn, Cu, and B) content in all Pedons had irregular trends along soil depth (Table 2.6a and 2.6b). All the soil's micronutrient content for this study was rated based on the criteria set by (Benton 2003). Accordingly, the concentration of available Fe for surface horizons was in the range of high (178.3 mg $kg^{-1}$) in Pedon 6 to very high (276.1 mg $kg^{-1}$) in Pedon 7. For the subsurface horizon, the lowest (46 mg $kg^{-1}$) and the highest (223.3 mg $kg^{-1}$) Fe content was recorded in the Pedons 8 and 10 respectively. The available Mn content was very high (between 152.4 to 293.6 mg $kg^{-1}$) for all the surface layers and moderate (20 mg $kg^{-1}$) to very high (202.4 mg $kg^{-1}$) in the subsurface horizon of pedons 8 and 9 respectively. The lowest (0.53 $kg^{-1}$) and highest (9.92 mg $kg^{-1}$) Zn content for surface horizons were recorded under Pedon 10 and 7 respectively and following the same trend, the lowest (0.07 mg $kg^{-1}$) and highest (2.94 mg $kg^{-1}$) Zn content for subsurface horizons were also recorded under Pedon 10 and 7 in that order. According to Benton, (2003), the surface horizon was in the range of moderate to high and the subsurface horizons were in the range of very low to high in Zn content.

For the surface horizons, the lowest Cu content (0.50 mg $kg^{-1}$) was recorded under Pedon 9 and the highest (3.53 mg $kg^{-1}$) was under Pedon 3. The lowest (0.19 mg $kg^{-1}$) and highest (3.15 mg $kg^{-1}$) Cu content of the subsurface horizon was recorded under Pedon 3 and Pedon 12 respectively. Based on the above rating, the Cu content of surface and sub-horizons was in the low to medium range which was insufficient for crop production.

The distribution of B follows an irregular trend across the soil depth. The lowest (0.01 mg $kg^{-1}$) and highest (0.56 mg $kg^{-1}$) content of B at surface horizons was recorded in Pedon 7 and Pedon 10 correspondingly.  In the subsurface horizon, the lowest (0.00 mg $kg^{-1}$) and highest (0.59 mg $kg^{-1}$) B content was recorded in Pedon 11 and Pedon 4 respectively.

Table 2.6a: Available micronutrients in Nitisolss and Luvisols profiles

| Depth (cm) | Horizon | mg kg$^{-1}$ | | | | |
|---|---|---|---|---|---|---|
| | | Fe | Mn | Zn | Cu | B |
| Pedon 1, BA/SK1/NT | | | | | | |
| 0-20 | Ap | 229 | 255 | 1.31 | 3.16 | 0.48 |
| 20-50 | Bt1 | 141 | 157 | 0.9 | 2.19 | 0.45 |
| 50-80 | Bt2 | 115 | 126 | 0.78 | 1.87 | 0.45 |
| 80-125 | Bt3 | 65 | 63.3 | 0.24 | 1.29 | 0.41 |
| 125-145 | Bt4 | 91 | 111 | 0.26 | 1.26 | 0.45 |
| 145-200+ | Bt5 | 76 | 86.5 | 0.34 | 1.11 | 0.37 |
| Pedon 2, BA/SK2/NT | | | | | | |
| 0-20 | Ap | 248 | 273 | 1.44 | 3.25 | 0.32 |
| 20-62 | A | 79 | 67 | 0.32 | 1.58 | 0.40 |
| 62-110 | B | 63 | 65 | 0.35 | 1.34 | 0.46 |
| 110-190$^{+}$ | Bt1 | 75 | 91 | 0.20 | 1.34 | 0.48 |
| Pedon 3, BA/CD1/NT | | | | | | |
| 0-15 | Ap | 246 | 238 | 1.38 | 3.53 | 0.22 |
| 15-28 | A | 233 | 189 | 1.16 | 3.15 | 0.12 |
| 28-60 | Bt1 | 96 | 108 | 0.22 | 1.22 | 0.27 |
| 60-140 | Bt2 | 66 | 81 | 0.16 | 1.11 | 0.26 |
| 140-200$^{+}$ | Bt3 | 99 | 128 | 0.34 | 1.31 | 0.34 |
| Pedon 4, BA/TS1/LV | | | | | | |
| 0-20 | Ap | 202 | 169 | 0.90 | 2.90 | 0.38 |
| 20-50 | AB | 177 | 105 | 0.56 | 3.02 | 0.50 |
| 50-80 | Bt1 | 185 | 118 | 0.47 | 2.87 | 0.49 |
| 80-110 | Bt2 | 104 | 46 | 0.37 | 2.53 | 0.52 |
| 110-153 | Bt3 | 53 | 20 | 0.20 | 1.73 | 0.59 |
| 153-200$^{+}$ | Bt4 | 64 | 59 | 2.36 | 1.38 | 0.51 |
| Pedon 5, BA/CD2/LV | | | | | | |
| 0-18 | Ap | 253 | 294 | 1.57 | 1.44 | 0.24 |
| 18-50 | Bt1 | 137 | 130 | 0.53 | 1.52 | 0.30 |
| 50-102 | B | 112 | 94 | 0.39 | 1.30 | 0.41 |
| Pedon 6, BA/CD3/CM | | | | | | |
| 0-10 | Ap | 178 | 244 | 1.20 | 1.69 | 0.26 |
| 10-28 | B | 158 | 119 | 0.35 | 1.25 | 0.36 |
| 28-55 | BC | 143 | 102 | 0.33 | 1.24 | 0.44 |

Note: Fe = iron; Mn = manganese; Zn = Zinc; Cu = copper; B = boron

Table 2.6b: Available micronutrients in Alisols andAndosols profiles

| Depth (cm) | Horizon | mg kg$^{-1}$ | | | | |
|---|---|---|---|---|---|---|
| | | Fe | Mn | Zn | Cu | B |
| Pedon 7, ON/Wak1/AL | | | | | | |
| 0-10 | Ap | 276 | 241 | 0.53 | 0.58 | 0.01 |
| 10-30 | AB | 135 | 168 | 0.26 | 0.42 | 0.02 |
| 30-110 | Bt1 | 71 | 91 | 0.07 | 0.23 | 0.05 |
| 110-200$^{+}$ | BC | 89 | 122 | 0.13 | 0.22 | 0.03 |
| Pedon 8, ON/Wak2/AL | | | | | | |
| 0-15 | Ap | 183 | 152 | 1.61 | 0.64 | 0.02 |
| 15-80 | A | 59 | 43 | 0.26 | 0.52 | 0.05 |
| 80-120 | Bt1 | 46 | 28 | 0.26 | 0.54 | 0.13 |
| 120-200$^{+}$ | Bt2 | 67 | 55 | 0.61 | 0.81 | 0.14 |
| Pedon 9, ON/Wak3/AL | | | | | | |
| 0-16 | Ap | 188 | 226 | 0.93 | 0.50 | 0.01 |
| 16-40 | A | 114 | 150 | 0.20 | 0.29 | 0.07 |
| 40-120 | Bt1 | 161 | 202 | 0.16 | 0.33 | 0.00 |
| 120-200$^{+}$ | Bt2 | 175 | 196 | 0.32 | 0.50 | 0.03 |
| Pedon 10, ON/CD1/AN | | | | | | |
| 0-20 | Ap | 261 | 244 | 9.92 | 1.12 | 0.56 |
| 20-60 | Bt1 | 218 | 177 | 6.88 | 1.01 | 0.36 |
| 60-120 | Bt2 | 223 | 193 | 2.94 | 0.51 | 0.24 |
| 120-200$^{+}$ | BC | 171 | 163 | 0.61 | 0.75 | 0.02 |
| Pedon 11, ON/CD2/AN | | | | | | |
| 0-15 | Ap | 238 | 190 | 5.46 | 0.87 | 0.24 |
| 15-60 | A | 217 | 161 | 3.64 | 0.88 | 0.21 |
| 60-100 | Bt1 | 118 | 75 | 0.65 | 0.74 | 0.00 |
| 100-200$^{+}$ | Bt2 | 102 | 79 | 0.21 | 0.33 | 0.00 |
| Pedon 12, ON/CD3/AN | | | | | | |
| 0-17 | Ap | 204 | 190 | 8.58 | 1.15 | 0.22 |
| 17-23 | Bt1 | 188 | 161 | 6.49 | 1.05 | 0.16 |
| 23-65 | Bt2 | 142 | 75 | 2.23 | 1.12 | 0.06 |
| 65-105 | Bt3 | 130 | 79 | 0.68 | 0.81 | 0.06 |
| 105-200$^{+}$ | Bt4 | 215 | 190 | 1.11 | 0.19 | 0.09 |

Note: Fe = iron; Mn = manganese; Zn = Zinc; Cu = copper; B = boron

## 2.4. DISCUSSIONS

### *2.4.1. Selected Soil Morphological Characteristics*

#### *2.4.1.1 Soil color*

Compared to the subsurface soils, the surface soil layers were darker in color as the organic matter content was higher in the latter. Soil color is a good indicator of soil quality since it gives an indirect measure of the other important properties of the soil that are not measured so simply and correctly. Mostly, darker soil color indicates more organic matter content in the soil. A change in soil color can be used as a general indicator of a change in organic matter under a specific land use or management. Soil color is affected noticeably by the chemical form such as the oxidation state of iron (Fe) and manganese (Mn).

The reddish color of the soil indicates good soil drainage condition, aerated, and oxidation of iron. Similarly, the difference in color among the pedons and within a pedon is most probably due to variations in forms of iron oxide, the types of parent material, OM content, and drainage conditions (Ali et al., 2010; Buol et al., 2011; Abate,2014). For Andosols (pedons 10, 11, and 12), the soil color differs between black (5YR 2.5/1) to dark reddish-brown (5YR3/4) which was attributed to the inherent high organic matter content of the Andosols.

#### *2.4.1.2 Soil structure and consistency*

The strong coarse subangular blocky structure and the subsurface soil layers had strong coarse angular blocky (ST CO AB) structure.  The surface soil (Ap) of pedons 4 had a strong coarse subangular blocky (ST, CO, SAB) structure in the subsurface soil layer, the Bt1 and Bt2 layers had a strong coarse subangular blocky (ST CO SAB) structure while the Bt3 and Bt4 had moderate medium subangular blocky (MO ME SAB) structure.  In pedon 5, the surface soil (AP) and subsurface Bt1 had a strong coarse subangular blocky (ST CO SAB) structure and the B horizon had a strong coarse angular blocky (ST CO

AB) structure. In the surface soil of Cambisols (pedon 6), the surface soils (Ap) had a strong

#### *2.4.1.3 Soil depth and horizon boundaries*

A very deep rooting depth of the soil of the study area indicates the soil holds more amount of plant nutrients and available water to plant roots which is conducive for most plant growth and crop production. The soils need less frequent and deep irrigation secludes. The gradual horizon boundaries of surface and sub-surface horizons in Nitisols (Pedons 1, 2, 3, and 5), indicate Nitisols and Luvisols are well developed, deep, and highly weathered soils. (Table 2.2a). On the other hand, in Andosols (pedons 10, 11, and 12) abrupt horizon boundaries with a sudden change to another kind of material, either geologic or formed by soil development show the soils are formed from different parent materials (Table 2.2b).

#### *2.4.1.4 Soil structure and consistency*

The strong coarse subangular blocky structure in the surface horizons of Nitisols (pedons 1, 2, and 3) was due to less OM content, and the strong coarse angular blocky structure at the subsurface soil layers was due to more clay accumulation in the Bt horizons. The moderate, medium, and granular surface soil structures for Alisols (pedons 7, 8, and 9) and Andosols (pedons 10, 11, and 12), were due to more OM content and gradually changed to strong, coarse, angular blocky structures in subsurface soil horizons were due to decrease in OM content of the soils across the soil depth.

This sticky, very sticky, and plastic and very plastic consistency at the subsurface layers is attributed to the decrease in OM content, the more clay particles, and the harder to work with the soils. Abay Ayalew et al., (2014) reported similar results in that the sticky and plastic consistency indicates the existence of high clay content and difficulty in working. Ali et al. (2010) reported that the existence of a very sticky and very plastic consistency mainly shows the soils contain smectic clay minerals.

### *2.4.2. Soil Physical Characteristics*

#### *2.4.2.1 Soil particle size distribution and silt/clay ratio*

For all pedons, the increase in clay content with increasing the depth of the soil profiles revealed most subsoil horizons as argic (Bt) were formed by clay illuviation except for Cambisols (pedon 6) in which the clay content decreased in the layer below the cambic horizon (Table 2.3a and 2.3b) which indicates the evidence of ongoing soil formation processes. The silt/clay ratio is an indicator used to evaluate the degree of soil weathering and establish the stage of soil development. According to VanWambeke, (1962), soils with a silt/clay ratio < 0.15 are considered to be highly weathered soils whereas soils with a silt/clay ratio value > 0.15 are young and contain readily weatherable minerals. The soil lab analysis data (Tables 2.3a and b) revealed that Nitisols are weathered soils and Andosols are young soils (Si/C >0.15) especially the younger soils are found at the surface layer of the Andosols. This finding is in line with that of McDaniel, *et al*, (2012) stated that, unlike many other soils, Andisol profiles commonly undergo "upbuilding pedogenesis" as younger tephra materials are deposited on the upper surface.

#### *2.4.2.2. Bulk density*

The bulk density (BD) of the surface and subsurface layers of all pedons were in the optimum range (1.3-1.6 g /cm$^{-3}$) Hazelton and Murphy, (2016) for agricultural crop production. Naturally, Andosols had a low bulk density value (0.9 g cm$^{-3}$ or less) due to their high OM content or volcanic parent materials naturally producing highly porous soil structures that allow for excellent water holding capacity and help to good drainage conditions for the soils. The reason for the decrease in the soils' BD across the soil depth was due to decreasing OM with increasing the soils' OM content. The BD of the soils under this study was optimum since it encourages favorable plant available water capacity, root growth, and movement of air and water through soil (Hazelton and Murphy, 2016).

#### *2.4.2.3. Soil moisture characteristics of the surface soils*

The highest AWHC (16%) for pedon 2 was most probably due to its lowest sand percentage (23%) and the highest silt (23%) and clay (55%) content and low bulk density (1.07 g cm3). Similarly, Reichert et al., (2009) reported that the amount of plant-available water capacity was lowest in the sand textural class due to low specific surface area, while the greatest AWHC was detected in the textural classes with higher silt content and clay. In line with this, various reports indicated that clay content had a positive relationship with the quantity of water retained at FC and PWP (Nagaraju & Gajbhiye, 2014). The water retention at PWP (1500 kPa) is roughly 0.4 times the clay percentage. The water content at air dryness is about 10 percent of the clay percentage, assuming complete dispersion of clay (USDA, 2017).

### *2.4.3. Soil Chemical Characteristics*

#### *2.4.3.1 Soil pH*

The increasing trend of soil pH across soil depth could be due to the washing down of basic cations from the surface to sub-surface soil and the decrease in OM content in the subsurface soil horizons. The low pH values of surface soil could be due to the effect of leaching of basic cations as a result of the high rainfall in the study area and the release of a proton ($H^+$) upon the decomposition of OM at the surface soil layers. The pH values (< 6.5) of the current study are generally considered non-calcareous. Soil pH of < 5.5 indicates the presence of Al and removal of exchangeable cations, revealing low phosphorus availability due to the binding effects of Al and Fe. As rated by Jones (2003), the pH ($H_2O$) values throughout the horizons of most pedons were within the strongly to slightly acidic range which is not a conducive pH range for most crop production. This strongly acidic soil reaction suggests the application of agricultural limes such as $CaCO_3$ or $CaMg(CO_3)_2$.

### *2.4.3.2 Soil organic carbon, total nitrogen, and available phosphorus*

Based on the ratings of Hazelton and Murphy (2016), 1.89% OC (Pedon 9) ranges from medium to very high (5.16% OC) in (pedon 11). The variation of OC across the surface soil could be due to relatively low biomass production as affected by very strong acidic soil reaction, a faster rate of organic matter decomposition at warmer climates, and frequent burning of crop residues while the highest OC content for Andosols was due to the fact that high amount of rainfall that favors high organic matter production, the cool climate at such a higher elevation (2530 m) causes the slow rate of decomposition of OM favors more accumulation of OM in the soil.

Naturally, Andosols accumulate a high quantity of OM due to the formation of allophane–organic matter complexes and metal–humus complexes (Arnalds, 2004). Due to the high productivity of Andosols, there is typically a large annual OM input via aboveground and belowground plant litter as well as root exudates into these soils. This also implies that Andosols preserve OC originating from previous land use for a long time. Similarly, Abayneh *et al*., (2006) stated that in soils located at elevations higher than 1850 m, the relatively lower temperatures may facilitate the OC accumulation. The decreasing trend of OM across the increasing depth of all pedons suggests a comparatively greater addition of decomposable organic materials on the surface horizons than in the subsurface soil horizon. Soils with the optimum quantity of OM have more aggregate stability and are resistant to soil erosion, porous to air circulation and water infiltration i.e. good in moisture storage and nutrient storage as the soil OM increases the CEC of the soils, and the plant roots easily penetrate it (Kögel-Knabner & Amelung, 2013).

There is a strong relationship between TN and AP with the OC content of the soils. Conversely, the soil N content is used to estimate the status of OM in the soil. This study was in agreement with the study of Meysner *et al*. (2006) stated that nearly 93-97% of total nitrogen in the soil is related to OC. Similarly, Cheng et al., (2016) reported a significant direct relationship between soil OC and TN. Based on the rating set by FAO (2006), the total N contents of the surface layers of the pedons were in the medium range (0.15- 0.35%) and it was optimum for agricultural soils if maintained with good management practices.

Based on the rating of FAO, (2006), the available P content of the surface soils was categorized in the deficient range (5-9 mg $kg^{-1}$) because of the acidic nature of the soils and the types of clay mineralogy of the soils. Therefore, P deficiency is one of the bottleneck problems for crop production in the study area. This study is in agreement with the findings of (Melese *et al.,* 2015; Daniel and Tefera, 2016; Kebede *et al*., 2017) who stated that phosphorus is the most commonly deficient element in Ethiopian soils. This is because of the slow diffusion of P in the soil, the high-fixation capacity of P in the soil, poor P management practices such as low external in-puts of P into the soil, *etc*(Johan et al., 2021) For this particular study, the soil's available P content shows a decreasing trained along the soil depth for all the soil pedons that are attributed to the decreasing of soil OM content and low external inputs of P sources at subsoil horizons.

### *2.4.3.3 Exchangeable bases, cation exchange capacity (CEC), and base saturation (BS)*

The highest quantity of exchange $Ca^{2+}$ was obtained in Pedon 10 (Andosols) which indicates a low leaching condition of $Ca^{2+}$ and other basic cations due to a very high OM content and a high CEC content of Andosols. Therefore, the basic cations were retained by the soils. On the other hand, the lowest value of $Ca^{2+}$ in Pedon 7 (Alisols) was due to low pH and OM hence low CEC of the soils that causes less retention of the bases due to leaching losses, and the dominance of the soil exchange sites by acid-forming cations such as $Al^{3+}$ and $H^{+}$ ions. This highest concentration of $Ca^{2+}$ indicates low leaching condition of $Ca^{2+}$ Hazelton and Murphy, (2016), and the Andosols under this study were the young soils with high $Ca^{2+}$ content. According to Hazelton and Murphy's (2016) rating of exchangeable $Ca^{2+}$, the soils were in the medium to high range in $Ca^{2+}$ content which is indicative of the soils varying in their weathering stage from well-developed Nitisols to the younger Andosols.

As retted by Hazelton and Murphy, (2016), the exchangeable $Mg^{2+}$ contents were rated as low to high and the exchangeable $K^{+}$ varied from very high to moderate whereas the level of exchangeable $Na^{+}$ was low throughout the profiles of the studied soils Therefore, currently, the exchangeable $Mg^{2+}$, $K^{+,}$ and $Na^{+}$ were not the limiting elements for crop production in the study area. As there is a strong relationship between CEC and OM, the CEC of surface horizons was higher than that of subsoil horizons. For this particular study, Alisols had the lowest CEC values and Luvisols had the highest CEC values followed by Andisols and Nitisols (contains high activity clays) both at surface and subsurface soil horizons which is very crucial for soil classification (Table 2.5a and 2.5b). This indicates the surface soils are more fertile than the sub-surface soil horizons and have to be maintained for sustainable land productivity.

Particularly, Nitisols (pedons 1, 2, and 3) and Alisols (pedons 4, 7, 8, and 9) are low in their percent base saturation due to the leaching loss of the bases. But Luvisols and Andosols were moderate in PBS while Cambisols (BC horizon of Pedon 6) was high in PBS. This was most probably because the BC sub-horizon of of Pedon 6 (Cambisols) was in the initial stage of soil development and the bases were not leached out yet compared to the well-developed soil pedons. Hazelton and Murphy (2016) described PBS rating as PBS of 0-20 = very low, 20-40 = low, 40-60 = moderate, 60-80 = high, and > 80 = very high. The variation observed in PBS indicates the degree of leaching which was used as a diagnostic character for classifying soils (Meena et al., 2014). Furthermore, the low PBS of the soils (Alisols) under this study indicates the leaching loss of bases due to the high rainfall in the Southwestern part of Ethiopia.

#### *2.4.3.4 The Ca/Mg ratio*

Hazelton and Murphy (2016), ratted the Ca: Mg ratio of 1-4:1 as low, and 4 - 6:1 as the optimum value. According to this rating, the Ca: Mg ratio 2.3:1- 5.2:1 for surface soil fell between the low and optimum ratio of Ca: Mg which is optimum for most crop production. The Ca: Mg ratio below 4:1 resulted in the unavailability of Ca Hazelton and Murphy, (2016); hence, a low ratio indicates the probable limitation of Ca uptake due to excess quantity of Mg or leaching of $Ca^{2+}$ by the high amount of rainfall. The variation in the Ca: Mg ratio for the soils suggests Andosols are at the initial weathering stage and the ratio of the cation is optimum for crop production while, Alisols are at the advanced stage of weathering (Appendix Table C) and most probably, Ca is leached out and replaced by oxides of aluminum and/ iron. The Ca: Mg ratio trend in this study is comparable to a study report by Yacob et al., (2014) for soils along the landscapes at Abobo Southwestern lowlands of Ethiopia.

#### *2.4.3.5 Available Micronutrients (Fe, Mn, Zn, Cu, and B)*

The distribution of Cu was consistently decreasing across the soil depth, which might be attributed to the strong association of Cu with soil organic matter. The B content of surface and subsurface horizons were in the range of very low to low (Benton, 2003). The application of external B inputs is highly important for optimum crop production. In general, the concentration of soil micronutrients was decreased trained across the soil depth *i.e.* it follows a similar trend with the soil organic matter content. This suggests that the soil's micronutrient content is closely associated with the quantity of organic matter in the soil. The finding is in harmony with the work of Yitbarek et al., (2016) who indicated the effect of organic matter on the available soil micronutrients.

## 2.5 Soil Classification Based on WRB, (2015) Legend

Pedon 1 was described at the upper slope and it was deep, clay in texture and strongly developed angular blocky structure, > 30% clay, silt/clay ratio of <0.4, CEC of <36 $\text{cmol}_{(+)}\text{kg}^{-1}$, medium in OC but low in PBS. These attributes of the Pedon qualify the diagnostic criteria for the Nitic subsurface horizon. Also, the Pedon has a base saturation of less than 50% between 20 and 50 cm of the soil surface, which qualifies for the hyperdystric principal qualifier. The presence of more than 1% OC to a depth of 50 cm from the mineral soil surface indicates the soil has a humic-supplementary qualifier. Accordingly, the soil is classified as Hyperdystric Nitisols (Humic) (IUSS Working Group WRB, 2015).

Pedon 2 and 3 were described at the middle slope position and deep, clay in texture and strongly developed angular blocky structure, > 30% clay, silt/clay ratio of <0.4, CEC of <36 $\text{cmol}_{(+)}\text{kg}^{-1}$, moderate in OC but low in PBS. These attributes of the Pedon qualify the diagnostic criteria for the Nitic subsurface horizon. Also, the Pedon has a base saturation of less than 50% between 20 and 50 cm of the soil surface, and >0.6% OC content with a layer of >20 cm thick which qualifies for the Umbric principal qualifier. Based on the diagnostic horizon and the qualifiers identified, the soil is classified as Umbric Nitisols (IUSS Working Group WRB, 2015).

Pedon 4 was described at the cultivated land of the middle slope positions. There was lower clay content in the topsoil than in the subsoil. An illuvial accumulation of clay formed an argic subsoil horizon. The soils had high activity clays (CEC >24 $cmol_{(+)}kg^{-1}$ soil) throughout the argic horizon and low base saturation in the 50–100 cm depth satisfies the definition of Alisols as a reference soil group. Within 25 and 150 cm of the soil surface, the soils have a layer 30 cm thick, that has, in 90% of its exposed area, a Munsell color hue redder than 5YR moist, a value of <4 (moist) prefixed as Rhodic. However, the presence of a base saturation of <50%; between 20 to 50 cm from the surface makes the use of a Hyperdystric supplementary qualifier to classify the soil as Rhodic Alisols (Hyperdystric).

Pedon 5 was described at the cultivated land at the upper slope positions. There was higher clay content in the subsoil than in the topsoil. An illuvial accumulation of clay formed an argic subsoil horizon (Bt1). Soils with high activity clays (CEC >24 $cmol_{(+)}kg^{-1}$ soil) throughout the argic horizon and high base saturation in the 50–100 cm depth satisfy the definition of Luvisols as a reference soil group. Within 25 and 150 cm of the soil surface, the soils have a layer 30 cm thick in 90% of its exposed area, a Munsell color hue redder than 5YR moist, and a value of <4 moist, prefixed as Rhodic. However, the presence of a base saturation of 50%; between 20 to 50 cm from the surface makes the use of a Hypereutric supplementary qualifier to classify the soil as Rhodic Luvisols (Hypereutric).

Pedon 6 was described at the upper slope position of the cultivated land. Soils in this Pedon have a strong medium to coarse sub-angular blocky structure, sandy clay in texture, silt/clay ratio of >0.4, evidence of pedogenic alteration, and absence of illuviated clay that satisfies the definition of Cambisols as a reference soil group, and the Cambic horizon (B) has higher clay content and OM than the underlying horizon (BC), a Munsell color hue 2.5, Chroma of >1, clay content of >4%. Since continuous rock starts < 100 cm from the soil surface, Leptic is prefixed; whereas the presence of more than 1% OC to a depth of 50 cm from the mineral soil surface indicates the soil has a humic supplementary qualifier. Based on the diagnostic horizon and the qualifiers identified, the soil is classified as Endoleptic Cambisols (Humic) (IUSS Working Group WRB, 2015).

Pedons 7 described at lower slope position of the cultivated land as characterized by subsurface horizons with higher clay content than the overlying horizon. An illuvial accumulation of clay resulted in the development of an *argic* subsurface horizon in this Pedon. The *argic* subsurface horizons in Pedons 7 are characterized by having a CEC of $\geq 24$ $\text{cmol}_{(+)}\text{kg}^{-1}$ clay throughout or to a depth of 50 cm of its upper limits and having a base saturation calculated on the sum of exchangeable bases plus exchangeable Al of < 50% in the major part between 50 and 100 cm from the mineral soil. Hence, these soils meet the definition of Alisols as a reference soil group. The soils have between 25 and 150 cm of the soil surface a layer, ≥ 30 cm thick, that has, in ≥ 90% of its exposed area, a Munsell color hue redder than 7.5YR and a chroma of > 4 (2.5YR4/6). These characteristics entirely defined the soil with the principal qualifiers and thus *Chromic* was prefixed. The presence of a base saturation of < 50% between 20 to 100 cm from the surface makes the use of a *Hyperdystric* supplementary qualifier and the presence of more than 1% OC to a depth of 50 cm from the mineral soil surface, *humic* is also suffixed to classify the soil as Chromic Alisols (Hyperdystric, Humic).

Pedons 8 described at the middle slope position of the cultivated field were characterized by subsurface horizons with higher clay content than the overlying horizon. The textural differentiation is caused by an illuvial accumulation of clay. This characteristic indicates the development of an *argic* subsurface horizon in these Pedons. The *argic* subsurface horizons in Pedon 8 are characterized by having a CEC of $\geq 24$ $\text{cmol}_{(+)}$ $\text{kg}^{-1}$ clay throughout the soil depth and having a base saturation, calculated on the sum of exchangeable bases plus exchangeable Al of < 50% in the major part between 50 and 100 cm from the mineral soil. Hence, these soils meet the definition of Alisols as a reference soil group. The soils have between 25 and 150 cm of the soil surface a layer, ≥ 30 cm thick, that has, in ≥ 90% of its exposed area, a Munsell color hue redder than 5YR and a value of < 4 (2.5YR3/4). These characteristics entirely defined the soil with the principal qualifiers and thus *Rhodic* was prefixed. The presence of a base saturation of < 50% between 20 to 100 cm from the surface soil makes the use of a *Hyperdystric* supplementary qualifier. *Hyperdystric* is suffixed and the soil is named Rhodic Alisols (Hyperdystric).

Pedons 9 described at the middle slope position of the cultivated field were characterized by subsurface horizons with higher clay content than the overlying horizon. The textural differentiation is caused by an illuvial accumulation of clay. This characteristic indicates the development of an *argic* subsurface horizon in the Pedon. The *argic* subsurface horizons in Pedon 9 are characterized by having a CEC of ≥ 24 $\text{cmol}_{(+)}$ $\text{kg}^{-1}$ clay throughout the soil depth and having a base saturation, calculated on the sum of exchangeable bases plus exchangeable Al of < 50% in the major part between 50 and 100 cm from the mineral soil. Hence, these soils meet the definition of Alisols as a reference soil group. The soils have between 25 and 150 cm of the soil surface a layer ≥ 30 cm thick, that has, in ≥ 90% of its exposed area, a Munsell color hue redder than 7.5YR and a chroma of > 4 (2.5YR4/6). These characteristics entirely defined the soil with the principal qualifiers and thus *chromic* was prefixed. The presence of a base saturation of < 50% between 20 to 100 cm from the surface soil makes the use of a *Hyperdystric* supplementary qualifier. Hence, the final soil name is Chromic Alisols (Hyperdystric).

Pedon 10 opened at the middle slope position of cultivated land. The surface layer was characterized by black (5YR2.5/1) moist; clay loam; with a weak medium granular structure; The soil has a dark-colored surface horizon with a high base saturation (by 1 *M* NH4OAc, pH 7) of >50% on a weighted average, with the thickness of 20 cm thus qualifying as Mollic epipedon. The soils below the Mollic horizon had a high amount of OM (5.74%), dark color, Munsell colors value, and chroma < 3 (value of 2.5 and chroma of 1) moist, soft, and light microstructure, low bulk density (0.93 g $\text{cm}^{-3}$), clay in texture which fulfill all the requirements of andic properties. The soils can satisfy the definition of Andosols as a reference soil group. The layer with an andic property had a pH ($H_2O$)

≥ 5 (6.75) indicating the silandic principal qualifiers. Additionally, the Pedon had a texture class of clay, in a layer ≥ 30 cm thick, within ≤ 100 cm of the mineral soil surface which satisfies the clayic supplementary qualifier. Therefore, the Pedon can be classified as Mollic, Silandic Andosols (Clayic).

Pedon 11 opened at the upper slope position had a moderate medium granular to angular blocky structure; friable (moist) and slightly hard (dry) consistency, a moderate amount of OM (2.22%), dark color, Munsell colors value, and chroma < 3 (value of 2.5 and chroma of 1) moist, soft and light microstructure, low bulk density (0.95 g $cm^{-3}$), clay in texture and the Bt1 layer can fulfill all the requirements of andic properties. The soils are classified as Andosols in the reference soil group. The layer with andic properties had a thickness of 40 cm, within ≤ 100 cm of the soil surface, and pH ($H_2O$) ≥ 5 indicating the silandic Principal qualifiers. Also, the soil has a low base saturation (by 1 *M* NH4OAc, pH 7) < 50% (43%) on a weighted average, with a thickness of 40 cm thus qualifying Dystric as a principal qualifier. Additionally, the Pedon had a textural class of clay, in a layer ≥ 30 cm thick, within ≤ 100 cm of the mineral soil surface which satisfies the clayic supplementary qualifier. Therefore, the Pedon can be classified as Dystric, Silandic Andosols (Clayic)

Pedon 12 opened at the upper slope position had a strong medium angular blocky structure; friable (moist) and slightly hard (dry) consistency, high amount of OM (3.6%), dark color, Munsell colors value, and chroma < 3 (value of 2.5 and chroma of 1) moist, soft and light microstructure, low bulk density, clay in texture which fulfill all the requirements of andic properties. The observed properties could qualify Andosols as a reference soil group. The layer with andic properties had a thickness of 42 cm, within ≤ 100 cm of the soil surface and starting ≤ 25 cm from the soil surface. It has a high base saturation (by 1 *M* NH4OAc, pH 7) of 50% on a weighted average, thus qualifying Eutric as the principal qualifier. The pH ($H_2O$) of the layers ≥ 5 (6.67) indicating the silandic principal qualifiers. The soils also have a clay texture, in a layer ≥ 30 cm thick, within ≤ 100 cm of the mineral soil surface satisfying the clayic supplementary qualifier. Therefore, the Pedon can be classified as Eutric, Silandic Andosols (Clayic)

## 2.6 Land Capability Classification

Land Capability Classification (LCC) is a system for classifying soils according to their limitation in use and productive capability (in agriculture) and other uses. The principle of LCC suggests that every plot of land must be used based on its capacity and limitations. The land characterization was carried out based on the USDA system of land capability classification (LCC) (Table 7) which applies certain land features such as slope, soil type, soil depth, and erosion conditions.

The lands on which the Pedons opened were suited for crop production with some limitations of moderate adverse effects of past erosion (e), soil fertility problems and shallow soil depth (s), and slope (L). Accordingly, Pedons 1, 3, 5, 7, 8, 9, 10, and 11 were grouped under LCC IIIes, Pedons 2 and 4 were categorized under IIs, and Pedon 6 was rated as LCC IVes, while Pedon 12 was categorized under LCC IIe (Table 2.8). The land characteristics of the studied Pedons 1-12 are displayed in Table 2.9. The major limitations for Pedon 1 were severe sheet erosion, low soil pH, low present base saturation, and moderate soil chemical fertility. Pedon 2, the land was affected by moderate rill erosion and partly good in chemical fertility. Pedon 3 was affected by moderate rill erosion and slow runoff and the land was moderate in chemical fertility. Pedon 4 was strongly acidic in reaction and also low (29 %) in percent base saturation. Pedon 5 exhibits severe limitations such as severe sheet and slight gully erosions, 25% stone coverage, and moderate (52%) percent base saturation (PBS). The land has moderate chemical fertility. Pedon 6 has limitations due to severe rill and slight gully erosion, moderately steep slope (19%), shallow rooting depth (55cm), and 40% stony coverage. The land was affected by rapid surface runoff, and minimum AWC storage compared to other pedons.

Pedon 7 had limitations such as severe past erosion, strongly acidic soil reaction, low present base saturation (33%), and moderate soil chemical fertility. Pedon 8, the land was sloppy and affected by moderate rill erosion, clay in texture, moderately acidic in reaction, and low in PBS. Pedon 9 was strongly slopy land, affected by severe rill erosion, strongly acidic in reaction, low in PBS, and partly good in chemical fertility. Pedon 10 was strongly slopy land, severe sheet erosion, slightly acidic in reaction, and also moderate (54%) in percent base saturation and good in chemical fertility. Pedon 11 exhibits limitations such as slopy lands, clay in texture, severe sheet erosions, moderate (48%) PBS, and partly good in chemical fertility. Pedon 12 has limitations such as slopy land, moderate sheet erosion, and good chemical fertility.

Table 2.7 Land capability parameters and thresholds (USDA, 2007)

| Parameters | Land capability class (LCC) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | I | II | III | IV | V | VI | VII | VIII |
| Slope (L) % | 0 to 2 | 2 to 8 | 8 to 15 | 15 to 30 | 0 to 30 | 30 to 50 | > 60 | 0 to 50 |
| Erosion (e) | No sign of a slightly | Moderate | Severe | Very severe | None or slight | Not class determining | | |
| Stoniness (% area coverage) | 0-40 | >40 | | | | >40 | | |
| Soil depth (cm) | >100 deep and very deep | >100 deep and very deep | 50-100 Moderately dep | 25-49 Shallow | 25-49 Shallow | 25-49 shallow | 10-24 Very shallow | < 10 extre. Shallow |
| Soil drainage | Never saturated | Never saturated | Rarely saturated | Saturated for a short period | Saturated for a long period | | | |
| Soil texture (t) | L, LS, SL | Si, SCL SiCL, SiL CL | SiC, SC | S, C | | Any | | |
| AWC at rooting depth (mm m$^{-1}$) | ≥ 100 from moderate to high | ≥ 100 from moderate to high | 51 – 99 Low | ≤ 50 very low | -- | -- | -- | -- |
| pH | 5.5 - 7.9 | 4.5–7.5 or 7.9-8.4 | < 4.5 or > 8.4 | | | < 4.5 or > 8.4 | | |
| OC (%) | > 1 | 0.8 -1 | 0.6 - 0.8 | 0.4 – 0.6 | | 0.2–0.4 | -- | -- |
| CEC (cmol$_{(+)}$ kg$^{-1}$ soil) | > 10 Good | 5- 10 partly good | < 5 Moderate | Any Low | Any From good to low | Any From good to low | Any Very low | Any |
| Base saturation (%) | > 50 Good | 35- 50 partly good | < 35 Moderate | Any Low | Any From good to low | Any From good to low | Any Very low | Any |

L = loam; SL = sandy loam; LS = loamy sand; Si = silt; SCL = sandy clay loam; SiL = silty loam; CL = clay loam; SiC = silty clay; SC = sandy clay; S = sand; C = clay.

Table 2.8. Land capability indices of the study sites

| Pedon (P) | Land capability Classes |
|---|---|
| P1 | IIIes |
| P2 | IIs |
| P3 | IIIes |
| P4 | IIs |
| P5 | IIIes |
| P6 | Ives |
| P7 | IIIes |
| P8 | IIIes |
| P9 | IIIes |
| P10 | IIIes |
| P11 | IIIes |
| P12 | IIe |

e = erosion is the dominant problem; s = soil limitations within the rooting zone.

Table 2.9: Land characteristics of the Pedons studied at Bako Tibe and Omo nada districts

| Pedons | Slope (%) | Soil depth (cm) | AWC at rooting depth (mm) | Texture | Stoniness (%) | Past erosion | Dra. | pH 1:2.5 (soil: $H_2O$) | OC % | CEC (cmol$_{(+)}$ kg$^{-1}$ soil) | BS (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| P 1 | 8 | > 200 | 110 | C | None | Mo | WD | 5.49 | 2.28 | 31.92 | 29 |
| P 2 | 6 | 190 | 160 | C | None | Mo | WD | 5.89 | 2.37 | 33.60 | 60 |
| P 3 | 9 | > 200 | 140 | C | None | Mo | WD | 5.76 | 1.96 | 32.56 | 64 |
| P 4 | 3 | > 200 | 110 | C | None | Sli | WD | 5.46 | 2.56 | 34.80 | 29 |
| P 5 | 10 | 102 | 110 | C | 25 | Sev | WD | 5.80 | 2.15 | 48.79 | 52 |
| P 6 | 19 | 55 | 100 | SC | 40 | Sev RE,<br>& Sli GE | WD | 5.94 | 1.93 | 41.09 | 63 |
| P 7 | 13 | > 200 | 120 | C | None | SevSE | WD | 5.23 | 3.03 | 22.89 | 33 |
| P 8 | 10 | > 200 | 140 | C | None | SevSE | WD | 5.84 | 3.38 | 27.9 | 47 |
| P 9 | 15 | > 200 | 140 | C | None | SevSE | WD | 5.35 | 3.10 | 24.28 | 38 |
| P 10 | 13 | > 200 | 120 | C | None | SevSE<br>Mo Gu | WD | 6.20 | 3.59 | 37.84 | 54 |
| P 11 | 10 | > 200 | 130 | C | None | SevSE<br>Mo Gu | WD | 6.26 | 3.63 | 33.97 | 48 |
| P 12 | 7 | > 200 | 150 | C | None | Mo SE | WD | 6.44 | 3.74 | 36.63 | 54 |

Note: C = clay, Mo = moderate; sev = severe; SevSE = Sever sheet erosion; Mo Gu = moderate gully erosion; Sli = slight erosion; WD = well drained

## 2.7 Possible Land Management Options

After the land was grouped under different capability classes and sub-classes (Table 2.8), some appropriate management practices were suggested based on observation, experience, and information from previous researchers and the guidelines of Soil and Water Conservation in Ethiopia, (M. Osman & Sauerborn, 2016). Based on USDA land capability classification, Pedons 2, 4, and 12 (in the same land capability units, LCC IIs, IIs, and IIe respectively) were good lands with moderate limitations and required similar management practices such as counter-cultivation and growing of cover crops and the integrated use of organic and inorganic fertilizers. Lime application is necessary particularly for Pedon s 2 and 4 to solve the soil acidity problem. Pedons 1, 3, 5, 6, 7, 8, 9, 10, and 11 were in the same land capability classes (LCC IIIes), were moderately good lands with severe limitations that restrict the choice of crops and need some combination of agronomic (the use of cover crops) and physical conservation measures such as graded bands combined with the integrated use of organic and inorganic fertilizers and liming as the management options to sustain the productivity of the land. Particularely, Pedon 6 (Cambisols) had a shallow depth (0.55m) and stored only a small quantity of moisture and plant nutrients. Thus, the land had limitations for crop production and was more suitable for grazing land or pasture production. If the land will be used for the cultivation of field crops, integrated use of organic and inorganic fertilizers, and growing of cover crops and graded bands can be used together.

## 2.8 SUMMARY AND CONCLUSIONS

Detailed information on soil properties used for soil characterization and grouping is essential to designing effective land use planning, soil fertility management, and boosting agricultural crop production. Soil classification is useful to identify the most suitable use of soil, estimate production, facilitate technology transfer, and knowledge exchange between soil scientists, policymakers, planners, researchers, and agricultural extension consultants. The morphological, physical, and chemical characteristics of the soils showed variation among the soil types and soil depth. The soils represented by Pedon 6 in the upper slop position were relatively shallow whereas the Pedons in the middle and lower slope positions were very deep. The clay content in the B (subsurface) horizons of all Pedons (except Pedon 6) was higher as compared to the surface horizons. Soil formation in most of the Pedons is characterized by clay illuviation from the surface to the subsurface soil horizons.

Soils differed from strongly acidic (Alisols) to slightly acidic (Andosols) in reaction. The exchangeable $Al^{3+}$ values of the surface horizons of (Pedons 4, 7, 8, and 9) were within the range that can adversely influence crop growth. The soils were medium in total N content (0.15-0.35%), medium (1.89%) to very high (5.16%) in OC content, deficient in available P (4-7.85 mg P $kg^{-1}$), medium to very high in CEC and exchangeable Ca, medium to high exchangeable Mg, high in exchangeable K and low in exchangeable Na. The PBS calculated from these cations was low to moderate (30-63%) for Nitisols, Luvisols, and andosols and low (23-33%) for Alisols.

The available micronutrients (Fe, Mn, and Zn) were in the sufficient range the level of available Cu was in the low to medium range and the available B was in the very low to low range. As the soil’s lab result of the study area revealed, the soil's physical characteristics did not adversely affect crop production. Most of the soil's chemical characteristics were in the optimum range but the soil reaction (pH), available P, available Cu, and B content were below the optimum range and affect the crop production. Therefore, the optimum quantity of deficient elements (P, Cu, and B) must be added to the soils by integrating their organic and inorganic fertilizer sources to maintain soil fertility and land productivity.

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# CHAPTER 3: EVALUATION OF PHOSPHATE SORPTION CAPACITY AND EXTERNAL PHOSPHORUS REQUIREMENT OF SOME AGRICULTURAL SOILS OF THE SOUTHWESTERN ETHIOPIAN HIGHLANDS

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## ABSTRACT

*One of the most common soil fertility management problems for crop production on acidic soils of the Ethiopian highlands is phosphorus fixation. The research was executed to assess the phosphorus sorption capacity and to determine the external P requirement of different acidic soils in the Bako Tibe and Omo Nada districts of Oromia, Ethiopia. Phosphorus sorption capacity (Kf) and its relation with selected soil characteristics were assessed for some major agricultural acidic soils in the study area to answer the questions, 'What is the phosphorus sorption capacity and external P requirement of Nitisols, Luvisols, Alisols, and Andosols in Ethiopia?' Twelve surface soil samples (at a depth of 0-30 cm) were gathered and the phosphorus sorption capacity was estimated. Phosphorus-sorption data were obtained by equilibrating 1 g of the 12 soil samples with 25 ml of* $KH_2PO_4$ *in 0.01 M* $CaCl_2$*, having 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300, and 330 mg P* $L^{-1}$ *for 24 hours. The data were adjusted to the Freundlich adsorption model and the relationship among phosphorus sorption and soil characteristics was established by correlation analysis. Clay content and exchangeable acidity, organic matter,* $Al_2O_3$*, and* $Fe_2O_3$ *oxides have affected phosphorus sorption at a significance level of* $(P < 0.05)$*. Alisols had the highest Kf value (413 mg* $kg^{-1}$*) but Nitisols had the lowest Kf (280 mg* $kg^{-1}$*). The external phosphorus fertilizer requirement of the soils was in the order of 25, 30, 32, and 26 mg P* $kg^{-1}$ *for Nitisols, Luvisols, Alisols, and Andosols sequentially. The Kf varies among different soil types of the study area. The magnitude of the soil's Kf was affected by the pH of the soil, soil OM content, and oxides of Fe and Al. Therefore, knowledge of the soils' P retention capacity is highly crucial to determining the correct rate of P fertilizer for crop production.*

**Keywords:** *External P requirement; Freundlich equation;* phosphorus*; phosphorus sorption capacity*

## 3.1. INTRODUCTION

Ethiopia has a diversity of topography, climate, vegetation, and parent materials, as a soil-forming factor, leading to the formation of various soil types (Elias & Status, 2019). Nitisols and Luvisols are among the most extensive soil types covering about 31 and 11% of the arable landscapes of the Ethiopian highlands, whereas the highly productive Andosols are less extensively distributed (<1%) (Eyasu E. et al., 2019). Alisols are particularly important in high rainfall upland farming systems of the Southwestern highlands of Ethiopia.

Regardless of their area extent and agricultural importance, the phosphorus limitation of these soils has been constraining agricultural productivity in the Ethiopian highlands. Preliminary reports about the nutrient content of the Ethiopian soils suggest that 99% of the Ethiopian highland soils are phosphorus-deficient by taking 30 ppm of available phosphorus as a critical level (Karltun et al., 2013). Studies on the nutrient status of the Ethiopian highland soils suggest that phosphorus deficiency is a major problem that negatively affects crop production (Eyasu E. et al., 2019; Melese et al., 2015).

A widespread problem of limited P-availability in soils might be due to severe P-fixation. Phosphate fixation is a process by which phosphate ions are retained on the active sites of the soil colloidal surfaces thus rendering it unavailable for plant uptake (Tamungang et al., 2014). Phosphorus fixation is a common problem in tropical rainfed upland farming systems (Hanyabui et al., 2020). The high P-retention by adsorption or precipitation reactions in soils results in low P-fertilizer use efficiency (15–30%) (Maluf et al., 2018). The estimated 80% of the applied phosphate is not available for crop uptake as the result of high phosphorus fixation in acid tropical soils (Kisinyo et al., 2013).

Most inherent characteristics of the soil that affect the degree of P-fixation include soil clay content, soil reaction (pH), OM content, hydrated oxides of Fe and Al, and the concentration of exchangeable aluminum and hydrogen (exch. $Al^{3+}$ and $H^{+}$) that varies with soil type (B. Wang et al., 2017). Likewise, Jiang et al., (2015) stated that the oxides of Fe and Al are the major adsorbents for phosphate ions in acidic tropical soils. When the clay fraction is composed of 1:1 minerals, iron, aluminum oxides, and hydroxides, most of the P is adsorbed on the soil colloidal surfaces. The phosphorus sorption capacity (Kf) of soil refers to the potential of the soil to bind phosphorus applied to it and is a principal factor regulating P concentration in the soil solution and available phosphorus (Gonzalez-Rodriguez & Fernandez-Marcos, 2018b). The external P requirement (EPR), also described as the standard P requirement (SPR), is the amount of P that must be applied to the soil to sustain a P level in the soil at 0.2 mg P $L^{-1}$ that meets the requirements in P for different crops (Wolde & Halie, 2015).

Determination of the Kf and $EPR_f$ of various types of soils supports sustainable agriculture through site-specific P fertilizer recommendations that avoid overdose P application that leads to adverse impacts on the economy and the environment. Underdoes application of P negatively impacts the growth potential of the crops and affects the living standard of the society through food self-insufficiency. Similarly, Thuy et al., (2020) stated that optimizing P fertilizer input could maximize the P fertilizers use efficiency that will decrease fertilizer costs, improve income, and lower the negative impacts on the soil for sustainable agriculture.

Different mathematical models and sorption isotherms have been formulated to explore the soil P sorption capacity (Kf); phosphorus sorption energy (1/n), the buffering capacity of soil *versus* P concentration gradient in solution, and the state of equilibrium between P in solution and the solid phases and their relation (Mwende Muindi, 2015). Freundlich model is the most commonly applicable model to determine phosphorus sorption characteristics of soils and estimate $EPR_f$ (Afsar et al., 2012). This model can differentiate soils according to their capacity to absorb P from soil solutions. Although studies have indicated the widespread phosphorus sorption problem in Ethiopian soils (Wolde & Halie, 2015). Information on phosphorus sorption disaggregated by soil type is rather limited in the Southwestern highlands of Ethiopia.

In recent years, Ethiopia has been in the process of transforming its soil fertility sector by moving away from blanket fertilizer recommendations to soil-specific management of fertilizer (Eyasu E et al., 2019). To this effect, to alleviate the phosphorus sorption problem through soil-specific management (e.g., liming and targeted P-fertilization), it is necessary to estimate the degree of P-fixation by dominant soil types. Hence, this research intended to evaluate the phosphorus sorption capacity and external P requirement of some acidic soils (Nitisols, Luvisols, Alisols, and Andosols) in the Southwestern highlands of Ethiopia.

## 3.2. MATERIAL AND METHODS

### *3.2.1. Description of Study Sites*

The experiment was carried out on four dominant agricultural soils based on (IUSS Working Group WRB, 2015) such as Nitisols, Luvisols, Alisols, and Andosols in the intervention sites of the project; Capacity building for scaling up of evidence-based best practices in agricultural production in Ethiopia (CASCAPE) intervention woredas of Oromiya region, (Fig.1.1 under section 1.4.1 above).

The district is designated by flat plains, high mountains, and hilly topography, a geological feature of the area is characterized by tertiary sediments of the Cenozoic era on the plain and basalt and volcanic rocks in the High Mountain and hilly ridges. The rainfall data obtained from the nearest weather stations (Bako and Jimma Agricultural Research Centers) reveals that the rainy season covers April to November and maximum rain is received in June, July, and August. The long-term (2009- 2018) mean annual rainfall is 1267-1730 mm. It has a warm humid climate with average air temperatures of 19 to 21 $^{0}$C and the altitudinal range of the sites is 1650 to 2800 masl.

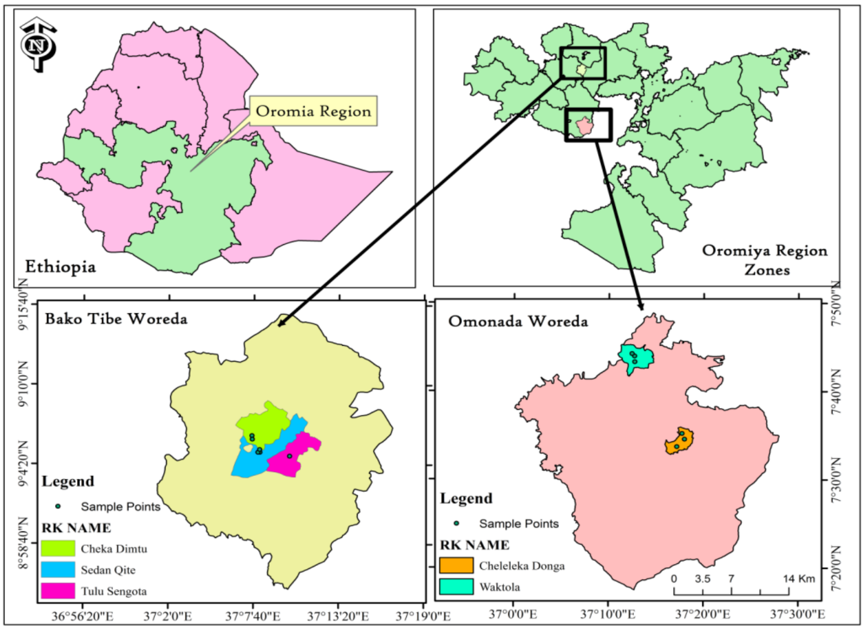

Figure 3.1. Location map of the study area

Note: Rk= Rural Kebele (Peasent association)

### *3.2.2. Soil sampling and laboratory procedures*

About ten representative sub-samples were taken from 0-30 cm depth randomly in a zig-zag manner from different spots of the sampling unit and one composite sample was formed (1 kg each). The sub-samples were thoroughly mixed on a flat plastic sheet and 12 composite soil samples (3 samples from each type of soil) were collected in clean new plastic bags and transported to the laboratory. In the laboratory, the samples were dried in the air, crushed, sieved, and passed through a 2 mm mesh, to determine the soil's physicochemical properties and P sorption capacity.

The soil particle size distribution was determined by the hydrometer method (Beretta et al., 2014). Soil pH ($H_2O$) was measured by a pH meter as described by (FAO, 2021). OM (%) was determined by the wet digestion method (Walkley-Black, 2019). Exch. $Al^{3+}$ and H ($cmol_{(+)}kg^{-1}$) were described by leaching with KCl followed by titration (Lestari et al., 2016). The determination of $Fe_2O_3$ and $Al_2O_3$ was following the X-ray fluorescence (XRF) spectrometer (Towett et al., 2013).

A laboratory study was conducted to evaluate the P sorption characteristics of the soils following the Bache & Williams, (1971) procedure by using three replicates of 1.0 g, dry soil samples that were weighed into 50 ml centrifuge tubes and suspended in 25 ml of 0.01 M $CaCl_2$ as supporting electrolytes that have 0, 30, 60, 90, 120, 150, 180, 210, 240, 270, 300 and 330 mg P $L^{-1}$ as $KH_2PO_4$ with increasing rate of 30 mg P $L^{-1}$. Three drops of toluene were applied to all containers to stop the microbial action. The tubes were then closed and shaken on an end-to-end shaker for 24 hours at a temperature of 25 ± 1 °C at 150 oscillations per minute. After equilibrium, the soil suspensions were centrifuged at about 3000 rpm for 10 minutes and then filtered through Whatman No. 42 to obtain a clear solution (Azeez et al., 2020). The phosphorus in the supernatant was then analyzed following the Olsen procedure. The quantity of P absorbed was calculated as the difference between the amount of P added and that left in the solution by Equation 1.

$$\frac{(Co-Cf)\mathrm{V}}{Weight\ of soil\ (kg)} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Eq. 1)}$$

Where: Co = initial concentration of P (mg $L^{-1}$), Cf = final concentration of P (mg $L^{-1}$), and V = volume of solution (L). The soil P sorption data were adjusted to the linearized forms of the Freundlich equation:

$X = KC^{1/n}$…………… (Eq. 2)

The logarithm of Eq. (2), changes into log X = log kf + 1/n log C, and the linear equation form 2 has been formulated by plotting Log C against Log X, X (mg $kg^{-1}$) = the concentration of P retained per unit mass of soil, C (mg $L^{-1}$) = the equilibrium concentration of P, 1/n (L $kg^{-1}$) represents the slope (the sorption energy) and Log Kf (mg $kg^{-1}$) represents the sorption capacity (Dari et al., 2015). The external phosphorus requirement ($EPR_f$) is calculated based on Freundlich models by using the required P quantity (0.2 mg P $L^{-1}$) in the linear form of Freundlich equations (Getie et al., 2021). The P-buffering capacity (PBC) of soil is its capacity to resist change in the P concentration of the solution phase (Shirvani et al., 2013). It was computed from the Freundlich adsorption isotherms at 0.2 mg $L^{-1}$ of solution P as PBC (Eq. 3).

$PBC = Kf * n * C^{n-1}$….. (Eq. 3)

Whereas,

PBC (L $kg^{-1}$) = Phosphorus buffering Capacity, Kf (mg $kg^{-1}$) = P sorption capacity
1/n (kg $L^{-1}$) = sorption energy, C (mg $L^{-1}$) = the equilibrium concentration of P .
The citrate bicarbonate dithionite (CBD) procedure was used for the determination of total free iron oxides in soils (Fan et al., 2016).

### *3.2.3 Statistical Analysis*

The measured soil parameters were arranged in a Completely Randomized Design (CRD) with three replicates and subjected to analysis of variance (ANOVA) using the Statistical Analysis System (SAS) software version 9.4 (SAS Institute Inc., 2019). The Least Significance Difference test (LSD) at the 5% probability level was used for the mean comparison when the ANOVA showed significant differences. Also, a simple regression and correlation coefficient analysis was executed to assess the degrees and directions of the relationship between Kf and the various soil parameters.

## 3.3. RESULTS

### *3.3.1. Phosphorus Sorption Capacity of Soils*

Table 3.1 shows highly significant ($P < 0.01$) variation in phosphorus sorption capacity (Kf), level of phosphorus sorption energy (1/n) ($P < 0.05$), and phosphorus buffering capacity ($PBC_f$) ($P < 0.01$) among soil types but no significant difference in the external phosphorus requirement (Table 1). The sequence of soils based on their Kf was Alisols > Luvisols > Andosols > Nitisols. Alisols had the highest Kf (413 mg $kg^{-1}$) and 1/n (1.67 kg $L^{-1}$) but Nitisols had the lowest Kf (280 mg $kg^{-1}$) and 1/n (1.40 kg $L^{-1}$).

The linear form of the Freundlich equation formed by taking log C versus log X is displayed in Figure 3.2. It confirmed a satisfactory agreement with the Freundlich equation ($R^2$ = 0.96-0.98) for the studied soils. The P sorption isotherms were formed by plotting the amount of P adsorbed on the soils surface (Nitisols, Luvisols, Alisols, and Andosols) against the solution P concentration.

Table 3.1. phosphorus sorption capacity (Kf), Slope (1/n), $EPR_f$, and $PBC_f$ values after 24 hours of equilibration

| Soil Type (RSG) | Kf (mg $kg^{-1}$) | 1/n (L $kg^{-1}$) | $EPR_f$ (mg $kg^{-1}$) | $PBC_f$ (mg $kg^{-1}$) | $R^2$ |
|---|---|---|---|---|---|
| Nitisols | $280^b$ | $1.40^b$ | 25 | $316^b$ | $0.95^b$ |
| Luvisols | $336^{ab}$ | $1.48^{ab}$ | 30 | $395^{ab}$ | $0.97^a$ |
| Alisols | $413^a$ | $1.67^a$ | 32 | $471^a$ | $0.98^a$ |
| Andosols | $299^b$ | $1.43^b$ | 26 | $346^b$ | $0.96^{ab}$ |
| Mean | 332 | 1.49 | 28 | 382 | 0.97 |
| LSD% | 66.07 | 0.15 | 37.41 | 80.27 | 0.003 |
| SE | 32.79 | 0.08 | 5.0 | 37.76 | 0.007 |
| F | 9.70 | 7.46 | 1.52 | 9.70 | 7.59 |
| P | 0.01 | 0.02 | 0.30 | 0.01 | 0.018 |

Note: In the same column, means indicated by different letters are significantly varied at $p < 0.05$; Kf = P sorption capacity; 1/n= sorption energy; $EPR_f$ = Freundlich External P Requirement; $PBC_f$ = P buffering capacity; RSG = Reference soil group (FAO 2006).

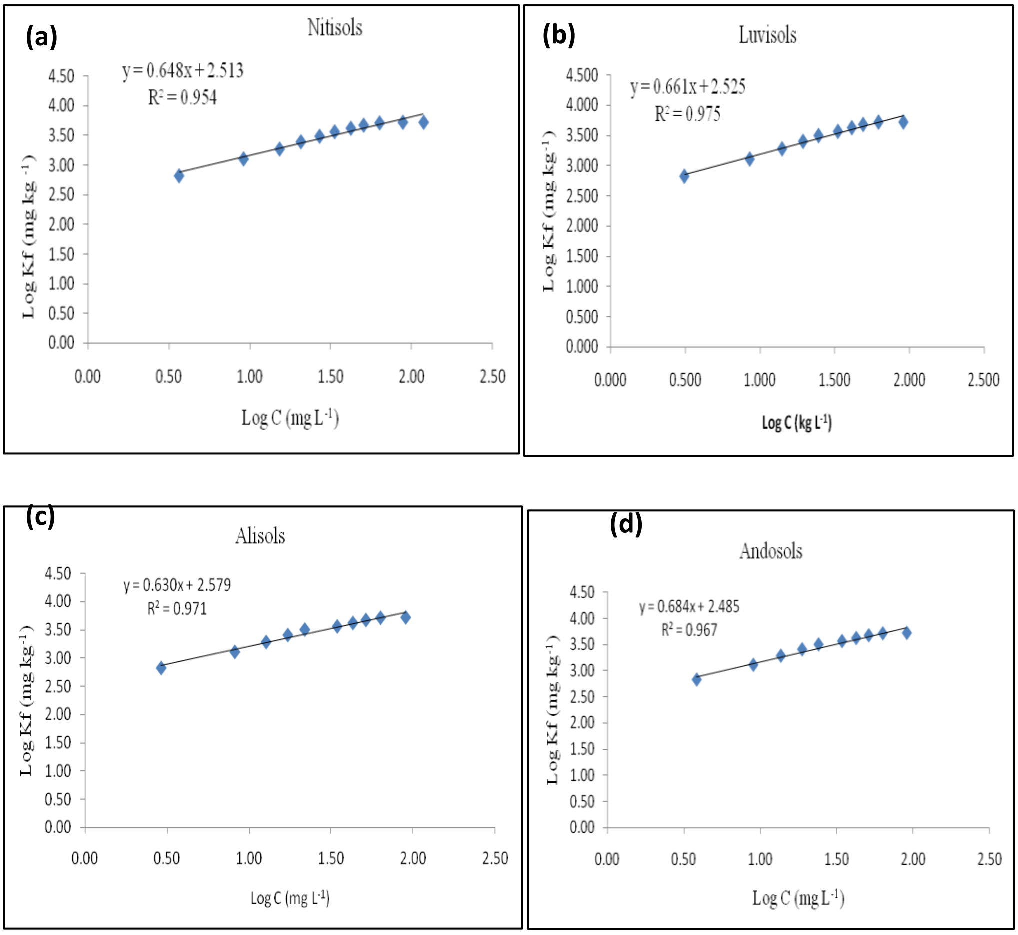

Figure 3.2. P sorption Isotherm for Nitisols (a), Luvisols (b), Alisols (c) and Andosols (d)

### *3.3.2 The Soil External Phosphorus Requirement (EPRf ) and Phosphorus Buffering Capacity (PBC)*

The actual quantities of P required by Nitisols, Luvisols, Alisols, and Andosols were 25, 30, 32, and 26 (mg kg$^{-1}$) respectively for optimum crop production in the study area (Table 1). The highest (32 mg kg$^{-1}$) and the least (25 mg kg$^{-1}$) values of $EPR_f$ were obtained for Alisols and Nitisols respectively. The buffering capacity of soils was computed from the Freundlich adsorption isotherms at 0.2 mg P L$^{-1}$ of solution in the 24 hours of equilibration were 316, 396, 471, and 346 for Nitisols, Luvisols, Alisols, and Andosols respectively (Table 3.1).

Table 3.2 shows there is variation in soil characteristics and Kf among the soils. Accordingly, the mean clay content was significantly varied ($p < 0.05$) among various soil types, and the highest value (54.67%) was observed under Alisols while the lowest value (36.0) was under Andosols. Even though statistically no significant difference in pH between the soils, Andosols had the highest (6.30) and Alisols had the lowest (4.80) pH. There was a strong and significant ($p < 0.001$) difference in mean OM content between the soils. The highest value (7.51%) and the lowest value (3.36%) of OM were observed under Andosols and Alisols respectively. Significant ($p < 0.05$) differences were observed in exchangeable aluminum (exch. $Al^{3+}$) and exchangeable acidity (exch. Ac) of the soils under this study. Alisols had the highest exch. $Al^{3+}$ (1.18 $cmol_{(+)}kg^{-1}$) and exch. Ac (1.67 $cmol_{(+)}kg^{-1}$) but Nitisols had the lowest (nill) exch. $Al^{3+}$ and exch. Ac (0.52 $cmol_{(+)}kg^{-1}$). The soils strongly and significantly ($p<0.001$) differ in both $Al_2O_3$ (%) and $Fe_2O_3$ (%) content. Nitisols had the highest mean $Al_2O_3$ (26.68%) and $Fe_2O_3$ (16%) while Andosols had the lowest mean $Al_2O_3$ (14.05%) and $Fe_2O_3$ (9.24%). A significant ($p < 0.05$) variation was observed among the soils in Kf. Accordingly, Alisols had the highest (413 mg $kg^{-1}$) and Nitisols had the lowest Kf (280 mg $kg^{-1}$) values.

The P sorption Isotherm for different soils is displayed in Figure 3.2., which indicates the progressive decrease in the slope of the line (adsorption energy) with increasing the fraction of the covered surface (increasing the quantity of P adsorbed). Therefore, the application of higher rates of chemical P-fertilizers saturates the soil’s adsorbing surfaces such as Fe and Al ions, and decreases the soil’s sorption capacity (Kf). Due to this, more P enters the soil solution and P becomes available for crop uptake. This finding is similar to the previous study (Muindi, 2015) which stated the adsorption of energy decreases when the amount of adsorption increases.

### *3.3.3. Correlation between Soil Properties and Phosphorus Sorption Capacity*

The relationship between the Kf and selected soil parameters is displayed in Table 3.3. Statistically, a positive and significant ($P < 0.05$) relationship existed between exch. $Al^{3+}$ and Kf. The Kf had a positive and non-significant ($P > 0.05$) relationship with clay content, exch. $H^+$, Exch Ac, and aluminum oxides ($Al_2O_3$) and iron oxides ($Fe_2O_3$). In addition, the Kf value had negative, non-significant ($P > 0.05$) elationships with the pH ($H_2O$) and OM content of the soil. The sorption energy (1/n) had a positive non-significant ($P > 0.05$) relation with clay content while it had strongly significant ($P < 0.001$) positive relation+nships with exch. $Al^{+3}$ and P sorption capacity (Kf) at a 5% significance level.

Table 3.2. Variability in soil properties and P-sorption capacity (Kf) for different soil types in Ethiopian highlands

| Soil type | Clay (%) | pH-$H_2O$ | OM (%) | Exch.$Al^{3+}$ (cmol $kg^{-}$) | Exch $H^{+}$ (cmol$kg^{-}$) | Exch Ac (cmol$kg^{-1}$) | $Al_2O_3$ (%) | $Fe_2O_3$ (%) | Kf (mg $kg^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|
| Nitisols | $51.7^{a}$ | 5.71 | $3.8^{b}$ | $0.0^{b}$ | 0.52 | $0.52^{ab}$ | $26.7^{a}$ | $16^{a}$ | $280^{b}$ |
| Luvisols | $48.7^{ab}$ | 5.73 | $3.83^{b}$ | $0.26^{ab}$ | 0.35 | $0.61^{ab}$ | $23.9^{ab}$ | $15.9^{a}$ | $336^{ab}$ |
| Alisols | $54.7^{a}$ | 4.8 | $3.36^{b}$ | $1.18^{a}$ | 0.49 | $1.67^{a}$ | $22.6^{b}$ | $13.3^{b}$ | $413^{a}$ |
| Andosols | $36^{b}$ | 6.3 | $7.51^{a}$ | $0.13^{b}$ | 0.11 | $0.24^{b}$ | $14.1^{c}$ | $9.24^{c}$ | $299^{b}$ |
| Mean | 47.8 | 5.63 | 4.62 | 0.39 | 0.37 | 0.76 | 21.8 | 13.6 | 332 |
| LSD% | 15.42 | 1.97 | 1.87 | 1.02 | 0.87 | 1.19 | 3.74 | 1.67 | 0.15 |
| SE | 5.45 | 0.69 | 0.66 | 0.36 | 0.30 | 0.42 | 1.30 | 0.59 | 32.79 |
| F-value | 6.79 | 2.34 | 25.52 | 6.50 | 1.09 | 6.63 | 50.8 | 86.6 | 9.70 |
| P-value | 0.02 | 0.17 | 0.008 | 0.02 | 0.42 | 0.02 | 0.001 | <0.00 | 0.01 |
| Sign. | 0.05 | Ns | 0.001 | 0.05 | Ns | 0.05 | 0.001 | 0.001 | 0.05 |

Note**:** In the same column, means indicated by different letters are significantly varied at $p < 0.05$, ns = non-significant ($P > 0.05$), OM = organic matter, Exch $Al^{3+}$ = Exchangeable aluminum, Exch $H^{+}$= Exchangeable hydrogen, Exch Ac = Exchangeable acidity, $Al_2O_3$ = aluminum oxide, $Fe_2O_3$ = iron oxide.

## 3.4. DISCUSSION

The variation in the Kf content of the soils could be attributed to the difference in the soil pH, exch. $Al^{3+}$, clay, and OM in the soils and the percentage of $Al_2O_3$ and $Fe_2O_3$ in the soil (Table 3.2). Clay minerals, Fe and Al oxides have more specific surface areas that give large numbers of adsorption sites for the phosphate ions. Very high clay content (54.7%), strongly acidic soil reaction (pH 4.8), high level of exchange. $Al^{3+}$ (1.18 mg $kg^{-1}$) in the soil solution and a moderate percentage of OM (3.36%) content in Alisols resulted in the highest Kf (413 mg $kg^{-1}$) and $EPR_f$ (32.33 mg $kg^{-1}$) while, moderately acidic soil reaction (pH 5.7), high OM content (3.8%) and nil exch. $Al^{3+}$ in Nitisols was resulted to the lowest Kf (280 mg $kg^{-1}$) and $EPR_f$ (25 mg $kg^{-1}$). Likewise, the Kf and $EPR_f$ of Luvisols and Andosols varied based on these soil properties. This finding is similar to the results of (B. Wang et al., 2017).

The Kf values of the soils of this study were the intermediate values (280 - 413 mg P $kg^{-1}$) detected by Melese et al., (2015) for the soils of the Farta district, in the Northwestern Highlands of Ethiopia which vary from 80 to 259 mg P $kg^{-1}$ and those Kf value stated by Wolde & Halie, (2015) in soils from Bule district, in the Southern Ethiopia, which varies from 479 to 487 mg P $kg^{-1}$. According to the rating established by Buresh et al., (2015) Nitisols, Luvisols, and Andosols were classified under moderate Phosphorus sorbing (280-336 mg P $kg^{-1}$) soils. Alisols with Kf values of 413 mg P $kg^{-1}$ were grouped under high P sorbing soils (Table 3.2).

The Soil External Phosphorus Requirement ($EPR_f$), Alisols with the highest PBC (471 mg P $kg^{-1}$) had the highest capacity to restore a unit change in soil solution P and Keep a productive solution P concentration and lower the amount of $EPR_f$. Because of this, the external phosphorus requirement did not significantly differ among the soil types. The determined $EPR_f$ in the soils is more than double the previously recommended amounts (20 kg P $ha^{-1}$) for Alisols and Andosols at Omo Nada, and 30 kg P $ha^{-1}$ for Nitisols and Luvisols at Bako Tibe districts. The result of this study revealed the need for twice phosphorus fertilizer application compared to the previously recommended phosphorus fertilizer of 20 kg P $ha^{-1}$ at Omo Nada and 30 kg P $ha^{-1}$ for maize production at Bako Districts of Oromiya region that supply only10-15 mg P $kg^{-1}$, which is half of the soils' $EPR_f$ of 25-32 mg P $kg^{-1}$. According to this finding, 50, 60, 64, and 52 kg P ha$^{-1}$ for Nitosols, Luvisols, Alisols, and Andosols respectively were recommended for the study areas. Similarly, the Ethio SIS team, Karltun et al., (2013) suggested an initial critical value of 30 mg P kg$^{-1}$ soil (60 kg P ha$^{-1}$) for soil fertility mapping and P fertilizer recommendations in Ethiopia was comparable to the finding of this study.

Correlation between Soil Properties and Phosphorus Sorption Capacity, The reason clay particles positively correlated with soils' sorption capacity (Kf) was due to, the fact that finer soil particles (clays) are more reactive and have larger surface area. Due to this, soils with higher clay friction has greater P-retention capacity compared to larger soil particles (Jiang et al., 2015). Weihrauch & Opp, (2018) also stated that most of the time clay minerals have a more net negative charge than chelating metal cations then sorb Phosphate. The equilibrium P conc. (C) was positively correlated with Kf for all soil types. The soil pH was negatively correlated with Kf. As the pH increased, Kf decreased due to the increase in electrostatic repulsion created by the increase in negative surface charges. The Kf had a negative relation with the soil OM. When the soil OM increased, the Kf decreased since organic acides (anions) are producd during the decomposition of OM and these organic acids blocks the P sorption sites. Similarly, Wolde & Halie, (2015) stated, presence of OM decreased Kf of the soils due to the organic anions occupying the adsorption sites.

Weihrauch & Opp, (2018) also noted, organic acids chelate Fe/Al/Ca/Mg on oxide surfaces and hinder P sorption. For this particular study, a significant ($P \leq 0.05$) positive relation between Kf and exch. $Al^{3+}$ revealed that $Al^{3+}$ was the main contributor to phosphate sorption in high P-fixing soils (Alisols). The current finding is in concord with the findings of Hoseini & Taleshmikaiel, (2013) described as insoluble Al phosphates are formed from the reaction of phosphate ions with $Al^{3+}$. A positive relationship between Kf and exch. $H^+$ indicates phosphate becomes less available at lower soil pH. Also, Kf had a positive relationship with $Al_2O_3$ and $Fe_2O_3$ as these oxides much contributed toward the increased Kf of the soils (Table 3). In addition, Al and Fe have a very high Kf in pure systems compared to their oxide forms since the oxides of Fe and Al are important cementing agents in soils which reduce the total surface area; therefore absorption sites (Reza, 2014).

Table 3.3. The correlation coefficient between soil properties and phosphorus sorption capacity (Kf)

| Selected Soil properties | Correlation coefficient (r) | p-value | Significance |
|---|---|---|---|
| Clay content vs Kf | 0.55 | 0.45 | Ns |
| Kf vs pH-$H_2O$ | -0.82 | 0.18 | Ns |
| Kf vs OM | -0.54 | 0.46 | Ns |
| Kf vs Exch. $Al^{3+}$ | 0.96* | 0.04 | * |
| Kf vs Exch. $H^+$ | 0.41 | 0.59 | Ns |
| Kf vs Exch. Ac | 0.73* | 0.27 | Ns |
| Kf vs $Al_2O_3$ | 0.17 | 0.83 | Ns |
| Kf vs $Fe_2O_3$ | 0.15 | 0.85 | Ns |
| 1/n vs Clay | 0.53 | 0.47 | Ns |
| 1/n vs Ph | -0.88* | 0.12 | Ns |
| 1/n vs OM | -0.45 | 0.55 | Ns |
| 1/n vs $Al^{3+}$ | 1.00*** | 0.00001 | *** |
| 1/n vs Kf | 0.95* | 0.05 | * |

**Note:** *** = very strongly significant ($P \leq 0.001$); * = Significant at ($P \leq 0.05$); ns = non-significant ($P > 0.05$); OM = Organic matter; Exch $Al^{3+}$ = Exchangeable aluminium; Exch H+ = Exchangeable hydrogen; Exch Ac = Exchangeable acidity; $Al_2O_3$ = aluminium oxide; $Fe_2O_3$ = iron oxide; 1/n = sorption energy.

## 3.5. CONCLUSION AND RECOMMENDATION

There were clear variations in P sorption capacity and, therefore, External Phosphorus Requirement between soils of the study areas. The highest Kf (413 mg $kg^{-1}$) was observed for Alisols and the lowest Kf (280 mg $kg^{-1}$) was for Nitisols, Even though, statistically no significant difference in the external phosphorus requirement. The actual quantity of P required by Nitisols, Luvisols, Alisols, and Andosols were 25, 30, 32, and 26 (mg $kg^{-1}$) respectively.

The previously blanket P fertilizer recommendation in the country without considering differences among soil types is inadequate for optimal crop production. From the current study, 50 kg P $ha^{-1}$, 60 kg P $ha^{-1}$, 56 kg P $ha^{-1}$ and 52 kg P $ha^{-1}$ can be recommended for optimum crop production of Nitisols, Luvisols, Alisols, and Andosols respectively.

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# CHAPTER 4: MAIZE (ZEA MAYS L.) YIELD RESPONSE TO LIME AND PHOSPHORUS RATES IN BAKO TIBE AND OMO NADA DISTRICTS OF OROMIA ETHIOPIA

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## ABSTRACT

*In Ethiopia, soil acidity and the associated phosphorus fixation is one of the major problems for maize production. The objectives of the study were to assess the integrated effects of lime and P fertilizer on maize yield parameters and selected soil chemical properties. The study was conducted on Nitisols, Luvisols, and Alisols in Bako Tibe and Omo Nada Districts for two years 2017/18-2018/19 in the main rainy seasons under field conditions. The experiment had eight treatments: (T1) control, (T2) 50% RL + 30 kg P ha*$^{-1}$ *+ 92 kg N ha*$^{-}$*, (T3) 100% RL +30 kg P ha*$^{-1}$ *+ 92 kg N ha*$^{-1}$*, (T4) twice RL + 30 kg P ha*$^{-1}$ *+ 92 kg N ha*$^{-1}$*, (T5) 50% RL + 15 kg P ha*$^{--1}$ *+ 92 kg N ha*$^{-1}$*, (T6) 100% RL alone, (T7) farmers Practice (200 kg NPSB +92 kg N ha*$^{-1}$*), (T8) 30 kg P ha*$^{-1}$ *+ 92 kg N ha*$^{-1}$ *arranged in RCBD with three replications. The optimum lime rate was determined for the soils based on the exchangeable acidity (EA) method. Lime application increased the soil pH (*$H_2O$*), available phosphorus (AP), and exchangeable calcium (*$Ca^{2+}$*) but decreased the EA for all three soil types. The application of recommended lime + 30 kg P ha*$^{-1}$ *increased the grain yield of maize by 89.88%, 81.49 %, and 84.38% over the control treatments and by 28.35%, 26.53%, and 26.73% over the farmers' practice for Nitisols, Luvisols, and Alisols respectively. The MRR analysis revealed that treatment 3 gave the highest MRR of 284.58%, 238.18%, and 325.58% for Nitisols, Luvisols, and Alisols respectively which is economically the most advantageous. Therefore, the use of 100% RL +30 kg P ha*$^{-1}$ *+ 92 kg N ha*$^{-1}$ *was recommended for optimum production of maize in the study area in a sustainable way.*

**Keywords:** Alisols, Nitisols, Critical P, Lime rates, Maize, Relative yield.

## 4.1. INTRODUCTION

In many regions of the world, maize [*Zea mays* L.] is the major cereal crop grown for human consumption and cattle feeds. After rice and wheat, maize is the third most-produced cereal crop worldwide (Alhassan, 2021). Similarly, in sub-Saharan Africa (SSA), it is the major staple food for humans, feeds for livestock, and is used as industrial raw materials and occupies more than 33 million ha each year (Matova et al., 2020).
In Ethiopia, out of the 12.7 million ha of total arable land, 10. 2 million ha was under cereal grain production. Among the major cereals produced in the country, maize is the second in the total area of production (2.1 million ha) next to Tef (3.02 million ha) and maize is the first (8.4 million qt) of all cereals in grain yield production (CSA, 2019). During the past 20 years, maize acreage increased from 1 to 2 million ha at a faster rate than all other main cereal crops in the country mostly because of the rising demand brought on by population growth and the crop's competitiveness. In Ethiopia, about 10.5 million smallholder households grow maize (CSA, 2019). More than 95% of Ethiopia's total maize area coverage and yield comes from these smallholder farmers (Matova et al., 2020). Most of the maize grain produced (76%) goes to producer households' consumption (CSA, 2019).

Maize grows and adapts in different agroecological regions of Ethiopia starting from dry lowlands of Somali, Afar, and parts of Oromia with an elevation of < 1000 m.a.s.l and annual rainfall of < 700 mm to moist upper mid-latitudes of Central highlands; highlands of SNNPR, Amhara, and Oromia with an elevation of 2000-2400 m.a.s.l having an annual rainfall of > 1200 mm (Abate et al., 2015). According to CSA statistics from 2011 cited in Abate et al. (2015), the five major maize-producing regions in Ethiopia are West Gojjam, East Gojjam, Jimma, East Welega, and West Welega in the mid-altitude within the altitude range of 1500–2000 masl.

The importance of maize to Ethiopia's food security is currently increasing. The high value of maize as a food crop and an increasing need for the stover as fuel for rural people and animal feed are both contributing factors to its popularity in Ethiopia (Ibsa

Aliyi et al., 2020). In Ethiopia, maize is grown primarily for food, both as green fruits and as dry grains (Abate et al., 2015). In the Oromia region of Ethiopia, Bako Tibe and Omo Nada are the most maize-growing districts. In these two districts (study area) the soils are acidic, and the soil available N, P, and B were below the critical level for crop production (Gezu & Tekalign, 2019b).

In the study districts, a consistent decline in soil fertility is observed due to the short fallow period, inadequate amount of fertilizer use, burning or continuous removal of crop residue from the field, continuous monocropping year after year, consumption of cow dung for household fuel and little or no conservation (Gezu & Tekalign, 2019b). Crop production on less fertile acidic soils can only be improved by the integrated use of soil amendments such as lime, compost as well as farmyard manure, and proper fertilizer management (Dawid, 2021).

Even though maize is the major cereal crop that contributes much to food self-sufficiency in Africa, soil acidity is the major problem that lowers its yield in tropical Africa's high-potential agricultural regions Opala et al., (2018) such as Bako Tibe and Omo Nada districts. CSA, (2021) also indicated that due to limitations caused by soil acidity and nutrient inadequacy, the potential maize production on farmers' fields in East Wollega is 4.5 t $ha^{-1}$. The above-mentioned amount of maize grain yield is by far lower than the national maize grain yield (8 t $ha^{-1}$).

Bako Tibe is the most suitable district for maize production in the Oromiya region which accounts for a total area of 32, 562 ha under maize production with a maize grain production of 2, 027, 207 Qt (Tesfaye & Tolcha, 2019). Still, there is a wide gap in maize grain yield (37%) as computed from the average yield obtained from the farmers’ field (5004 kg $ha^{-1}$) in the Bako Tibe district and the average optimum grain yield obtained (7960 kg $ha^{-1}$) from the research field (Tesfaye & Tolcha, 2019). This yield gap resulted from the decline in soil fertility and the lack of integrated nutrient management practices by the community to sustain land productivity.

### *4.1.1 Statement of the problem*

One of the key factors contributing to low agricultural yields is the reduction in soil fertility brought on by soil acidity (Eyasu, et al., 2020). The improper application of inorganic fertilizers resulted in soil acidification (Han et al., 2019). Maize production in southwestern and western Oromia is reduced because of the decline in soil fertility affected by strongly acidic soil reactions accompanied by strong P-fixation characteristics.

Even though different technologies and agronomic practices were recommended for maize production in the study districts, the technologies and full packages were not fully promoted to the farming community and site-specific fertilizer recommendations for optimum maize production in the study district were lacking. Additionally, the farmers have no information on the quantity of lime used, and the lime rates were not determined for different soil types in the study area. These various soil types in the study districts uniformly received the same rate of lime without considering the difference in their properties and their various fertility levels (Tesfaye & Tolcha, 2019).

Due to this, the high-yielding maize varieties do not give their maximum yield on the farmer's field compared to the average yield obtained at the research station. This wide maize yield gap can be filled through the application of an optimum rate of lime and P fertilizers based on the soil types which is very helpful to sustain the fertility status of the soils and alleviate soil acidity-related problems.

### *4.1.2 Objectives:*

The objectives of the study were to (1) determine the lime requirement of different soils and ameliorate the soil acidity, (2) evaluate the response of maize to different rates of lime and phosphorus in the Bako Tibe and Omo Nada Districts, and (3) assess the integrated effects of lime and P fertilizer on maize yield parameters and some soil chemical properties such as soil pH, exchangeable aluminum (Al), and available P.

## 4.2. MATERIALS AND METHODS

In this section, the geographical location of the study sites was described. The different materials such as inputs and the equipment used to carry out the field experiment, the equipment used in the laboratory, and the lab procedures that followed were described. In addition to these, the research methodology that followed during the implementation of the field trial was elaborated here.

### *4.2.1 Description of the Experimental Sites*

(Refer to section 1.4.1 above)

### *4.2.2. Experimental Materials*

The hybrid maize BH-661 variety which is most preferred by the farming community was used as a test crop. The variety was released by Bako Agricultural Research Center (BARC) in 2012. It is very high-yielding and is more suitable for mid to higher-altitude areas (Abate et al., 2015)**.** Triple superphosphate (TSP) containing 46% $P_2O_5$ and NPSB containing 18 N + 36 $P_2O_5$ + 7S + 0.71 B (95 kg NPS + 4.9 kg Borax) were used. Urea contains 46% nitrogen and was used as a source of nitrogen. The liming material used in the experiment was ground limestone ($CaCO_3$) of standard particle size (fine enough to pass a U.S. Standard No. 60 sieve) and CCE (Calcium Carbonate Equivalent) of 85% confirmed by laboratory test (Oromia Agricultural and Natural Resource Bureau, at Guder Limestone Crushing Factory).

### *4.2.3. Treatments and Experimental Design*

The experiment was conducted on farmers' fields on three major acidic agricultural soils, namely Nitisols and Luvisols at Bako Tibe and Alisols at Omo Nada Districts of Oromiya Regional State permanently for two consecutive years (2017/18-2018/19) during the main rainy season. The treatments used were (1) control (no addition of fertilizers and lime), (2) 50% recommended lime rate (RL) + 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ (3) 100% RL +30 kg

P $ha^{-1}$ + 92 kg N $ha^{-1}$ (4) 2*( twice) RL + 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ (5) 50% RL + 15 kg P $ha^{--1}$ + 92 kg N $ha^{-1}$ (6) 100% RL alone, (7) farmers Practice (200 kg NPSB +92 kg N $ha^{-1}$), (8) 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ arranged in a randomized complete block design (RCBD) with three replications.

The experiment consisted of 8 treatments and a total of (3 * 8) 24 plots. The plot size is 4.8 m *5 m = 24 $m^2$. The spaces between blocks and plots were 2 m and 1 m respectively. The inter and intra-row spacing used was 0.8 m and 0.5 m respectively. Two maize seeds were placed per hill to have an optimum plant population. The total number of rows per plot was 6 and there were 20 maize plants per row **(**6 * 20 = 120 plants per plot), or 50, 000 plants $ha^{-1}$. There were 4 harvestable central rows and two border rows per plot. Two plants at each end of the harvestable rows were used as border plants. Therefore, the net harvestable plot was 4 m * 4.5 m = 18 $m^2$.

### *4.2.4. Experimental Procedures and Field Management*

The land was plowed by oxen to prepare a fine seedbed following farmers' practice**.** Agricultural lime ($CaCO_3$) was evenly applied on the surface of the plots (plots with treatments № 2, 3, 4, 5, and 6,) and incorporated into the soil up to 15 cm depth with a hand hoe one month before maize planting. Two maize seeds were placed beside the fertilizers (5 cm apart) starting from May 1st to mid-month. Phosphorus was applied once at the time of planting as triple superphosphate (TSP) and NPSB in the rows as per the treatment and mixed with soil while the recommended N rate (92 kg N $ha^{-1}$) was applied uniformly to all experimental plots except the absolute control and 100% LR alone (treatments № 1 and 6 respectively) as urea in two split applications; a half dose of N at seed sowing and the remaining half dose of N was side-dressed when the maize seedlings reached knee height (at forty-five days after planting). Then, all recommended cultural practices were followed for the management of the field experiment starting from sowing to harvesting.

### *4.2.5. Data Collection and Measurements*

From agronomic data, yield parameters such as straw yield (kg $ha^{-1}$), dry biomass yield (kg $ha^{-1}$), and grain yield (kg $ha^{-1}$) were recorded when 90% of the plants reached their respective physiological maturity stages. Soil data were obtained from activities carried out under sections 1.4.2.1 and 1.4.2.2 (Soil sampling, sample preparation, and analysis).

### *4.2.6 Partial Budget Analysis*

During the 2017/18-2018/19 cropping season, the price of maize grain in Bako Tibe and Omo Nada districts was 10 Ethiopian birr (EB) $kg^{-1}$. The prices for NPSB and TSP were taken as 10.00, EB $kg^{-1}$ and the price of lime ($CaCO_3$) was 1.5 EB kg $^{-1}$. The labor cost for incorporation and transportation of lime was taken at 21.50 EB 100 $kg^{-1}$ lime, and the application and transport cost for fertilizer was 600 EB $kg^{-1}$ with consideration of 6 men per hector of field can incorporate fertilizer within a day (100 Birr/day for one labor). A similar additional cost (600 EB) was incurred during the side dressing of urea for plots that received urea.

Based on CIMMYT, (1988), a partial budget analysis was used to identify economically acceptable treatments. To compute costs, only total variable costs (TVC) were used. The cost of applying lime and fertilizers as well as the current price of maize were all taken into consideration. With a mean market price of 10.00 Birr $kg^{-1}$, maize grain yield was calculated to determine the economic parameters. Costs associated with managing the field, harvesting, transporting the maize grain, and storage were not taken into account because they were the same for all treatments. The gross yield was adjusted by 10% to align the maize grain yield with the actual yield of a farmer. Costs/expenses and benefits were provided per hectare basis, with prices in Ethiopian Birr (EB). The treatments' net benefits (NB) and TVC were compared using dominance analysis outlined by CIMMYT, (1988) below.

$$NB = AGY \times FP - TC \ldots\ldots (Eq\ 4.3)$$

Where FP is the maize grain field price per unit, AGY is the adjusted grain yield per hectare, and NB is the gross field benefit (GFB).

The next phase was listing the TVC in increasing order based on a dominance analysis. Since they were dominated and excluded from further analysis, all treatments with NB less than or equal to treatments with lower TVC were designated with the letter "D" (CIMMYT, 1988). The undominated treatments were further used for marginal rate of return (MRR) analysis, moving from one lower TVC to the next, as indicated below:

$$\mathrm{MRR}(\%) = \frac{\text{Change in NB (NB2} - \text{NB1)}}{Change\ in\ TVC\ (TVC2 - \mathrm{T}VC1)}\ x\ 100 \ldots .(\mathrm{Eq.}\,4.4)$$

where TVC1 is the next lowest TVC, TVC2 is the highest TVC, NB1 is the NB with the immediately lower NB, and NB2 is the NB with the next higher NB.

## 4.3. RESULTS

### *4.3.1. Initial Soil Properties of the Study Area*

The pre-planting soil property of the study area is displayed in Table 4.3.1. All three soil types (Nitisols, Luvisols, and Alisols) were clayey in texture. Based on the rating criteria of Jones, (2003), the soil pH-$H_2O$ for Nitisols (5.71) and Luvisols (5.73) were characterized as moderately acidic and that of Alisols (4.81) was very strongly acidic in reaction. As rated by Hazelton & Murphy, (2016), the OC% content of Nitisols (2.20%) and Luvisols (2.21%) was grouped under high categories while the OC content of Alisols (1.95%) was in the medium range. The total N (TN) content of 0.17%, 0.19%, and 0.16% for Niisls, Luvisols, and Alisols in this order were in the medium range (Hazelton & Murphy, 2016). According to the rating of Hazelton & Murphy, (2016), the available P content of 6.69, 6.71, and 5.27 mg $kg^{-1}$ soil for Nitisols, Luvisols, and Alisols sequentially was in the low range. As rated by Wagi (2021), Nitisols with 17.21 mg S $kg^{-1}$ soil and Luvisols with 20.77 mg S $kg^{-1}$ soil were low whereas Alisols with 13.36 mg S $kg^{-1}$ soil were medium in their available S content.

Both the exchangeable Ca and Mg levels were high for Nitisols and medium for Luvisols and Alisols (FAO, 2006). According to the rating of Hazelton & Murphy, (2016), the CEC values of 32.69 $mg_{(+)}kg^{-1}$ for Nitisols, 41.56 $mg_{(+)}kg^{-1}$ for Luvisols, and 25.02 $mg_{(+)}kg^{-1}$ for Alisols were categorized as high, very high, and medium respectively. The PBS values of 51% and 50% were in the medium category for Nitisols and Luvisols but low (28%) for Alisols. The available B contents of both Nitisols and Luvisols (0.43 mg B $kg^{-1}$) were in the low range but the value (0.01 mg B $kg^{-1}$) was very low for Alisols (Jones, 2003).

Table 4.1: Mean selected soil physicochemical properties of Nitisols, Luvisols, and Alisols before planting

| | Soil Type (RSG) | | | | |
|---|---|---|---|---|---|
| Soil parameters | NT | LV | AL | Status | Reference |
| Particle Size Dist. | | | | | |
| Sand (%) | 33 | 37 | 40 | | |
| Silt (%) | 15 | 14 | 19 | | |
| Clay (%) | 52 | 49 | 41 | | |
| Textural class | Clay | Clay | Clay | | The USDA textural triangle (Soil Survey Division Staff, 1993). |
| BD (g /cm$^3$) | 1.45 | 1.42 | 1.44 | Normal range | Hazelton & Murphy (2016) |
| pH ($H_2O$) | 5.71 | 5.73 | 4.81 | M, M, VSA | Benton (2003) |
| OC (%) | 2.20 | 2.21 | 1.95 | H, H, M | Hazelton & Murphy (2016) |
| TN (%) | 0.17 | 0.19 | 0.16 | M, M, M | Hazelton & Murphy (2016) |
| Av P (mg kg$^{-1}$) | 6.69 | 6.71 | 5.27 | L, L, L | Hazelton & Murphy (2016) |
| Av S (mg kg$^{-1}$) | 17.21 | 20.77 | 13.36 | L, M, L | Wogi. L et al., 2021 |
| Ca (cmol$_{(+)}$kg$^{-1}$) | 8.17 | 8.02 | 6.21 | M, M, M, | FAO (2006b) |
| Mg (cmol$_{(+)}$kg$^{-1}$) | 3.64 | 2.54 | 2.66 | H, M, M | Hazelton & Murphy (2016) |
| K (cmol$_{(+)}$kg$^{-1}$) | 1.36 | 0.79 | 3.10 | VH, H, VH | FAO (2006b) |
| CEC(cmol$_{(+)}$kg$^{-1}$) | 32.69 | 41.56 | 25.02 | H, VH, M | Hazelton & Murphy (2016) |
| PBS % | 51 | 50 | 28 | M, M, L | Hazelton & Murphy (2016) |
| Exc Ac (cmol$_{(+)}$kg$^{-1}$) | 1.19 | 1.90 | 2.24 | --- | — |
| Ava. B (mg kg$^{-1}$ ) | 0.43 | 0.43 | 0.01 | L, L, VL | Benton (2003) |

Note: NT = Nitisols, LV = Luvisols, AL Alisols, Crt= critical, M = Medium, H = high, L= low, VSA= very strongly acidic.

### *4.3.2. Lime determination for Nitisols, Luvisols, and Alisols in Southwestern Ethiopia*

The lime rates were determined for the three soil types (Nitisols, Luvisols, and Alisols) based on the exchangeable acidity (Exch.Ac) methods indicated by Getachew et al., (2019), equation 4.1. Different rates of lime: 2.28 t $ha^{-1}$, 3.61 t $ha^{-1}$, and 4.22 t $ha^{-1}$ were recommended for Nitisols, Luvisols, and Alisols respectively (Table 4.2).

Table 4.2: Lime determination for Nitisols, Luvisols, and Alisols in Bako Tibe and Omo Nada districts of Oromia, Ethiopia

| Soil types | EA ($cmol_{(+)}kg^{-1}$) | BD (g $cm^{-3}$) | LR (t $ha^{-1}$) | Actual LR (t $ha^{-1}$) |
|---|---|---|---|---|
| Nitisols | 1.19 | 1.45 | 1.94 | 2.28 |
| Luvisols | 1.90 | 1.44 | 3.05 | 3.60 |
| Alisols | 2.24 | 1.42 | 3.59 | 4.22 |

Note: Exch.Ac = exchangeable acidity; BD = bulk density; LR = lime requirement

### *4.3.3.Effect of Lime and P Rates on Selected Soil Properties*

The effect of lime application was evaluated from the values of pre-planting and post-harvesting soil chemical properties of each lime-applied treatment. The evaluation of soil properties revealed that the application of different rates of lime decreased some values but increased the level of the other soil's chemical properties when compared to the initial values of soil characteristics.

#### *4.3.3.1 Effect of lime and phosphorus rates on soil pH (H2O)*

As indicated in Table 4.3, the soil pH significantly ($P < .05$) varies for Nitisols and highly significantly ($P < .0001$) differs for Luvisols and Alisols due to the application of lime rates. In Nitisols, the soil pH ($H_2O$) was increased from 5.35 to 6.16 with the application of the recommended rate of lime **(**2.28 t $ha^{-1}$). The highest soil pH (6.63) was obtained under treatments that received twice the RL rate followed by the treatment that received the RL (6.16). The lowest pH (5.21) was recorded under farmers' practice (application of 200 kg NPSB ha$^{-1}$ + 92 kg P ha$^{-1}$).

In Luvisols, a highly significant ($P$ < .0001) variation of pH ($H_2O$) was observed due to lime application. The application of the recommended rate of lime (3.60 t ha$^{-1}$) increased the soil pH from 4.94 to 6.70. The highest pH value (7.22) and lowest pH value (4.82) were recorded from the treatments that received twice the recommended lime rate and farmers' practice, respectively.

In Alisols, a strongly significant ($P$ < .0001) variation in pH ($H_2O$) was obtained due to the effect of lime application. The application of the recommended lime rate (4.22 t ha$^{-1}$) increased the soil pH from 4.81 to 6.23. The highest pH value (6.92) and lowest pH value (4.80) were recorded from the treatments that received twice the recommended lime rate and farmers' practice, respectively.

Table 4.3: Effect of lime and P rates on soil reaction (pH-$H_2O$) for Nitisols, Luvisols, and Alisols in Bako Tibe and Omo Nada districts of Oromia, Ethiopia.

| | pH $H_2O$ (1: 2.5) | | |
|---|---|---|---|
| Treatments | Nitisols | Luvisols | Alisols |
| 1. Control (no lime and no fertilizer) | 5.35$^{c}$ | 4.94$^{e}$ | 4.81$^{d}$ |
| 2. 50% RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 5.44$^{bc}$ | 6.17$^{c}$ | 5.98$^{c}$ |
| 3. 100% RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 6.16$^{a}$ | 6.70$^{b}$ | 6.23$^{bc}$ |
| 4. 2*( twice) RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 6.63$^{a}$ | 7.22$^{a}$ | 6.92$^{a}$ |
| 5. 50% RL+ 15 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 5.58$^{abc}$ | 5.59$^{d}$ | 5.97$^{c}$ |
| 6. 100% RL alone | 5.85$^{ab}$ | 6.82$^{b}$ | 6.46$^{b}$ |
| 7. farmer’s practice (200 kg NPSB) + 92 kg N ha$^{-1}$ | 5.21$^{c}$ | 4.82$^{e}$ | 4.80$^{d}$ |
| 8. 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 5.28$^{c}$ | 5.48$^{d}$ | 5.53$^{cd}$ |
| *SE* | 0.15 | 0.10 | 0.13 |
| *F* | 4.44 | 63.42 | 37.69 |
| *P* | 0.0135 | <.0001 | <.0001 |
| *CV%* | 4.64 | 2.95 | 4.19 |

Note: RL for Nitisols = 2.28 t $ha^{-1}$, RL for Luvisols = 3.61 t $ha^{-1}$, RL for Nitisols = 4.20 t $ha^{-1}$, RL = recommended lime rate, ha = hectare, t = ton. Means indicated by different letters in the same column vary significantly ($P < 0.5$) among treatments.

### *4.3.3.2 Effect of lime and phosphorus rates on soil exchangeable bases ($Ca^{2+}$, $Mg^{2+}$, & $K^{+}$)*

As indicated in Table 4.4, among the soil exchangeable bases, $Ca^{2+}$ showed highly significant ($P < .001$) variation due to lime application on Nitisols, Luvisols, and Andosols. Statistically, significant variation was not observed in exchangeable $Mg^{2+}$ and $K^{+}$ for Nitisols and Alisols but strongly and significantly ($P < .0001$) varied in the Luvisols. The lowest values of exchangeable $Ca^{2+}$ 7.52, 6.53, and 4.82 $cmol_{(+)}kg^{-1}$ for Nitisols, Luvisols, and Alisols were obtained from the farmers' practice while the highest values of exchangeable $Ca^{2+}$ (13.40, 32.26, and 16.92 $cmol_{(+)}kg^{-1}$ for Nitisols, Luvisols, and Alisols respectively) were obtained from the treatment that received twice the recommended lime rate for all soil types followed by the treatments that received the recommended lime rate alone and the recommended lime rate plus P fertilizer rate.

The exchangeable $Mg^{2+}$ and $K^{+}$ did not significantly ($P > .05$) vary for Nitsols and Alisols but highly and significantly ($P < .001$) varied for Luvisols. The highest exchangeable Mg and K (4.51 $cmol_{(+)}kg^{-1}$ $Mg^{2+}$ and 0.58 $cmol_{(+)}kg^{-1}$ $K^{+}$) were recorded on the recommended lime rate alone in Luvisols.

Table 4.4: Effect of lime and P rates on soil exchangeable $Ca^{2+}$, $Mg^{2+}$, and $K^{+}$ ($cmol_{(+)}kg^{-1}$) for Nitisols, Luvisols, and Alisols in Bako Tibe and Omo Nada districts of Oromia, Ethiopia.

| | $Ca^{2+}$ ($cmol_{(+)}kg^{-1}$) | | | $Mg^{2+}$ ($cmol_{(+)}kg^{-1}$) | | | $K^{+}$ ($cmol_{(+)}kg^{-1}$) | | |
|---|---|---|---|---|---|---|---|---|---|
| Treatments | NT | LV | AL | NT | LV | AL | NT | LV | AL |
| 1. Control (no lime and no fertilizer) | $7.66^{d}$ | $6.43^{d}$ | $4.87^{c}$ | 2.40 | $1.87^{e}$ | 1.67 | 0.47 | $0.46^{b}$ | 1.02 |
| 2. 50% RL + 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | $8.82^{cd}$ | $14.15^{c}$ | $5.98^{bc}$ | 2.31 | $1.95^{e}$ | 1.50 | 0.47 | $0.28^{d}$ | 0.95 |
| 3. 100% RL + 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | $12.76^{bc}$ | $21.94^{b}$ | $16.23^{a}$ | 2.48 | $3.27^{b}$ | 1.66 | 0.33 | $0.36^{c}$ | 1.03 |
| 4. 2*(twice) RL+30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | $13.40^{a}$ | $32.36^{a}$ | $16.92^{a}$ | 2.28 | $2.63^{c}$ | 1.64 | 0.57 | $0.45^{b}$ | 1.02 |
| 5. 50% RL 15 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | $8.16^{d}$ | $12.72^{c}$ | $4.97^{c}$ | 2.52 | $1.78^{e}$ | 1.53 | 0.61 | $0.49^{b}$ | 0.98 |
| 6. 100% RL alone | $11.17^{b}$ | $31.64^{a}$ | $6.46^{b}$ | 2.45 | $4.51^{a}$ | 1.89 | 0.59 | $0.58^{a}$ | 0.99 |
| 7. Farmers Practice (200 kg NPSB) + 92 kg N $ha^{-1}$ | $7.52^{d}$ | $6.53^{d}$ | $4.82^{c}$ | 2.43 | $2.29^{d}$ | 1.48 | 0.48 | $0.36^{c}$ | 1.13 |
| 8. 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | 7.96 | 7.16 | 5.55 | 2.39 | $1.94^{e}$ | 2.33 | 1.09 | $0.54^{a}$ | 0.70 |
| *SE* | 0.71 | 1.21 | 3.56 | 0.13 | 0.08 | 0.19 | 0.13 | 0.01 | 0.08 |
| *F* | 9.56 | 76.29 | 6.78 | 0.46 | 143.7 | 0.53 | 0.52 | 33.88 | 0.50 |
| *P* | 0.0005 | <.0001 | 0.0025 | 0.83 | <.0001 | 0.78 | 0.79 | <.0001 | 0.79 |
| *CV%* | 12.77 | 11.48 | 46.12 | 9.40 | 5.44 | 20.5 | 46.4 | 6.87 | 13.6 |

Note: NT= Nitisols, LV= Luvisols, AL= Alisols, RL for Nitisols = 2.28 t $ha^{-1}$, RL for Luvisols = 3.61 t $ha^{-1}$, RL for Nitisols = 4.20 t $ha^{-1}$, RL = recommended lime rate, ha = hectare, t = ton. Means indicated by different letters in the same column vary significantly ($P < 0.5$) among treatments.

#### *4.3.3.3. Effect of lime and phosphorus rates on soils exchangeable acidity (Exch. Ac)*

The Exchangeable acidity (Exch.Ac) showed a strong significant ($P < .0001$) variation between treatments for the three soil types (Nitisoil, Luvisols, and Alisols) (Table 4.5). For Nitisols, the highest value of Exch.Ac (0.93 $cmol_{(+)}kg^{-1}$) was recorded from the control treatment and followed by farmers' practice (0.80 $cmol_{(+)}kg^{-1}$) and the lowest 0.03 $cmol_{(+)}kg^{-1}$ value of Exch. Ac was obtained from treatment 4 (twice of the recommended lime plus critical P) followed by 0.05 $cmol_{(+)}kg^{-1}$ Exch. Ac which was recorded under treatment 6 (recommended lime rate alone). Also, the exchangeable $Al^{3+}$ followed the same trend as Exch.Ac in Nitisols (Table 4.5).

For Luvisols, the highest value of exchangeable acidity (2.01 $cmol_{(+)}kg^{-1}$) was recorded from farmers' practice followed by the control treatment (1.34 $cmol_{(+)}kg^{-1}$), and the lowest value (almost nil) was recorded under treatments that received twice the recommended and the recommended rates of lime alone or in combination with the critical P rate (30 kg P $ha^{-1}$).

In Alisols, the highest value of exchangeable acidity (2.80 $cmol_{(+)}kg^{-1}$) was recorded from farmers' practice followed by the control treatment (2.31 $cmol_{(+)}kg^{-1}$) and the lowest value (almost nill) was recorded under treatments that received twice and the recommended rates of lime alone or in combination with critical P rate (30 kg P $ha^{-1)}$. For both Luvisols and Alisols, the values of exchangeable $Al^{3+}$ followed the same trend as those of the EA. The highest mean values of exchangeable acidity from the three soils (1.85 $cmol_{(+)}kg^{-1}$ Exch. Ac) were recorded under the farmers' practice followed by the control treatment of 1.55 $cmol_{(+)}kg^{-1}$ Exch. Ac. The lowest mean values of Exch. Ac (0.01, 0.02, and 0.03) were observed under treatments 4, 6, and 3 respectively.

Table 4.5: Effect of lime and P rates on soil exchangeable acidity and aluminum (Al) for Nitisols, Luvisols, and Alisols in Bako Tibe and Omo Nada districts of Oromia, Ethiopia.

| | Exch. Ac (cmol$_{(+)}$kg$^{-1}$) | | | Exch.Al (cmol$_{(+)}$kg$^{-1}$) | | |
|---|---|---|---|---|---|---|
| Treatments | Nitisols | Luvisols | Alisols | Nitisols | Luvisols | Alisols |
| 1. Control (no lime and no fertilizer) | $0.93^{a}$ | $1.34^{b}$ | $2.31^{b}$ | $0.70^{a}$ | $0.78^{a}$ | $1.52^{a}$ |
| 2. 50% RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | $0.20^{b}$ | $0.00^{c}$ | $0.51^{d}$ | $0.20^{bc}$ | $0.00^{b}$ | $0.49^{c}$ |
| 3. 100% RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | $0.08^{b}$ | $0.00^{c}$ | $0.00^{e}$ | $0.08^{c}$ | $0.00^{b}$ | $0.00^{d}$ |
| 4. 2*( twice) RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | $0.03^{b}$ | $0.00^{c}$ | $0.00^{e}$ | $0.03^{c}$ | $0.00^{b}$ | $0.00^{d}$ |
| 5. 50% RL 15 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | $0.32^{b}$ | $1.20^{b}$ | $1.55^{c}$ | $0.32^{b}$ | $0.69^{a}$ | $0.95^{b}$ |
| 6. 100% RL alone | $0.05^{b}$ | $0.00^{c}$ | $0.00^{e}$ | $0.05^{c}$ | $0.00^{b}$ | $0.00^{d}$ |
| 7. Farmers Practice (200 kg NPSB) + 92 kg N ha$^{-1}$ | $0.80^{a}$ | $2.01^{a}$ | $2.80^{a}$ | $0.69^{a}$ | $1.05^{a}$ | $1.89^{a}$ |
| 8. 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 0.43 | 0.49 | 1.16 | 0.00 | 0.00 | 0.34 |
| *SE* | 0.10 | 0.10 | 0.15 | 0.07 | 0.14 | 0.14 |
| *F* | 12.66 | 64.82 | 62.52 | 3.05 | 10.87 | 30.14 |
| *P* | 0.0001 | <.0001 | <.0001 | 0.0472 | 0.0003 | <.0001 |
| *CV%* | 44.18 | 28.07 | 25.46 | 18.95 | 67.48 | 35.61 |

Note: RL for Nitisols = 2.28 t ha$^{-1}$, RL for Luvisols = 3.61 t ha$^{-1}$, RL for Nitisols = 4.20 t ha$^{-1}$, RL = recommended lime rate, ha = hectare, t = ton. Means indicated by different letters in the same column vary significantly (P <0.5) among treatments.

#### *4.3.3.4. Effect of lime and phosphorus rates on soil exchangeable aluminum (Exch.Al)*

The exchangeable Al was strongly and significantly (P < .0001) vairy among treatment means for Nitisols, Luvisols, and Alisols (Table 4.5). For Nitisols, the highest value of Exch. Al (0.70 $\text{cmol}_{(+)}\text{kg}^{-1}$) was recorded under the control treatment and followed by the farmers' practice (0.69 $\text{cmol}_{(+)}\text{kg}^{-1}$ Exch. Al) while the lowest value of Exch. Al was recorded in treatments 4 and 3 (treatments received twice RL plus 30 kg P $\text{ha}^{-1}$ and recommended RL plus 30 kg P $\text{ha}^{-1}$). For Luvisols, the highest value of Exch. Al (1.05 $\text{cmol}_{(+)}\text{kg}^{-1}$ was recorded under the farmers' practice and followed by the control treatments (0.78 $\text{cmol}_{(+)}\text{kg}^{-1}$). The lowest value of Exch. Al (nill) was recorded under treatments that received the twice and full recommended rate of lime alone or in combination with P rates.

Alisols, the soil that is highly saturated with active exchangeable Al showed the highest value (1.89 and 1.52 $\text{cmol}_{(+)}\text{kg}^{-1}$ Al) of exchangeable Al under the farmers' practice and control treatments respectively. The lowest values of exchangeable Al (nill) were recorded for treatments 3, 4, and 6 which received a full and twice dose of lime. The highest mean values of exchangeable Al from the three soils (1.06 $\text{cmol}_{(+)}\text{kg}^{-1}$ Al) were recorded under the farmers' practice followed by the control treatment. The lowest mean value of exchangeable Al (nill) was observed under treatments 3, 4, and 6.

#### *4.3.3.5. Effect of lime and phosphorus rates on soil available phosphorus*

The available P (Av. P) values revealed a strong significant ($P < .0001$) variation between treatments for all soil types because of the difference in the quantity of lime applied (Table 3.6). The highest available P values (15.42, 22.27, and 40.92 mg P $\text{kg}^{-1}$) were recorded under treatment 3 that received the recommended lime rates for Nitisols, Luvisols, and Alisols, respectively while the lowest values of available P values of 2.62, 6.53, and 5.23 mg $\text{kg}^{-1}$ for Nitisols, Luvisols, and Alisols respectively were recorded in the control treatment. The value of available P in the soil increased with the soil pH up to pH 7.

The highest mean available P value (26.20 mg $kg^{-1}$ P) was obtained under treatment 3, followed by treatment 4 (22.50 mg $kg^{-1}$) but the lowest mean value of available P (4.79 mg $kg^{-1}$ available P) was obtained under the control treatment. Application of 200 kg $ha^{-1}$ NPSB (farmers' practice) increased the soil available P content from 6.69 to 12.36, 6.71 to 15.10, and 5.27 to 24.01 mg P $kg^{-1}$ soil respectively, and also the application of recommended rate of lime alone increased the soil available P from 6.69 to 10.60, 6.71 to 12.79, and 5.27 to 13.04 mg P $kg^{-1}$ soil for Nitisols, Luvisols, and Alisols in this order.

#### *4.3.3.6. Effect of lime and phosphorus rates on soil available sulfur (AS)*

Statistically, there was no significant variation ($P > .05$) in the sulfur content due to tratement application for Nitisols and Luvisols (Table 4.6). However, the lowest S content was recorded under the control treatment. For Alisols, there was a highly significant ($P < .001$) variation in S content among treatments. The highest S content (30.21 mg $kg^{-1}$) was observed under the treatment that received twice the recommended lime rate (8.40 t lime $ha^{-1}$) and the lowest S content (16.88 mg $kg^{-1}$) was recorded under the control treatment followed by the treatment with the application of recommended lime alone.

Table 4. 6: Effect of Lime and P rates on soil available P (Av. P) and sulfur (S) for Nitisols, Luvisols, and Alisols in Bako Tibe and Omo Nada districts of Oromia, Ethiopia.

| | Ava. P (mg $kg^{-1}$) | | | Ava. S (mg $kg^{-1}$) | | |
|---|---|---|---|---|---|---|
| Treatments | Nitisols | Luvisols | Alisols | Nitisols | Luvisols | Alisols |
| 1. Control (no lime and no fertilizer) | $2.62^{d}$ | $6.53^{d}$ | $5.23^{d}$ | 15.12 | 16.45 | $18.55^{cd}$ |
| 2. 50% RL + 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | $13.11^{ab}$ | $17.78^{ab}$ | $27.93^{b}$ | 12.68 | 15.06 | $26.40^{ab}$ |
| 3. 100% RL + 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | $15.42^{a}$ | $22.27^{a}$ | $40.92^{a}$ | 12.13 | 18.25 | $23.56^{bc}$ |
| 4. 2*( twice) RL + 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | $14.53^{ab}$ | $14.75^{bc}$ | $38.18^{a}$ | 10.88 | 19.87 | $30.21^{a}$ |
| 5. 50% RL 15 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | $12.42^{bc}$ | $12.72^{c}$ | $16.02^{c}$ | 11.13 | 18.28 | $18.61^{cb}$ |
| 6. 100% RL alone | $10.60^{c}$ | $12.79^{c}$ | $13.04^{c}$ | 11.49 | 12.46 | $16.88^{d}$ |
| 7. farmers Practice (200 kg NPSB) + 92 kg N $ha^{-1}$ | $12.36^{bc}$ | $15.10^{bc}$ | $24.01^{b}$ | 11.32 | 18.10 | $21.32^{bcd}$ |
| 8. 30 kg P $ha^{-1}$ + 92 kg N $ha^{-1}$ | $13.50^{ab}$ | $14.29^{bc}$ | $16.20^{c}$ | 14.38 | 10.69 | 14.49 |
| *SE* | 0.76 | 1.55 | 2.20 | 1.35 | 1.81 | 1.87 |
| *F* | 31.05 | 9.71 | 35.45 | 1.17 | 1.88 | 6.59 |
| *P* | <.0001 | 0.0005 | <.0001 | 0.3815 | 0.1649 | 0.0029 |
| *CV%* | 11.41 | 18.50 | 16.20 | 19.35 | 18.57 | 14.60 |

Note: RL for Nitisols = 2.28 t $ha^{-1}$, RL for Luvisols = 3.61 t $ha^{-1}$, RL for Nitisols = 4.20 t $ha^{-1}$, RL = recommended lime rate, ha = hectare, t = ton. Means indicated by different letters in the same column vary significantly ($P < 0.5$) among treatments.

### *4.3.4. Effect of Lime and Phosphorus Rates on Maize Yield Parameters*

#### *4.3.4.1. Effect of Lime and Phosphorus rates on maize straw yield (SYLD)*

Statistically, there was no significant ($P < .05$) variation in straw yields (SYLD) for Nitisols and Alisols, but there was a highly significant variation ($P < .001$) in SYLD for Luvisols. The maximum (11729 kg ha$^{-1}$**)** and the minimum (4565.55 kg ha$^{-1}$) SYLD of maize were obtained from the recommended LR + 30 kg P ha$^{-1}$ and the control treatments respectively for Luvisols (Table 4.7). Compared to the control, treatment 3 which received the recommended LR + 30 kg P ha$^{-1}$ showed a SYLD increment of 61.07% for Luvisols. Uniformly 92 kg N ha$^{-1}$ of nitrogen fertilizer was applied to all treatments other than the control treatment and therefore, its effect (the effect of N) was non-significant on the yield parameters.

#### *4.3.4.2. Effect of Lime and Phosphorus rates on maize total biomass yield (BYLD)*

As displayed in Table 4.7, there was a strongly significant ($P <.0001$) variation of BYLD among treatments in Nitisols and Luvisols and a highly significant ($P < .01$) variation of BYLD between treatments in Alisols. The highest (15823, 18792, and 20728 kg ha$^{-1}$) and lowest (7367, 5873, and 12268 kg ha$^{-1}$) values of BYLD were obtained from treatment 3 that received recommended LR plus 30 kg P ha$^{-1}$ and the control treatments respectively for Nitisols, Luvisols, and Alisols in that order.

Table 4.7: Effect of lime and P rates on straw yield (SYLD) and biomass yield (BYLD kg ha$^{-1}$) on Nitisols, Luvisols, and Alisols in Bako Tibe and Omo Nada districts of Oromia, Ethiopia.

|  | SYLD (kg ha$^{-1}$) |  |  | BYLD (kg ha$^{-1}$) |  |  |
|---|---|---|---|---|---|---|
| Treatments | Nitisols | Luvisols | Alisols | Nitisols | Luvisols | Alisols |
| 1. Control (no lime and no fertilizer) | 6722.70 | 4565.55$^{cd}$ | 11263.62 | 7367$^{d}$ | 5873.02$^{d}$ | 12268.13$^{c}$ |
| 2. 50% RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 8167.55 | 7542.94$^{bc}$ | 12331.43 | 13444$^{ab}$ | 13370.51$^{b}$ | 17527.93$^{ab}$ |
| 3. 100% RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 9509.31 | 11729.33$^{a}$ | 14293.37 | 15823$^{a}$ | 18791.87$^{a}$ | 20727.84$^{a}$ |
| 4. Twice RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 8410.42 | 8089.13$^{b}$ | 13110.46 | 14424$^{ab}$ | 14633.75$^{b}$ | 18381.05$^{ab}$ |
| 5. 50% RL 15 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 7348.76 | 6159.82$^{bc}$ | 10197.70 | 11530$^{bc}$ | 11031.75$^{c}$ | 14933.93$^{bc}$ |
| 6. 100% RL alone | 7298.73 | 4665.04$^{c}$ | 11483.69 | 9291$^{cd}$ | 6279.29$^{d}$ | 13858.79$^{bc}$ |
| 7. farmers Practice (200 kg NPSB) + 92 kg N ha$^{-1}$ | 8140.60 | 5857.17$^{bc}$ | 12940.64 | 12703$^{b}$ | 13046.74$^{c}$ | 17654.86$^{ab}$ |
| 8. 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 9115 | 11565.62$^{a}$ | 11040.06 | 13659.4$^{cd}$ | 16716.12$^{cd}$ | 15591.29$^{bc}$ |
| *SE* | 1189.70 | 1082.87 | 1516.57 | 236.65 | 799.20 | 1649.84 |
| *F* | 0.59 | 6.11 | 0.81 | 7.75 | 33.17 | 3.13 |
| *P* | 0.7350 | 0.0002 | 0.5721 | <.0001 | <.0001 | < .01 |
| *CV%* | 36.69 | 37.50 | 30.37 | 21.44 | 16.50 | 24.52 |

Note: BYLD = biomass yield, RL for Nitisols = 2.28 t ha$^{-1}$, RL for Luvisols = 3.61 t ha$^{-1}$, RL for Nitisols = 4.20 t ha$^{-1}$, RL = recommended lime rate, ha = hectare, t = ton. Means indicated by different letters in the same column vary significantly ($P < 0.5$) among treatments.

### *4.3.4.3. Effect of Lime and Phosphorus rates on maize grain yield (GYLD)*

The maize grain yield (GYLD) follows the same trend as maize BYLD. There is a strongly significant ($P < .0001$) variation in GYLD among the treatment means due to the application of different rates of lime and P for Nitisols, Luvisols, and Alisols. The maximum (6367, 7063, and 6434 kg ha$^{-1}$) and the minimum grain yield (644, 1307, and 1005 kg ha$^{-1}$) were obtained from treatment 3 (recommended LR plus 30 kg P ha$^{-1}$) and the control treatment respectively for Nitisols, Luvisols, and Alisols in that order (Table 4.8). The grain yield of maize was increased for all treatments compared to the control treatment. The maize grain yield increased in treatment 3 received recommended lime rate plus critical P (30 kg P ha$^{-1}$), over the control treatment by 89.88%, 81.49 %, and 84.38%; over the farmers' practice by 28.35%, 26.53%, and 26.73%; over the critical P (30 kg P ha$^{-1}$) by 28.61%, 27.07%, and 29.26%; over the recommended lime rate only by 68.70%, 61.56%, and 63.09% and over the twice recommended lime rate plus critical P rate by 5.55%, 7.33% and 16.53% for Nitisols, Luvisols, and Alisols respectively.

### *4.3.4.4. Effect of Lime and Phosphorus rates on maize harvest index (HI%)*

There was a strong significant ($P < .0001$) variation of harvest index (HI%) due to treatment application for Nitisols and Alisols and a significant ($P < .05$) variation of HI% for Luvisols (Table 4.8). The maximum HI% values were recorded under treatment 3 which received both recommended lime and P in combination followed by 50% recommended lime plus 50% recommended P. The value of HI% for the farmers' practice was an intermediate value that is above the control and treatment 6 that received the recommended lime alone. The minimum HI% of 11.24, 17.29, and 13.33% were recorded under the control treatment and followed by treatment 6 which received recommended lime alone for Nitisols, Luvisols, and Alisols.

Table 4.8: Effect of lime and P rates on grain yield (GYLD kg ha$^{-1}$) and harvest index (HI) for Nitisols, Luvisols, and Alisols in Bako Tibe and Omo Nada districts of Oromia, Ethiopia.

| | GYLD (kg ha$^{-1}$) | | | Harvest index (HI%) | | |
|---|---|---|---|---|---|---|
| Treatments | Nitisols | Luvisols | Alisols | Nitisols | Luvisols | Alisols |
| 1. Control (no lime and no fertilizer) | 644.20$^{e}$ | 1307.47$^{f}$ | 1004.51$^{d}$ | 11.24$^{c}$ | 27.39$^{b}$ | 13.33 $^{b}$ |
| 2. 50% RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 5276.7$^{b}$ | 5827.57$^{bc}$ | 5196.50$^{b}$ | 41.17$^{a}$ | 43.38$^{a}$ | 32.61$^{a}$ |
| 3. 100% RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 6367$^{a}$ | 7062.54$^{a}$ | 6434.47$^{a}$ | 41.04$^{a}$ | 39.69$^{a}$ | 35.75$^{a}$ |
| 4. 2*( twice) RL + 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 6013.50$^{a}$ | 6544.62$^{ab}$ | 5270.59$^{b}$ | 43.90$^{a}$ | 45.24$^{a}$ | 30.71$^{a}$ |
| 5. 50% RL 15 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 4181.20$^{c}$ | 4871.93$^{d}$ | 4736.24$^{b}$ | 36.95$^{a}$ | 46.09$^{a}$ | 35.61$^{a}$ |
| 6. 100% RL alone | 1992.50$^{d}$ | 2714.26$^{e}$ | 2375.12$^{c}$ | 22.32$^{b}$ | 45.03$^{a}$ | 19.84$^{b}$ |
| 7. farmers Practice (200 kg NPSB) + 92 kg N ha$^{-1}$ | 4562.40$^{c}$ | 5189.07$^{cd}$ | 4714.22$^{b}$ | 36.08$^{a}$ | 40.31$^{a}$ | 28.62$^{a}$ |
| 8. 30 kg P ha$^{-1}$ + 92 kg N ha$^{-1}$ | 4544.89$^{c}$ | 5150.50$^{cd}$ | 4551.23$^{bc}$ | 33.91$^{ab}$ | 32.90$^{ab}$ | 36.55$^{a}$ |
| *SE* | 3.22 | 264.67 | 326.18 | 9.0 | 3.88 | 2.52 |
| *F* | 78.98 | 61.68 | 33.22 | 13.79 | 2.84 | 11.21 |
| *P* | <.0001 | <.0001 | < .0001 | <.0001 | 0.02 | < .0001 |
| *CV%* | 13.99 | 13.53 | 18.81 | 23.78 | 23.27 | 22.03 |

Note: RL for Nitisols = 2.28 t ha$^{-1}$, RL for Luvisols = 3.61 t ha$^{-1}$, RL for Nitisols = 4.20 t ha$^{-1}$, RL = recommended lime rate, ha = hectare, t = ton. Means indicated by different letters in the same column vary significantly (P <0.5) among treatments.

### *4.3.5. Economic Analysis*

During the 2017/18-2018/19 cropping seasons, the field price of maize grain in Bako Tibe and Omo Nada districts was 10 Ethiopian birr kg$^{-1}$. The prices for TSP and NPSB were taken as 10.00, EB kg$^{-1}$ and the field price of lime ($CaCO_3$) was 1.5 EB kg $^{-1}$. The labor cost for transportation and incorporation of lime was taken at 21.50 EB 100 kg$^{-1}$ lime, and the application and transport cost of fertilizer was 3 EB kg$^{-1}$ with 6 men per ha for incorporation of fertilizer within a day (100 Birr/day for one labor). A similar cost was incurred during the side dressing of urea. For plots that received urea, 600 EB was used as 100 EB paid per day for one person.

As displayed in Tables 4.9, 4.10, and 4.11, the marginal analysis of treatments 2, 3, and 7 on Nitisols, Luvisols, and Alisols had an MRR of more than 100%. The maximum net benefit of 49,000 Ethiopian Birr and the maximum MRR of 284.58% were obtained from treatment 3 which received 2.28 t lime + 30 kg P ha$^{-1}$ (recommended lime rate plus critical P value) on Nitisols (Table 4.9). The maximum net benefit of 53762.9 Ethiopian Birr and the maximum MRR of 238.18% were obtained on Luvisols from treatment 3 which received 3.60 t lime + 30 kg P ha$^{-1}$ (Table 4.20). Similarly, on Alisols, the maximum net benefit of 48473.23 Ethiopian birr and the maximum MRR of 325.58% were obtained from treatment 3 which received 4.22 t lime + 30 kg P ha$^{-1}$ (Table 4.2).

Table 4.9: Partial budget analysis of the effects of lime and P fertilizer rates for maize production on Nitisols of Bako Tibe District, Oromia, Ethiopia.

| Trt | Inputs | Yield (kg ha$^{-1}$) | Adj. yield (kg ha$^{-}$) | Gross return (EBha$^{-1}$) | TVC (EB ha$^{-1}$) | Net benefit (EB ha$^{-1}$) | MRR (%) |
|---|---|---|---|---|---|---|---|
| 1 | Control | 644.2 | 579.78 | 5797.8 | 0 | 5797.8 | |
| 7 | farmers' practice (200 kg NPSB ha$^{-1}$) | 4562.4 | 4106.2 | 41061.6 | 3200 | 37861.6 | 1002 |
| 8 | 30 kg P ha$^{-1}$ | 4544.9 | 4090.4 | 40904.0 | 3300 | 37604.01 | D |
| 5 | 1.14 t lime + 15 kg P ha$^{-1}$ | 4181.2 | 3763.1 | 37630.8 | 4151.5 | 33479.3 | D |
| 6 | 2.28 t lime ha$^{-1}$) | 1992.5 | 1793.3 | 17932.5 | 5103 | 12829.5 | D |
| 2 | 1.14 t lime + 30 kg P ha$^{-1}$ | 5276.7 | 4749.1 | 47490.3 | 5751.5 | 41738.8 | 151.96 |
| 3 | 2.28 t lime + 30 kg P ha$^{-1}$ | 6367 | 5730.3 | 57303 | 8303 | 49000 | 284.58 |
| 4 | 4.56 t lime + 30 kg P ha$^{-1}$ | 6013.5 | 4512.2 | 54121.5 | 13406 | 40715.5 | D |

D = dominated treatment, EB = Ethiopian birr, ha = hectare

Table 4.10: Partial budget analysis of the effects of lime and P fertilizer rates for maize on Luvisols of Bako Tibe District, Oromia, Ethiopia

| Trt | Inputs | Yield (kg ha$^{-1}$) | Adjusted yield (kg ha$^{-1}$) | Gross return (EB ha$^{-1}$) | TVC (EB ha$^{-1}$) | Net benefit (EBha$^{-1}$) | MRR (%) |
|---|---|---|---|---|---|---|---|
| 1 | Control | 1307.47 | 1176.72 | 11767.23 | 0 | 11767.2 | |
| 7 | Farmers' Practice (200 kg NPSB ha$^{-1}$) | 5189.07 | 4670.16 | 46701.63 | 3200 | 43501.6 | 991.70 |
| 8 | 30 kg P ha$^{-1}$ | 5150.50 | 4635.45 | 46355 | 3300 | 43055 | D |
| 5 | 1.80 t lime + 15 kg P ha$^{-1}$ | 4871.93 | 4384.74 | 43847.37 | 5480.5 | 38347.4 | D |
| 6 | 3.60 t lime alone | 2714.26 | 2442.83 | 24428.34 | 6480.5 | 17828.3 | D |
| 2 | 1.80 t lime + 30 kg P ha$^{-1}$ | 5827.57 | 5244.81 | 52448.13 | 6561 | 45748.1 | 75.17 |
| 3 | 3.60 t lime + 30 kg P ha$^{-1}$ | 7062.54 | 6356.29 | 63562.86 | 9761 | 53762.9 | 238.18 |
| 4 | 7.22 t lime + 30 kg P ha$^{-1}$ | 6544.62 | 5890.16 | 58901.58 | 16322 | 44101.6 | D |

D = dominated treatment, EB = Ethiopian birr, ha = hectare

Table 4.11: Partial budget analysis of the effects of lime and P fertilizer rates for maize production on Alisols of Omo Nada District, Oromia, Ethiopia

| Trt | Inputs | Yield (kg ha$^{-1}$) | Adjusted yield (kg ha$^{-1}$) | Gross return (EB ha$^{-1}$) | TVC (EB ha$^{-1}$) | Net benefit (EB ha$^{-1}$) | MRR (%) |
|---|---|---|---|---|---|---|---|
| 1 | Control | 1004.51 | 904.059 | 9040.59 | 0 | 9040.59 | |
| 7 | farmers' Practice (200 kg NPSB ha$^{-1}$) | 4714.22 | 4242.798 | 42427.98 | 3200 | 39227.98 | 943.35 |
| 8 | 30 kg P ha$^{-1}$ | 4551.23 | 4096.12 | 40961.07 | 3300 | 37661.07 | D |
| 5 | 2.11 t lime + 15 kg P ha$^{-1}$ | 4736.24 | 4262.616 | 42626.16 | 5891 | 36735.16 | D |
| 2 | 2.11 t lime + 30 kg P ha$^{-1}$ | 5196.5 | 4676.85 | 46768.5 | 6819 | 39949.5 | 19.94 |
| 6 | 4.22 t lime ha$^{-1}$ alone | 2375.12 | 2137.608 | 21376.08 | 7237 | 14139.08 | D |
| 3 | 4.22 t lime + 30 kg P ha$^{-1}$ | 6434.47 | 5791.023 | 57910.23 | 9437 | 48473.23 | 325.58 |
| 4 | 8.44 t lime + 30 kg P ha$^{-1}$ | 5270.59 | 4743.531 | 47435.31 | 17675 | 29760.31 | D |

D = dominated treatment, EB = Ethiopian Birr, ha = hectare

## 4.4. DISCUSSION

### *4.4.1 Initial Physicochemical Properties of the Soils*

The study showed that the initial soil physicochemical properties of all the soil types were clayey in texture. Because of this clay texture, the soils had medium to very high CEC (25.02 - 41.56 $cmol_{(+)}kg^{-1}$ and medium nutrient retention and water-holding capacity (data in Table 2.3a and 2.3b). The mean values of bulk density (BD) were near the critical BD value of (1.4 g $cm^{-3}$) and this property of the soils does not restrict the plant root growth hence not affecting the water and nutrient uptake of the plants. The reference for a rating of selected soil chemical properties is displayed in Table 4.1 in the result section.

The medium to high range of OC (1.95% -2.21%) in the soils was most likely associated with a high amount of rainfall in the area that could contribute to more plant biomass production that in turn more OM production. Even though the quantity of total N was sufficient (Table 4.1) for crop production, the maintenance application of N is required every year to sustain land productivity. According to Hazelton and Murphy, (2016), the initial soil available P content was low (< 10 mg P $kg^{-1}$ soil) for the three soil types. The reasons for low P values were the initial low soil pH (pH < 6 ) which determines the solubility and availability of soil P, the high P-fixing capacities of the soils (280, 336, 413 mg P $kg^{-1}$ for Nitisols, Luvisols, and Alisols respectively) and the presence of high levels of acid-forming cations such as exchangeable $Al^{3+}$, traditional soil management practices, inadequate or under optimal external P inputs and the like. The current result is supported by Muktamar & Lifia, (2020) who state that P becomes deficient in acid soils due to the reaction of P with Fe and Al and the formation of insoluble Fe and Al-phosphates which becomes unavailable to plant root uptake. Based on the rating of (Wogi et al., 2021), the values of available S for Nitisols (17.21 mg $kg^{-1}$) and Alisols (13.36 mg $kg^{-1}$) were in the low range.

This low availability of S was due to a strongly acidic soil reaction (low soil pH) that affects the activities of soil microbes in turn reduces the rate of decomposition of soil OM and removal of S from the soil with crop harvest and low external S inputs. This finding is in harmony with the finding of Rahman et al.,( 2021) who stated that the activities of microbes in the soil are affected by soil properties such as pH, nitrogen, and soil moisture.

The cation exchange capacity (CEC) of the soils was high (32.69 $cmol_{(+)}kg^{-1}$) , very high (41.56 $cmol_{(+)}kg^{-1}$), and medium (25.02 $cmol_{(+)}kg^{-1}$) for Nitisols, Luvisols, and Alisols respectively. The clay fractions and OM content of the soils contributed to medium to very high values of soil CEC. The result was similar to that reported by Sulieman et al., (2018) who stated that CEC was highly and significantly ($P < .001$) correlated to the soil's clay and OM content. The soils' percent base saturation (PBS) was 51% and 50% for Nitisols and Luvisols respectively which is medium value but low (28%) for Alisols. This could be due to a very strong acidic reaction (4.81 pH) of Alisols (Table 4.1). This also implies that Alisols had a higher amount of acid-forming cations ($Al^{3+}$) that saturate the cation exchange sites compared to Nitisols and Luvisols.

The Exch.Ac was highest (2.24 $cmol_{(+)}kg$) for Alisols compared to Nitisols and Luvisols with 1.19 and 1.90 $cmol_{(+)}kg^{-1}$ Exch.Ac respectively. Because of their higher value of Exch.Ac, Alisols required more quantity of lime (4.22 t $ha^{-1}$) to neutralize the acidity in the soil compared to Nitisols and Luvisols which received 2.28 t $ha^{-1}$ and 3.60 t $ha^{-1}$ of lime respectively to raise the level of soil pH to the optimum range for crop production (Table 4.2). The available boron (available B ) content of both Nitisols and Luvisols was 0.43 mg $kg^{-1}$ (in the low range) and Alisols with 0.01mg $kg^{-1}$ was in the very low range (Table 4.1) which could be attributed to the pH value of below 5.0. This finding is in harmony with the finding of Br et al., (2018) which stated that in strongly acidic soils with a pH less than 5, the available B becomes less available since it is sorbed on the surfaces of iron and aluminum oxides.

### *4.4.2. Effects of Lime and Phosphorus Rates on Selected Soil Chemical Properties*

#### *4.4.2.1. Effects of lime and phosphorus rates on soil pH-(H2O) after harvesting*

The application of the recommended rate of lime which was determined for each soil type (presented in Table 3.2) increased the level of soil pH-$H_2O$. Application of the recommended lime rate (2.28 t $ha^{-1}$, 3.60 t $ha^{-1}$, and 4.22 t $ha^{-1}$ lime to Nitisols, Luvisols, and Alisols respectively) plus critical P rate (30 kg P $ha^{-1}$) brought the soil pH into the optimum range (6.16, 6.70 and 6.23 pH for Nitisols, Luvisols, and Alisols in that order) that was suitable for maize production (Table 4.3). The increase in soil pH was due to the dissociation of applied calcium carbonate ($CaCO_3$) into $Ca^{2+}$, $HCO_3^-$ and $OH^-$. The $H^+$ and $Al^{3+}$ replaced by $Ca^{2+}$ react with $HCO_3^-$ and $OH^-$ then, $CO_2$ (g) and $H_2O$ are formed and finally, the soil acidity decreases. This result is in harmony with the findings of Antoniadis et al., (2015); Getachew et al., (2021), Getachew et al., (2017), Enesi et al., (2023) which stated that the addition of lime decreased the active acidity but increased the level of pH in the soil since values of active acidity and pH are inversely related. Similarly, Workineh et al., (2023) and Enesi et al., (2023) explained that lime application appreciably raised the level of soil pH, available phosphorus, and exchangeable bases however significantly decreased exchangeable $Al^{3+}$ contents in the soil. The application of the recommended rate of lime alone increased the pH for all soil types (Table 4.3.) which was comparable with the pH increase for the treatment that received the recommended lime rate combined with the critical P rate next to the treatment that received the twice recommended lime rate combined with the critical P rate for all soil types.

The highest pH was observed under treatment 4 received twice lime rate combined with critical P rate (30 kg P $ha^{-1}$) (6.63, 7.22, and 6.92), and the lowest (5.21, 4.82, and 4.80) was recorded under treatment with the farmers' practice (200 kg NPSB $ha^{-1}$) for Nitisols, Luvisols, and Alisols respectively. Compared to the control treatments (5.35, 4.94, and 4.81 pH), the treatments under the farmers' practice had lower pH for the three soil types. The most probable reason for this lowest pH value for the farmers' practice received inorganic fertilizers (200 kg NPSB kg $ha^{-1}$ and 92 kg N $ha^{-1}$) alone and the basic cations initially present in the soil could be removed with crop harvest. On top of that chemical fertilizers encouraged the formation of soil acidity. This suggests that the farmers' practice aggravated the problem of soil acidity compared to all the treatments used in this study (Table 4.3). This result is in harmony with the findings of (Fufa et al., 2021) which stated that the addition of NPSB blanded fertilizer reduces the soil pH compared to the control treatment that does not receive any blanded chemical fertilizer.

Luvisols treated with the twice recommended lime rate (over-limed) combined with critical P rate (Treatment 4) had the highest pH of 7.22. The value of pH for all soil types follows an increasing trend with the increasing quantity of lime applied to the soils. It was because of the neutralization of $Al^{3+}$ and $H^{+}$ by lime application and an increase in soil solution Ca and Mg content. This finding is argued with the finding of Tadesse et al., (2018) reported that the highest increase in soil pH was observed under the maximum rate (6 t lime $ha^{-1}$) of lime application to the soil.

### *4.4.2.2. Effects of lime and phosphorus rates on exchangeable Ca2+, Mg2+, and K+*

Calcium ion ($Ca^{2+}$) was the predominant cation in the soils of the study area. The increase in exchangeable $Ca^{2+}$ after the lime application was due to the supply of $Ca^{2+}$ by the liming material ($CaCO_3$) (Dang et al., 2022). According to the FAO, (2006) rating, the value of exchangeable $Ca^{2+}$ of 7.52, 6.53, and 4.82 $cmol_{(+)}kg^{-1}$ for Nitisols, Luvisols, and Alisols respectively were categorized under medium for Nitisols and Luvisols and low for Alisols. The reason for the lowest values of $Ca^{2+}$ for farmers' practice (treatment that received 200 kg NPSB $ha^{-1}$) was that lime was not applied as the external $Ca^{2+}$ source (lime) in the soils and the initial $Ca^{2+}$ might have been absorbed by the maize plant from the soil solution for its growth and development.

Based on the FAO, (2006) rating, these values of $Ca^{2+}$ for treatment 4 (13.40, 32.26, and 6.92 $cmol_{(+)}kg^{-1}$ were rated as high, very high, and medium for Nitisols, Luvisols, and Alisols respectively. As indicated in Table 4.3, under section 4.3.3.1, due to very high value of exchangeable $Ca^{2+}$ in Luvisols (32.26 $cmol_{(+)}kg^{-1}$) the soil pH was elevated beyond the optimum level (7.22) that reduces the solubility and availability of nutrient particularly, the available P and plant micronutrients. This finding is similar to the finding of Johan et al., (2021) who stated that over-liming causes P precipitation when Phosphate ions react with calcium by forming insoluble calcium phosphate which is unavailable to the plants. However, the effect of lime was not consistent on the soil exchangeable magnesium ($Mg^{2+}$), and potassium ($K^+$) across the soil types.

### *4.4.2.3. Effects of lime and Phosphorus rates exchangeable acidity (Exch.Ac)*

The highest Exch.Ac of 0.80, 2.01, and 2.80 $cmol_{(+)}kg^{-1}$ was recorded under the farmers' practice for Nitisols, Luvisols, and Alisols respectively. The reason for the high values of Exch. Ac for the farmers' practice was due to the application of inorganic fertilizers (NPSB) without the lime application having an acidifying effect on the soils (Fufa et al., 2021). Also, without lime application, the soil acidity ($H^+$) could not be neutralized. For the reasons mentioned above, the current farmers' practice (application of 200 kg P $ha^{-1}$) aggravated the problems of soil acidity even more than the control treatment. This result is in line with the findings of Goulding, (2016) who states the addition of various forms of S-containing compounds lowers the soil pH (increases the soil acidity-related problems). The lowest value of Exch. Ac (nil, 0.00) was observed under treatments 3, 4, and 6 (treatment received full and twice doses of recommended lime rate) for Nitisols, Luvisols, and Alisols. This could be attributed to the acid-neutralizing effect of the lime. Our finding is in line with the findings of Antoniadis et al., (2015) who stated that the addition of lime consumes proton ($H^+$) and reduces active acidity. Opala et al., (2018) also stated that the level of Exch. Ac was decreased due to the application of lime.

It was observed that the quantity of Exch. Ac neutralization was increased with the increasing quantity of the lime determined for each soil type (Table 4.5). The current finding is in harmony with the findings of Tadesse et al., (2018) who stated that the highest lime rate (6 t $ha^{-1}$) reduced the Exch. Ac from 0.96 to 0.19 $cmol_{(+)}kg$ compared to the application of 4 t $ha^{-1}$ lime which decreased the level of Exch. Ac from 0.96 to 0.35 $cmol_{(+)}kg$.

The highest mean value of Exch. Ac for the three soils (Nitisols, Luvisols, and Alisols) (1.85 $cmol_{(+)}kg$ soil) was recorded under the farmers' practice followed by the control treatment (1.55 $cmol_{(+)}kg^{-1}$ soil). The lowest mean value of Exch. Ac was nil (0) for Nitisols, Luvisols, and Alisols with treatments that received the recommended and twice the recommended lime rates. (Table 4.5). This finding is consistent with that of Li et al., (2018) who stated lime application is the commonly used practice that effectively neutralizes the soil acidity.

#### *4.4.2.4. Effects of lime and phosphorus rates on exchangeable Al (Exch.Al)*

The most probable reason for the reduction in the quantity of exchangeable $Al^{3+}$ from 0.70 to below 0.08 for Nitisols, 0.78 to 0.00 for Luvisols, and 1.52 to 0.00 $cmol_{(+)}kg^{-1}$ for Alisols was due to the displacement of $Al^{3+}$ by $Ca^{2+}$ from the soil colloidal surfaces and precipitation of the $Al^{3+}$ with increasing soil pH and formation of insoluble $Al(OH)_3$ by the base ($OH^-$) formed on the dissociation of the lime. This result is in agreement with the previous work of Matiyas et al., (2023) who stated that the addition of lime decreased the soil acidity, particularly as the exchangeable $Al^{3+}$ precipitated into $Al(OH)_{3(Solid)}$ and decreased to a nil level.

The reason for the highest mean value of Exch. $Al^{3+}$ for farmers' practice (1.05 $cmol_{(+)}kg^{-1}$ soil) and control treatments of 0.80 $cmol_{(+)}kg^{-1}$ soil (Table 4.5) was the low mean soil pH of 4.94 and 5.03 (Table 4.3) that increased the dissociation and availability of the exchangeable $Al^{3+}$ in the soil solution. In harmony with this finding, Tadesse et al., (2018) reported that the application of 4 t $ha^{-1}$ of lime increased the soil pH from 5.07 to 5.64 and decreased the exchangeable Al from 0.37 to 0.0 $cmol_{(+)}$ $kg^{-1}$. This is because lime is an alkaline material that can neutralize soil acidity and increase soil pH. When soil pH increases, the solubility of phosphorus in the soil also increases making it more available for plants to absorb

#### *4.4.2.5. Effects of lime and phosphorus application on available phosphorus*

The reason for the lowest available p under control treatment for all soil types was no external P inputs (TSP and NPSB) to compensate for the P taken up from the soil by the crop plant. Also, the low pH (< 5.5 pH) favored the solubility and availability of a high quantity of Fe and Al. These cations react with phosphate ions and form insoluble iron and Al-phosphate i.e. the phosphate fixation problem that resulted in the low solubility and availability of phosphate at lower soil pH. A similar result by Muktamar & Lifia, (2020) indicated that the formation of insoluble Al and Fe-phosphate compounds at low soil pH resulted in phosphorus deficiency in the soil.

The maximum value of available P was recorded under the recommended lime plus critical P for all the soil types. The quantity of available P in the soil increased with the increasing soil pH up to pH 7 but declined above 7 soil pH (Table 4.6), implying that maximum P availability in the soil is in the pH range of 6-7 and above this pH range, $Ca^{2+}$ may become more available and react with phosphate ions and forms insoluble Ca-phosphate. This result is in harmony with the findings of Moreira et al., (2017) who stated that over-liming could cause the insufficiency of available P and soil micronutrients such as Fe, Mn, Cu, and Zn.

After the addition of recommended lime rate plus 30 kg P $ha^{-1}$ (treatment 3) on Nitisols, luvisols, and Alisols, the highest available P was recorded under Alisols since it adsorbed the highest quantity of P (413 mg P $kg^{-1}$ soil) compared to Nitisols and Luvisols that adsorbed 280 and 336 mg P $kg^{-1}$ soil respectively (under Chapter 3, section 3.3.3, in Table 3.2). Because of its highest P retention property, Alisols released more P from its initial highest P reserve after lime application.

The most probable reason for the decreased available P value with doubling the recommended lime rate (treatment 4) compared to 100% recommended lime rate (treatement 3) (Table 4.6 ) was that in the former, the soil pH raised above pH 7 and more $Ca^{2+}$ react with phosphate ions and forms a precipitate of Ca-P and P become less available due to lime-induced P deficiency. A similar result was reported by Erkihun et al., (2022) who stated that the available P is fixed by $Ca^{2+}$ at a higher pH when the excess quantity of lime is added. Likewise, Johan et al., (2021) reported a similar result stating that the precipitation of phosphate takes place when it reacts with the $Ca^{2+}$ at a higher pH and is caused by the application of an excess quantity of lime and makes the P unavailable to the plants.

Hazelton and Murphy, (2016) rated the soil available P as < 5, 5-9, 10-17, 18-25, and > 25 mg P $kg^{-1}$ soil as very low, low, medium, high, and very high respectively. Based on this rating, the application of 100% optimum lime rate (treatment 3), increased the available P content to a medium level of 12.36 and 15.10 mg P $kg^{-1}$ soil for Nitisols and Luvisols respectively while high (24.01 mg P $kg^{-1}$ soil) for Alisols. It was observed that 200 kg $ha^{-1}$ NPSB application alone (under farmers' practice) sufficiently increased the available P content of the soils from the low level into the medium-high P levels.

The increase in the available P values after the lime application was due to the initial high fixed P content of the soils. The applied lime ($CaCO_3$) was dissolved in the soil solution and the $Ca^{2+}$ and $OH^-$ were produced. The $Ca^{2+}$ ion displaces the $H^+$ ion on the soil colloidal surfaces and then, the $H^+$ consumed by $OH^-$ and $H_2O$ was produced. Because of this, the soil pH was increased after lime addition. A similar finding was reported by Kisinyo et al., (2013) as the increase in the soil available P was most likely due to the decrease in phosphorus sorption by $Al^{3+}$ and $Fe^{3+}$ ions when the soil pH increased after lime application.

The highest combined mean value of available P (26.20 mg $kg^{-1}$ ava. P) for the three soils was recorded under treatment 3 and followed by treatment 4 (22.50 mg P $kg^{-1}$) but the lowest combined mean available P values of 4.79 mg $kg^{-1}$ was obtained under the control treatment followed by the treatment 6 that received the recommended lime alone (12.14 mg P $kg^{-1}$) (Table 4.6). Therefore, except for the control treatment, the application of a full or half-recommended dose of lime in combination with the critical P rate or recommended lime alone increased the Olsen available P above the critical soil P level (10 mg P $kg^{-1}$). Particularly, the half dose of the recommended lime in combination with the critical P rate (treatment 2) can satisfy the P requirement of the crop when the farmers are unable to afford the full recommended lime rate.

#### *4.4.2.6. Effects of lime and phosphorus rates on available Sulfur*

The lowest value of available sulfur (S) (13.61 mg S kg$^{-1}$) content in treatment 3 was due to an increased soil pH to the optimum range (6-7) that increased the microbial population and activities that encouraged more OM decomposition, more nutrient solubility and availability hence the available S was more utilized and get depleted in the soil. According to Wogi et al. (2021), the available S content of <10, 10-20, 20-35, 35-45, and > 45 mg S kg$^{-1}$ soil were rated as very low, low, medium, high, and very high respectively. Based on his ratting, the S content of the soil in the study area was insufficient for optimum maize production without external S application in the form of fertilizers.

### *4.4.3. Effect of Lime and Phosphorus Rates on Maize Yield Parameters.*

#### *4.4.3.1. Effect of lime and phosphorus rates on straw yield and above-ground biomass yields*

As stated in the result section, treatments 3 and 8 showed a straw yield increment of 61.07% and 60.51% respectively over the control treatment for Luvisols. The reason for the lowest values of SYLD on the control plot might be due to nutrient depletion and reduction in soil fertility attributed to continuous crop production with little or no external nutrient inputs. In line with this result, Liu et al., (2020) stated acidic soil conditions substantially reduced the plant's root and aboveground biomass production. Similarly, Birtukan et al., (2021) reported that the lowest straw yield of 9333 kg ha$^{-1}$ was obtained from the control treatment. The reason for the highest SYLD for treatments 3 and 8 was due to an overall increase of the above-ground vegetative part of maize due to the addition of the optimum lime rates and NP fertilizers (that correct the soil acidity) that create the optimum pH range for the sufficient nutrient availability and reduced many of the adverse effects related to soil acidity problems.

Compared to the total above-ground biomass produced on the control treatment, treatment 3 produced 53.4%, 67.7%, and 40.8% higher biomass yield under Nitisols, Luvisols, and Alisols respectively. The reason for the highest biomass yields of maize production with treatment 3 under all soil types might be due to the multiple benefits of lime and a balanced supply of plant nutrients (N and P).

The integrated application of optimum lime rate with N and P maximized the maize BYLD due to the decline in soil acidity and Al toxicity, and the increase in the soil available P and other plant nutrients including the basic cations. Additionally, maximum BYLD production under optimum lime application was due to improved root development and N uptake through increased microbial activities. This result is in agreement with the findings of Anderson et al., (2018) who stated that when soil pH increased from 4.7 to 6.7, there was an increase in the soil microbial communities hence, increased decomposition in soil organic matter. A similar finding was also reported by Birtukan et al., (2021) as the highest biomass yield of 11,500 kg ha$^{-1}$ was obtained from plots treated with lime, compost, and NPSB and N fertilizer, while the lowest (3,433 kg ha$^{-1}$) from the control treatment.

#### *4.4.3.2. Effect of lime and phosphorus rates on grain yield (GYLD) and harvest index*

The application of the recommended lime and critical P rates increased the grain yields of maize by 89.9%, 81.5 %, and 84.4% over the control treatments and by 28.3%, 26.5%, and 26.7% over the farmers' practice for Nitisols, Luvisols, and Alisols respectively. This grain yield increment over the control treatments could be due to the decline in soil acidity, Al toxicity, and increase in the soil available P and other essential plant nutrients. The lime application increases the soil pH and could stimulate the activities of myriad beneficial microbes hasten the OM decomposition, and N-fixation, and improves soil structure. This result is supported by Junior et al. (2020); and Mahmud et al. (2022) who report liming improves some soil physical attributes including flocculation, aggregate stability, porosity, and bulk density. The above grain yield increments were because in cereal crops P is essential for root development, vegetative growth, seed formation, and faster grain maturity.

It was also indicated in Table 4.8 that the maize grain yield obtained from the treatment received recommended lime plus P fertilizer was superior compared to the yield obtained from the separate application of lime or chemical fertilizer alone. The current finding agreed with the works of Oloo, (2016) and Peter et al., (2018) stated that the addition of both lime and P fertilizer in combination gave a higher maize grain yield compared to lime or P fertilizer alone.

The application of the recommended rate of lime alone (without mineral P fertilizer) also resulted in the grain yield increase of 67.67%, 51.8%, and 57.70% over the control treatment for Nitisols, Luvisols, and Alisols respectly (Table 4.8). This could be because of the reduction of Al toxicity, decreased P fixation, and increased Ca and P availability due to the application of lime, which led to better grain yield compared to the unlimed plots (Appendix Figure K). Similarely, Enesi et al., (2023) stated, that liming positively increased crop yields.

Compared to the treatment that received the recommended lime rate alone (treatment 6) the treatment that received 200 kg NPSB ha$^{-1}$ (farmer's practice) showed yield increments of 56.32%, 47.69%, and 49.61% for Nitisols, Luvisols, and Alisols respectively (Table 4.8). The most probable reason for this could be the application of lime alone might not satisfy the nutrient demand of the crop unless the initial nutrient content of the soil was high enough. The result showed that the application of inorganic fertilizer alone is better for producing maximum crop yield compared to applying lime alone (without inorganic fertilizer application) to fulfill the immediate nutrient demand of the crop if the environmental issue is not a serious problem. A similar result was reported by Antoniadis et al., (2015) who stated the application of P alone is more important for better crop development than the application of lime alone in acidic soils with initial low P content.

On the other hand, the application of twice the recommended lime rate plus the critical P rate (treatment 4) did not result in the highest maize grain yield compared to the treatment that received a recommended rate of lime in combination with the critical P rate (treatment 3). Doubling the lime rate resulted in a pH increase above the optimum range for nutrient availability, causing an over-liming-induced P deficiency and deficiency of micronutrients. In agreement with the results of this study, Getachew et al., (2017) reported that adding more lime and P fertilizers above the recommended rate is not beneficial for barley grain production. In general, the treatments increased the grain yield of maize in the following sequence of control → 100% RL rate alone → 50% RL + 50% critical P → farmers practice (200 kg NPSB $ha^{-1}$) → 100% critical P rate (30 kg P $ha^{-1}$) → 50% RL + 100% critical P → twice of the RL + 100% critical P → 100% RL + 100% critical P.

Compared to the control treatment, the increased percentage of harvest index for lime-treated plots might be due to greater photo assimilates production and its ultimate partitioning to the portion of the seeds compared to the partition to the straw part. The current study is similar to the findings of Alemayehu & Tamado, (2021) who stated, that Bradyrhizobium strain inoculation results in an enhanced harvest index, which also suggests more dry matter partitioning into the grain.

### *4.4.4. Economic Analysis*

The partial budget analysis of lime and P showed that treatment 4, with the twice lime rate plus 30 kg P $ha^{-1}$, treatment 5 with 50% RL rate plus 15 kg P $ha^{-1}$, treatment 6 with RL rate alone and treatment 8 received 30 kg P $ha^{-1}$ for Nitisols, Luvisols, and Alisols were coast dominated since their net benefit was lower than that of the preceded treatments. For this reason, the treatments were excluded from the analysis of the marginal rate of return (MRR). The MRR analysis revealed that treatment 3 which received a recommended rate of lime combined with critical P rate (30 kg P $ha^{-1}$) gave the highest MRR of 285%, 238%, and 326% for Nitisols, Luvisols, and Alisols respectively. It indicates that with treatment 3, for an investment of 1 birr per hectare, there is a return of 1 birr plus 2.85 birr ha$^{-1}$ for Nitisols, 1 birr plus 2.38 birr ha$^{-1}$ for Luvisols, and 1 birr plus 3.26 birr ha$^{-1}$ for Alisols in the net benefit that is economically the most advantageous compared to other treatment combinations.

The treatment received 200 kg NPSB ha$^{-1}$ (farmers' Practice) had the highest MRR but, since the issue of soil acidity was a high concern in the current study, the recommendation was not based on this treatment. Treatment 2 with 50% RL rate plus 30 kg P ha$^{-1}$ for Luvisols and Alisols had the MRR of less than 100% (75.17%, and 19.94%) which showed that these are not economically optimum for maize production. The current recommendation is also supported by previous studies conducted by Birtukan et al., (2021) and Workineh et al., (2023) who suggested that the maximum wheat grain yield was obtained from the combined use of lime and recommended rate of inorganic fertilizers.

## 4.5 CONCLUSIONS AND RECOMMENDATIONS

In most previous studies, an equal rate of agricultural lime was recommended for different soils without considering variation among soil types. However, in this particular study, different rates of lime were determined for different soil types. Therefore, the combined application of recommended lime and optimum P rates significantly affected some of the soil's chemical properties and the maize yield parameters on Nitisols, Luvisols, and Alisols of the study area. The recommended lime rates (2.28, 3.60, and 4.20 t $ha^{-1}$ of lime for Nitisols, Luvisols, and Alisols respectively) combined with 30 kg P $ha^{-1}$ gave the highest maize grain yield as well as the highest profit from a unit investment that could be recommended for optimum maize production for the study area.

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# CHAPTER 5: WHEAT RESPONSE TO PHOSPHORUS APPLICATION RATES AND FERTILIZER RECOMMENDATION ON ANDOSOLES IN THE SOUTHWESTERN ETHIOPIAN HIGHLANDS

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## ABSTRACT

*Andosols are the dominant soil type (covers about 13, 000 hectares) in the Omo Nada district and are among the potential soils for crop production. The high P-fixing property of this soil makes the amount of available P below the crop demand. Therefore, wheat production in Andosols of the study district is highly constrained by the low availability of p and there is a need to determine and supply an optimum input of P fertilizer for proper crop production. The response of wheat to phosphorus fertilization trial was carried out on Andosols at three locations in the Omo Nada district of Oromia, in the Southwestern Ethiopian highlands during the main growing seasons of 2017/18-2018/19. There were seven treatments, containing six rates of phosphorus fertilizer (0, 10, 20, 30,40, and 50 kg P ha*$^{-1}$*) and a farmer's practice as a positive control (18-36-7-0.71 N-*$P_2O_5$*-S-B kg ha*$^{-1}$*), laid down in a randomized complete block design with three replications. The yield variation among treatments without P and P treatments indicates that 85% of the area showed a yield increase due to P application. The application of external P inputs improved the wheat yield by 39% compared to the treatments without external P inputs. The critical P level for 85% relative yields was 14.30 mg kg*$^{-1}$*. All the soil samples analyzed had Olsen P values of <10 mg kg*$^{-1}$*. The use of 40 kg P ha*$^{-1}$* which produced the maximum wheat grain yield of all treatments can be recommended. The current study determines the critical P values (PC) and the optimum rate of P-fertilizer for wheat production is helpful for wheat producers and policymakers and produces an optimum grain yield of wheat on Andosols.*

Keywords: Andosols, phosphorus, phosphorus fixation, Wheat.

## 5.1. INTRODUCTION

In Africa, Ethiopia is the second-largest wheat-producing country next to South Africa, and 59% and 28% of the country's wheat is produced in the Oromia and Amhara regions, respectively. Additionally, 10% of the wheat grain was produced in the Southern Nations, Nationalities, and Peoples Region (SNNPR) and 3% was in the other regions (Abu., 2013). About 1.79 million ha of land was under wheat production but grain yield was 2.76 tons $ha^{-1}$ (Abu, 2013, CSA, 2021).

In comparison to the worldwide standard cereals yield of 3.97 t $ha^{-1}$, in Ethiopia, there is a lower average grain yield of wheat (2.7 t $ha^{-1}$) Abebaw, (2018) which is attributed to a decrease in the nutrient content of the soils and conventional way of crop productions. Van Beek et al., (2016) also stated that soil nutrient depletion is the major reason behind low agricultural crop production in Ethiopia. Insufficient application of chemical fertilizers, particularly NPK and some plant micronutrients is the major constraint contributing to yield decline. The nutritional balance in sub-Saharan Africa is negative and the nutritional loss is even greater, especially in Ethiopia, with a rapid soil nutrient decrease of 33, 14, and 41 % for N, P, and K, respectively each year (Van Beek et al., 2016). A similar study indicated mineral nutrient imbalance and insufficient soil moisture are among the factors frequently limiting crop yields (Zingore et al., 2015).

Phosphorus (P) is a crucial nutrient for plant growth and agricultural production depends on a non-renewable resource (finite rock phosphate) ( Li, B. et al., 2016). The intensive use of rock phosphate for crop production and industrial raw materials creates pressure on the world P market (Khabarov & Obersteiner, 2017). To ensure the sustainability of this finite resource, an application of P fertilizers to the soil must be carried out in ways that satisfy the most effective possible use of Olsen soil-P and P applied as fertilizer by the crop.

In different parts of the world, different rates of P fertilizer have been used for wheat production. Excluding Africa, all continents have increased the soil P concentration at heavy to excess levels. Africa, the only continent that has used low P fertilizer even has a negative P balance Sattari et al., (2016); this low P utilization lowers crop yield in Africa compared to the other continents (Tadele, 2017). Most Ethiopian soils are less responsive to P supply at lower application rates (Birhan et al., (2017); Meille et al., (2012) stated that the correct dosage of phosphorus (P) fertilizer can be applied to the soil in three consecutive steps: the first is the determination of the level of available P in the soil then, the soil P fertility level can be calibrated and finally, the recommended rate of P fertilizer can be determined. Accordingly, soil testing is the primary step of P fertilizer recommendation. Next to the fertilizer recommendation, the soil P analysis results are ratted with the wheat yield response.

Soil test calibration is the process of relating soil test values to crop yield responses or relative yields (treatment that produces an optimal level of the yield of all nutrients other than P, divided by the highest yield produced on the field experiment at the same season with the optimal level of total plant nutrients in addition to P that helps for a different level of comparisons. Meille et al., (2012) stated Andosols in the highlands of Ethiopia are slightly to extremely inadequate in their phosphorus content which is the major limitation of wheat production. The soil solution phosphorus level is determined by the retention of phosphorus with aluminum and iron oxides and hydroxides in the Andisols (Redel et al., 2016).

For a long period, the blanket fertilizer recommendation has been practiced in Ethiopia and the growers have been using a similar rate of phosphorus fertilizer for crop production without considering the fertility status of their soils (Getachew et al., 2015). However, the addition of an optimum phosphorus fertilizer dose can be calculated depending on soil laboratory analysis and yield responses. Soil-test calibration studies with specific soil–crop type combinations are crucial to making site- and crop-specific fertilizer recommendations (Dejene et al., 2020) Still, such studies are uncommon, for the most agriculturally potential areas of Ethiopia like the Omo Nada District. There is no adequate information on the agronomic critical value of soil Olsen-P for wheat grown in volcanic soils (Andosols) of the Southwestern highlands of Ethiopia, where wheat is widely produced. The calculation of the optimal phosphorus fertilizer application rate is essential for better management of the soil Olsen phosphorus and phosphorus fertilizer use efficiency. Therefore, the objectives of this study were to 1) Calculate the critical level of soil phosphorus and recommend agronomic optimum phosphorus fertilizer rates for wheat production, and 2) Evaluate wheat yield response to phosphorus fertilization on Andosols of the southwestern highlands of Ethiopia.

## 5.2. MATERIALS AND METHODS

### *5.2.1. Soil Sampling, Sample Preparation, and Analysis*

(Described under sections 1.4.2.1 and 1.4.2.2)

### *5.2.2. Experimental Procedures*

The field trial was laid down in a randomized complete block design and repeated three times. The treatments, consisting of six phosphorus levels (0, 10, 20, 30, 40, and 50 kg P ha$^{-1}$), were applied in the form of triple superphosphate (TSP) and 18-36-7-0.71 N-$P_2O_5$-S-B ha$^{-1}$ (as local farmers practice). The plot size was 3 m by 4 m (12 m$^2$), and the spacing between blocks and plots was 1 m and 0.5 m, respectively. The inter-row spacing was 30 cm. Improved wheat (Senate variety) was drilled in the row at the seeding rate of 100 kg ha$^{-1}$ on 15–20 July 2017 and 16–21 July 2018.

The total dose of P fertilizer was added during sowing time. The recommended nitrogen fertilizer dosage of 46 kg N ha$^{-1}$ was uniformly applied as urea to every plot in 2 split applications, 50% at sowing and the remaining 50% at 25 to 30 days after sowing (at the tillering stage). To control broad-leaved weeds, 2, 4-D weed killer was applied one month after wheat emergence accompanied by one-hand weeding. Recommended agronomical activities for wheat production were followed during the field experiment starting from seedbed preparation to harvesting. The treatments on the experimental plots were evaluated based on the farmer's criteria (crop stand *i.e.* vigorous or weak, resistance to lodging, disease resistance, plant height, days to maturity, spike length, crop yield, *etc*). Harvesting was done in December each year.

### *5.2.3. Agronomic Data Collection and Analysis*

The agronomic data gathered were plant height (average of 10 plants), number of effective tillers, spike length, aboveground total biomass, and grain yield. Eight central rows from 9.6 m$^2$ were harvested at maturity from each plot to estimate the above-ground total biomass and grain yields. The whole materials were sun-dried threshed, and wheat grains were cleaned and weighed. The grain weight was adjusted to 12% moisture content. The above-ground total biomass and grain yield data collected from each plot were changed to kg ha$^{-1}$ for statistical analysis (Shengu, 2017; Tandzi & Mutengwa, 2020).

### *5.2.4. Determination of Critical P Concentration (Pc)*

To correlate the relative yield with the phosphorus content in the soil test and determine the critical level of phosphorus, the Olsen method was used to extract available phosphorus from soil samples collected 21 days after sowing for every plot in the whole field trial. The Cate-Nelson graphical method cited in Getachew et al., (2015) was followed to calculate the critical P-value based on soil analysis P values and relative yields. Percent of relative grain yields were obtained from the relationship between wheat yield response to P doses and soil analysis phosphorus values based on the following formula:

$$\text{Relative Yield } (\%) = \frac{Yield\ of\ Trt.\ with\ all\ nutrient\ but\ P}{Yield\ of\ Trt.\ with\ all\ nutrients}\, x\ 100 \quad \ldots\ldots\ldots\ldots\ldots.. (5.1)$$

The relative yield (Y-axis) is plotted against the soil test P value (X-axis) on the scatter diagram. The value on the Y-axis ranged between 0 to 100%. The data was divided into four quadrants by the two intersecting perpendicular lines that were drawn parallel to the Y and X-axis. The line parallel to the Y-axis shows the responsive and non-responsive regions. The points in quadrant 2 overestimate the phosphorus fertilizer demand, while the points in quadrant 4 underestimate the phosphorus fertilizer demand. The crossing lines move horizontally and vertically along the graph, and the 2 lines are always parallel to the X-axis and Y-axis of the graph. The spot at which the vertical line intersects the X-axis has been determined as the best critical soil test value (Girma & Obsa, 2020).

### *5.2.5. Determination of Phosphorus Requirement Factor (Pf)*

The phosphorus requirement factor (Pf) is the amount of P needed in kg per hectare to increase the soil P by 1 mg $kg^{-1}$ and to calculate the value of P fertilizer needed per hectare to get the amount of available P to the critical level. It was computed from available P values in soil samples taken from plots without P addition (control) and with P addition three weeks after planting wheat. Then, the P requirement factor was determined based on the available P values found in the soil test of the soil samples that received various doses of P fertilizer. The phosphorus requirement factor was calculated as;

$$\mathrm{Pf} = \frac{Kg\ P\ applied}{\triangle in\ soil\ P} \ \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \ (5.2)$$

Also, the amount of P fertilizer to be applied (Pa) per hectare was calculated from critical P concentration (Pc), initial soil P-value (Pi), and P requirement factor (Pf) using the following formula:

The amount of P fertilizer to be applied kg/ha (Pa) = (Pc - Pi) x Pf …………. (5.3)

## 5.3. RESULTS

### *5.3.1. Initial Soil Characteristics*

As presented in Table 5.1, the mean values of soil properties before planting revealed that the particle size distribution of the surface soils was in the range of clay loam (CL) to clay (C). The bulk density ranged between 0.92 - 0.98 mg cm$^{-3}$. The mean soil pH ($H_2O$) value was 6.30. The mean soil organic carbon (OC) content was 4.37%. The total nitrogen (TN) content was 0.29% (Table 5.1). The mean available P content was 6.87 mg kg$^{-1}$. The mean exchangeable Ca and Mg were 13.95 cmol$_{(+)}$ kg$^{-1}$ and 3.13 cmol$_{(+)}$kg$^{-1}$ respectively and the mean K content was 1.67 cmol$_{(+)}$kg$^{-1}$. The mean exchangeable Na content was 0.17 cmol$_{(+)}$kg$^{-1}$. The mean cation exchangeable capacity (CEC) of the soils was 35.15 cmol$_{(+)}$kg$^{-1}$. The mean percent base saturation (PBS) was 53.80%. The mean exchangeable hydrogen ($H^+$) of the soils in the study area was 0.11 cmol$_{(+)}$kg$^{-1}$, while the exchangeable Al was 0.13 cmol$_{(+)}$kg$^{-1}$. The value of total exchangeable acidity was 0.24 cmol$_{(+)}$kg$^{-1}$. The mean available Fe, Mn, Cu, and Zn were 234.45, 199.88, 1.05, and 7.99 mg kg$^{-1}$ respectively (Table 5.1).

Table 5.1: Soil properties (0–30 cm depth) of the experimental sites at Omo Nada district, Ethiopia, in 2017 before planting the phosphorus trials.

| Soil properties | Sites | | | |
|---|---|---|---|---|
| | CD1(Ajaliye A.) | CD2(Kadir A.) | CD3(Abadiga A.) | Mean |
| Sand (%) | 43 | 40 | 44 | 44 |
| Silt (%) | 23 | 22 | 15 | 20 |
| Clay (%) | 34 | 38 | 41 | 36 |
| Textural class | CL | CL | C | --- |
| Bulk density (g $cm^{-3}$) | 0.99 | 1.04 | 1.09 | 1.04 |
| pH ($_{H2O}$) 1:2.5 soil: $H_2O$ | 6.20 | 6.26 | 6.44 | 6.30 |
| Organic C (%) | 3.78 | 5.16 | 4.16 | 4.37 |
| Total N (%) | 0.29 | 0.35 | 0.31 | 0.32 |
| Ava. P ($mg_{(+)}kg^{-1}$) | 7.78 | 6.84 | 6.0 | 6.87 |
| Exch.Ca ($cmol_{(+)}kg^{-1}$) | 15.93 | 11.44 | 14.49 | 13.95 |
| Exch. Mg ($cmol_{(+)}kg^{-1}$) | 3.07 | 3.10 | 3.22 | 3.13 |
| Exch. K ($cmol_{(+)}kg^{-1}$) | 1.37 | 1.58 | 2.06 | 1.67 |
| Exch. Na ($cmol_{(+)}kg^{-1}$) | 0.21 | 0.18 | 0.11 | 0.17 |
| Exch Al ($cmol_{(+)}kg^{-1}$) | -- | 0.30 | -- | 0.10 |
| Exch. Ac. ($cmol_{(+)}kg^{-1}$) | 0.17 | 0.47 | 0.09 | 0.24 |
| CEC ($cmol_{(+)}kg^{-1}$) | 37.84 | 33.97 | 33.63 | 35.15 |
| PBS | 54.83 | 49.76 | 56.81 | 53.80 |
| Ava. Fe (mg $kg^{-1}$) | 261.40 | 237.85 | 204.11 | 234.45 |
| Ava. Mn (mg $kg^{-1}$) | 244.13 | 189.52 | 165.99 | 199.88 |
| Ava. Cu (mg $kg^{-1}$) | 1.12 | 0.87 | 1.15 | 1.05 |
| Ava. Zn (mg $kg^{-1}$) | 9.92 | 5.46 | 8.58 | 7.99 |

Note: C = clay; CL= clay loam; CD1= Cheleleka Donga site 1; CD2 = Cheleleka Donga site 2 and CD3 = Chealeleka Donga site 3, ECEC = effective cation exchangeable capacity, Ava = available, Exch, = exchangeable.

### *5.3.2. Yield and Yield Components*

The two-year combined analysis of variance showed that wheat yield and yield components to a larger extent depend on the main effect of the year and the use of phosphate fertilizer (Table 5.2). Due to the interaction between the year and the applied phosphorus fertilizer, plant height is the only parameter that differs significantly ($P \leq 0.01$). The wheat grain yield and yield component in 2018/19 were higher than in 2017/18 (Table 5.3). The maximum total crop biomass, number of productive tillers, and spike length were recorded in 2018 under treatments that received 40 kg P ha$^{-1}$ while the maximum plant height was obtained in 2017/18 (Tables 5.2). Grain yield and yield components varied significantly ($P \leq 0.001$) between years and the addition of P fertilizer. The maximum mean grain yield of 5789 kg ha$^{-1}$ was recorded at a P level of 40 kg ha$^{-1}$ in 2018/19, while the minimum grain yield of 3318 kg ha$^{-1}$ was recorded at the control treatment in 2017/18 (data not shown).

The addition of P fertilizer at the levels of 0, 10, 20, 30, 40, and 50 kg P ha$^{-1}$ resulted in a significant linear response with mean grain yield increments of 8.5, 17.4, 19, 28, and 23.7%, respectively, compared to the control treatment without application of P fertilizer which received only 46 kg N ha$^{-1}$. The farmers' practice treatment (18-36-7-0.71 N-$P_2O_5$-S-B kg ha$^{-1}$) was the recommended P level for wheat production in the study area and gave an 11.2% grain yield advantage over the control treatment.

The maximum biomass yield of 8578 kg ha$^{-1}$ was obtained from the addition of 40 kg P ha$^{-1}$ while the lowest biomass yield of 7134 kg ha$^{-1}$ was obtained from the treatment without P application (0 P level). Grain yield, total biomass, plant height, number of productive tillers, and spike length consistently increased with increasing P levels up to 40 kg ha$^{-1}$ but declined with further addition of P rate beyond 40 kg ha$^{-1}$ (Table 5.3). Taller plants and earlier headings were observed in plots that received different rates of P-fertilizer than the control plots without P-fertilizer (Table 5.1).

Table 5.2: means for main effects of year and P fertilizer rate on wheat grain yield and yield components in Omo Nada district.

| Factor | Grain yield (kg ha$^{-1}$) | Total biomass (kg ha$^{-1}$) | Plant height (cm) | Number of productive tillers (NPT) | Spike length (SpL) (cm) |
|---|---|---|---|---|---|
| Year | | | | | |
| 2017/18 | 3936$^{b}$ | 6016$^{b}$ | 95.30$^{a}$ | 4.70$^{b}$ | 5.60$^{b}$ |
| 2018/19 | 4938$^{a}$ | 9312$^{a}$ | 93.10$^{b}$ | 5.10$^{a}$ | 7.20$^{a}$ |
| Significance level | *** | *** | *** | *** | *** |
| LSD $_{0.05}$ | 385 | 409 | 0.92 | 0.13 | 0.09 |
| Phosphorus rate (kg ha$^{-1}$) | | | | | |
| 0 | 3714$^{d}$ | 7134$^{c}$ | 90.89$^{e}$ | 4.60$^{d}$ | 6.60$^{b}$ |
| 10 | 4059$^{cd}$ | 7277$^{bc}$ | 90.61$^{e}$ | 4.60$^{d}$ | 6.70$^{b}$ |
| 20 | 4497$^{bc}$ | 7274$^{bc}$ | 94.17$^{cd}$ | 4.60$^{d}$ | 6.80$^{ab}$ |
| 30 | 4584$^{bc}$ | 7662$^{bc}$ | 95.78$^{bc}$ | 5.10$^{bc}$ | 7.00$^{ab}$ |
| 40 | 5157 $^{a}$ | 8578$^{a}$ | 98.27$^{a}$ | 5.40$^{a}$ | 7.30$^{a}$ |
| 50 | 4868$^{ab}$ | 8163$^{ab}$ | 97$^{ab}$ | 5.20$^{ab}$ | 7.20$^{a}$ |
| 100 kg NPSB$^{@}$ | 4181$^{bcd}$ | 7461$^{bc}$ | 93$^{de}$ | 4.80$^{cd}$ | 6.70$^{b}$ |
| Significance level | *** | *** | *** | *** | *** |
| Phosphorus (P) level | *** | *** | *** | *** | *** |
| Year × P | Ns | Ns | * | Ns | Ns |
| LSD $_{0.05}$ | 728.20 | 1021 | 2.40 | 0.40 | 0.50 |
| CV (%) | 24.70 | 20.10 | 3.90 | 11.40 | 10.90 |

Note: *, **, and *** shows a significancy levels at $P \leq .05$, $P \leq .01$, and $P \leq .001$respectivelly; ns, not significant; LSD, least significant difference, $^{@;}$ Farmers practice.

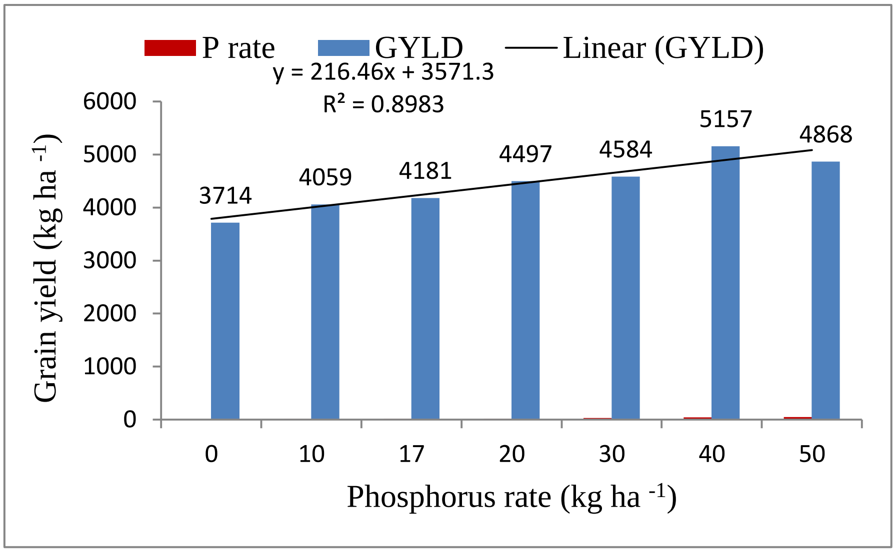

Figure 5.1: Relationship between P fertilizer application rate and wheat grain yield on Andosols at Chelelelka Donga of Omo Nada district of Jimma Zone

### *5.3.3. Critical Soil Phosphorus Concentration and Phosphorus Fertilizer Requirement*

The soil P-value measured 21 days after sowing varied significantly ($P < .01$) between the P fertilizer rates. Average soil P values of 6 to 18.74 mg kg$^{-1}$ were obtained from the application of different phosphorus doses. The initial P-value in the Olsen soil test was less than 10 mg kg$^{-1}$, which was within the low range. The response of soil phosphorus to phosphorus application increased linearly, up to 50 kg P ha$^{-1}$. The maximum average phosphorus content in the soil (15.45 mg kg$^{-1}$) was obtained from 50 kg P ha$^{-1}$ (Figure 5.2).

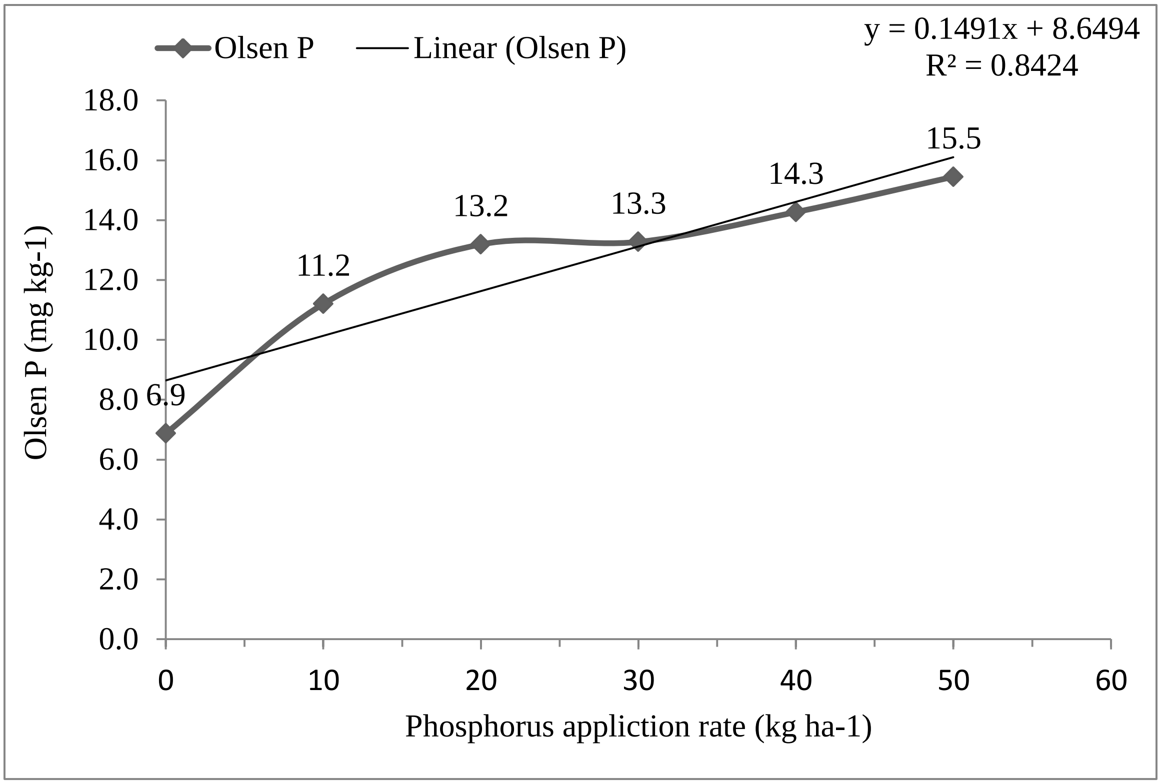

Figure 5.2: Relationship between soil phosphorus concentration, analyzed 3 weeks after planting, and P fertilizer application rate in Omo Nada district.

The relationships among relative yield responses of wheat and Olsen soil P are shown in Figure 5.3. The P critical level (Pc) was obtained by using a scatter plot constructed from the relative wheat grain yields and the soil test P values for all P levels (0 to 50 kg P ha$^{-1}$). The Pc indicated by the Cate Nelson procedure cited in Getachew et al., (2015) for this particular work was about 14.30 mg P kg$^{-1}$, with an average relative yield response of 85% (Figure 5.3).

Compared to the critical P-value, when the amount of P in the soil lab analysis result is lower, there is a need to determine the quantity of P applied in the form of fertilizer to bring the soil P to the desired quantity (Pc). This is the P requirement factor (Pf), that is, the quantity of P needed to raise the soil P test value by 1 mg kg$^{-1}$, calculated based on the variation among the soil test available P levels from plots received 0 to 50 kg P ha$^{-1}$

based on the second formula indicated above. Therefore, the computed Pf was in the range of 2.32 to 5.83 mg P kg$^{-1}$, and the mean total Pf of all treatments in the experimental site was 4.30 mg P kg$^{-1}$ (Table 5.3).

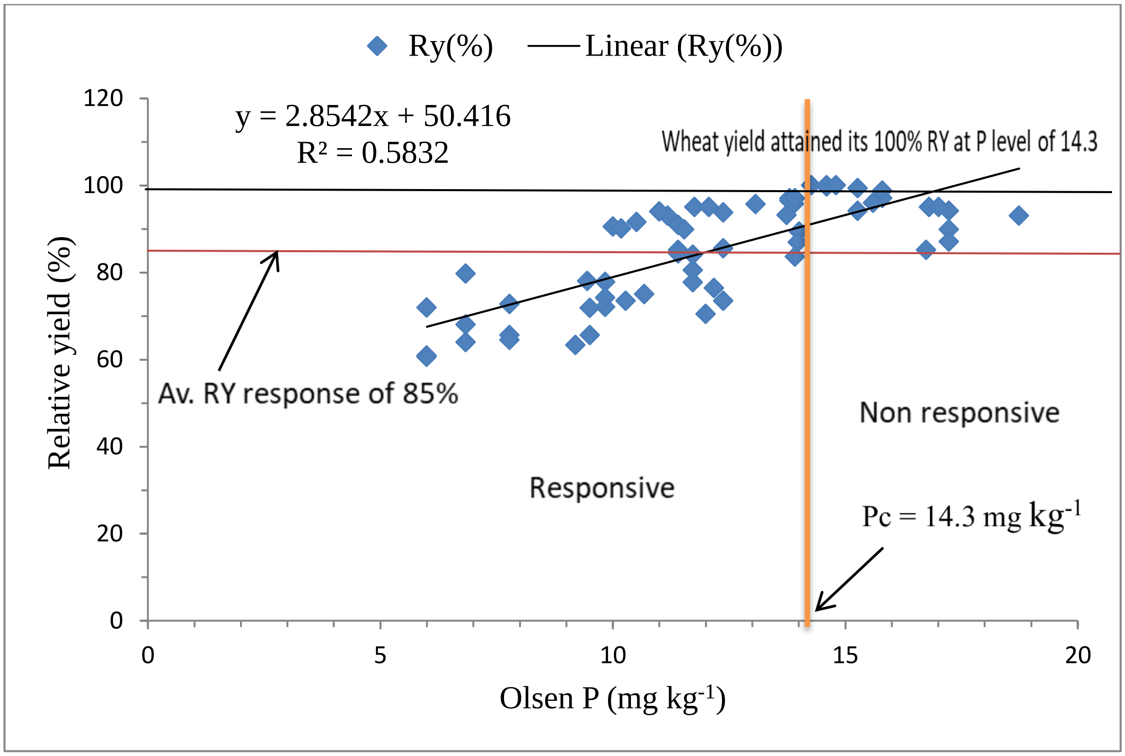

Figure 5.3: Relationships among relative yield response of wheat and soil-test P 21 days after planting on Andosols in Omo Nada District of Jimma Zone.

Table 5.3: Determination of P requirement factor for wheat on Andosols

| Phosphorus rate (kg ha$^{-1}$) | Soil test P Range | Average Soil test P | P increase over Control | P requirement factor (Pf) $\mathrm{Pf} = \frac{Kg\ P\ applied}{\triangle\ in\ soil\ P}$ |
|---|---|---|---|---|
| 0 | 6.00 – 7.78 | 6.87 (a) | 0 | - |
| 10 | 9.51 – 13.92 | 11.20 (b) | (b-a) = 4.33 | b÷(b-a) = 2.32 |
| 20 | 11.72 - 18.80 | 13.19 (c) | (c-a) = 6.32 | c÷ (c-a) = 3.17 |
| 30 | 11.18- 17.23 | 13.27 (d) | (d-a) = 6.40 | d÷ (d-a) = 4.69 |
| 40 | 12.07 - 16.80 | 14.27 (e) | (e-a) = 7.40 | e÷ (e-a = 5.41 |
| 50 | 11.74 -18.74 | 15.45 (f) | (f-a) = 8.58 | f÷ (f-a) = 5.83 |
| Average | | | | 4.30 = Pf |

NB: Pf = soil test P divided by P increase over control

Accordingly, the amount of P fertilizer to be added (Pa) per hectare could be calculated from the P critical concentration (Pc) in the soil, the initial P of the soil (Pi) determined for every plot before sowing (Table 5.1), and the P requirement factor (Pf), as expressed in the fourth formula above.

## 5.4. DISCUSSION

The lab analysis data for soil physicochemical properties indicated in Table 5.1 shows the soil textural class was clay loam (CL) to clay which is ideal for agricultural activities since it is good in nutrient and water retention capacity and allows excess water to drain away. The relatively lower bulk density of the soil at the experimental sites indicated that Andosols are mostly high in organic matter content and also the parent materials of volcanic ash soils naturally form highly porous soil structures. The findings of Mcdaniel et al., (2012) agree with this finding. According to the retting of Hazelton and Murphy, (2016), the slightly acidic mean pH ($H_2O$) value (6.30) was the soil pH range at which most plant nutrients become more available and conducive for the activities of beneficial soil microorganisms and satisfactory for most crop production.

A very high amount of mean OC content (4.37%) in Andosols could be due to high rainfall that encourages more biomass production and the low temperature resulted in a lower decomposition rate and more accumulation of soil organic matter (OM). The mean soil TN content (0.32%) was rated as high following a similar trend with soil OC. The Olsen available P content (6.87 mg $kg^{-1}$) of the soil was in the deficient range Hazelton and Murphy, (2016) which is most probably because of the unique high P fixing properties of Andosols. Gonzalez-Rodriguez & Fernandez-Marcos, (2018) reported similar work with this finding.

The major cations occupying the soil's exchange sites in decreasing order were $Ca^{2} > Mg^{2+} > K^{+} > Na^{+} > Al^{3+}$ Table 5.1. This result was similar to the finding of Berhanu, D & Eyasu, E. (2021a) for Bako Tibe soils. Of the total effective cation exchangeable capacity (ECEC), 73%, 16%, 9%, 0.88%, and 0.52% of the exchange sites were occupied by exchangeable $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, $Na^{+}$, and $Al^{3+}$ respectively, As ratted by Hazelton & Murphy, (2016), these levels of the exchangeable cations were in the desired range for the growth of many plants.

Among the exchangeable cations occupying the soil's exchange site, $Ca^{2+}$ is the most abundant cation (13.95 $cmol_{(+)}kg^{-1}$) in the soils of the study area. As rated by FAO, (2006), the value of exchangeable $Ca^{2+}$ was in the high category which indicates the soils (Andosols) are relatively younger soils and very weakly leached. The mean soil exchangeable $Mg^{2+}$ (3.13 $cmol_{(+)}kg^{-1}$), $K^{+}$ (1.67 cmol $_{(+)}kg^{-1}$), Na 0.17 ($cmol_{(+)}kg^{-1}$), and Al (0.1$cmol_{(+)}kg^{-1}$) were in the optimum range (Hazelton & Murphy, 2016). The Ca: Mg ratio data (4.45:1) in this study shows a balanced level of the two plant nutrients.

The mean CEC of the soil was 35.15 $cmol_{(+)}kg^{-1}$ which was in the high range and indicates the potential of the soils to retain nutrients against leaching and resupply it later to the plants. The clay fraction and high OM content of the soil have contributed to the cation exchange capacity of the soil. The mean percent base saturation (PBS) was 54% which indicates about 54% of the soil's exchange sites were saturated by basic cations ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $Na^{+}$). According to Hazelton & Murphy, (2016), the soil's PBS was rated as high indicating high potential fertility of the soils.

Jones, (2003) interpreted the values of available micronutrients in the soil. Based on his ratting, the soils under the study had high Fe (234.45 mg $kg^{-1}$), very high Mn (199.88 mg $kg^{-1}$), and very high Zn (7.99 mg $kg^{-1}$) content because of the high OM content of the soils and the nature of the parent material from which the soils was formed. According to the same rating, the level of available Cu (1.05 mg $kg^{-1}$) was in the deficient range. The most probable reason for a low level of available Cu in the soils of the study area is high OM, TN, and Zn content in the soils and crop uptake without the addition of Cu-containing fertilizers. The soil lab analysis data indicate good soil fertility status that is suitable for crop production except for low levels of available P and Cu.

The results of the study revealed that cropping season and application of P fertilizer show a significant effect on yield and yield components of wheat in the study area. The grain yield of wheat was higher by 25.50% in 2018/19 than in the 2017/18 cropping season. The main reason for a minimum yield of wheat in 2017/18 could be due to the cutworm attack of wheat at the early growth stage and the low adaptability of the newly introduced wheat variety (var.*Senate*) to the local climatic condition of the study area. As indicated in Table 5.2, yield and some yield components of wheat increased steadily and significantly until 40 kg P ha$^{-1}$ but decreased after this level. The reason, in this case, could be the P level until 40 kg ha$^{-1}$ could be sufficient for wheat growth in that particular location. The decline in grain yield above the 40 kg P ha$^{-1}$ was because the extra P application was used for luxury consumption by the crop rather than for grain yield increase and a higher P level causes P-induced nutrient deficiency mainly Zn & Fe. Similarly, previous studies on winter wheat by Teng et al., (2013) stated that wheat grain yield increased at an increasing rate at the beginning and then gradually to a plateau. Also, Zhan et al., (2015) stated that above the optimum, a higher rate of phosphorus application does not result in a higher grain yield increase.

The year-by-P fertilizer application interaction was not significant for yield and yield components of wheat, except plant height, implying that the effect of year on the availability of P to plants was not significant unless a remarkable fluctuation was observed in the rainfall amount and distribution between years in the study area. Similarly, Legesse, (2017) reported that year by P fertilizer interaction was not significant for yield and yield components of malt barley on Nitisols of central Ethiopian highlands.

According to the Cate-Nelson procedure, the critical level of Olsen P in the upper 15 cm of surface soil is about 14.30 mg kg$^{-1}$. In soils with an available P level of less than 14.30 mg kg$^{-1}$, the yield of wheat could show a significant response to additions of P fertilizers. At values equal to 14.30 mg P kg$^{-1}$, the wheat attained almost 100% of its highest yield (Figure 5.3). This means that phosphate fertilizer can be recommended to enrich or maintain the phosphorus in the soil to a critical level. In areas where the available phosphorus content exceeds 14.30 mg kg$^{-1}$, the phosphorus level in the soil is more than the crop requirement, and the additional application of phosphorus fertilizer will not be economical for an extra increase in yield. Similar results were also obtained by Girma & Zeleke, (2015) who found that by applying P above the critical rate, the cost of extra P fertilizer to get additional yield can be more than the amount of extra yield.

Andosols in Ethiopian highlands are low in their available P and require high external P inputs for wheat production. The initial (before sowing) soil test results indicated that all the soil P values (6 – 7. 87 mg P $kg^{-1}$) were less than the critical soil P value (Table 5.1). The response of soil available P to applied P fertilizer rate was inadequate (Figure 5.2), showing some of the applied P was fixed and exists in unavailable forms.

The result of the current study indicated that P fertilizer could be recommended for Andosols in the Southwestern highlands of Ethiopia based on initial soil Olsen P content (Pi), critical P-value (Pc), and the P requirement factor (Pf) (Eq.5.3). Accordingly, the recommended application rate would be 35 - 40 kg P $ha^{-1}$, which corresponded with the amount of 40 kg P $ha^{-1}$ (the agronomic critical P level) that produced the highest wheat grain yield of 5157 kg P $ha^{-1}$. All the soil samples analyzed had Olsen P values <10 mg $kg^{-1}$ (the lowest boundary of optimum P level). Thus, without soil lab analysis results, the application of 40 kg P $ha^{-1}$ (which resulted in the highest total yield) can be recommended for wheat production in the study area. As stated by Getachew et al., (2015) it is reasonable to recommend a minimum of 5-12 kg P $ha^{-1}$ each year to compensate for the P taken up from the soil in wheat grain if 3500 kg $ha^{-1}$ dry matter with a P content of 0.15% is exported during wheat harvest.

## 5.5. CONCLUSIONS AND RECOMMENDATIONS

Blanket fertilizer recommendation is still practiced in most parts of Ethiopia. It can result in the application of fertilizers below or above the crop nutrient requirement that if in less amount causes the loss of money and the crop yield or if it is in excess, environmental problems such as eutrophication. The current study shows a low level of available phosphorus among other factors that limit wheat yield in the study area. This study determined the critical level of soil phosphorus recommends the agronomic optimum phosphorus fertilizer rates, and evaluated the wheat yield response to phosphorus fertilization on Andosols of the Southwestern highlands of Ethiopia. From the results of this study, 40 kg P ha$^{-1}$ which gave the highest yield response of 5157 kg ha$^{-1}$ GYLD (28% and 19% GYLD increase compared to the control and farmers' practice respectively) can be recommended on Andosols of the Southwestern highlands of Ethiopia. The critical soil Olsen P concentration was 14.30 mg kg$^{-1}$. The correlation of crop yield response with the soil test P value revealed that 40 kg P ha$^{-1}$ was recommended for wheat production in the study area. The result can also be used for future intensification of Andosols in other locations for developing a system of soil test-based and site-specific fertilizer recommendations.

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# CHAPTER 6: GENERAL DISCUSSION/CONCLUSIONS AND RECOMMENDATIONS

In this chapter, the major findings of the current studies and their key implications were discussed. The chapter then concludes with a summary of the research as well as suggestions for future directions. Also, recommendations and appropriate soil management options were suggested in this section.

## 6.1 DISCUSSION

Under this sub-heading, the results from the soil's morphological, physical, and chemical properties were discussed. The extent of soil acidity and its major effects, the soil's phosphorus sorption capacity the external phosphorus fertilizer required to keep the standard soil solution P, and the rate of lime that is required by various agricultural soils were discussed. Likewise, the effect of different phosphorus and lime rates on selected soil properties and maize yield was discussed. The response of wheat to various phosphorus rates was evaluated. Based on the study results, appropriate management options were designed to protect, and maintain the environment sustain the land productivity, and increase the crop yield. Finally, from the current study, appropriate conclusions and recommendations were made and the feature research direction was indicated.

### *6.1.1 Characterization and Classification of the Acidic (low-pH) Soils*

The core idea of soil characterization and classification is to assess the potentials and the limitations of the soil resources for agriculture and many other uses and devise the right soil management options. By understanding the characteristics and classification of soil, scientists and professionals can make appropriate decisions regarding land use planning, crop selection, construction projects, and environmental management. Overall, soil characterization and classification provide valuable insights into the behavior and suitability of soil for different purposes, ultimately contributing to sustainable development and resource management

#### *6.1.1.1 The soil properties*

Generally, all the surface and subsurface soils were clay in texture except the sub-soils of Pedon 6 which was sandy clay. For all Pedons studied, the clay content slightly increased with increasing the depth of profiles that revealed most subsoil horizons as argic (Bt) except for Pedon 6 in which the clay content decreased as the soil depth increased. The clay skins (cutans) were found on the sides of ped faces, implying that clay illuviation (argilluviation) occurred as a pedogenic process.

The silt/clay ratio and the quantity of the basic cations were indicators used to evaluate the degree of weathering and establish the stage of soil development. Based on Wambeke, (1962) rating, the silt/clay ratio of 0.15 was the demarcation point between young and old soils. Soils with a silt/clay ratio of > 0.15 were considered to be young and contained readily weatherable minerals while soils with a silt/clay ratio value < 0.15 were highly weathered soils.

Accordingly, Andosols (Pedons 10, 11, and 12) and Cambisols (Pedon 6) with the highest value of silt/clay ratio were the young soils at the beginning stage of weathering. The results in Tables 2.3a and 2.3b revealed that Andosols and Cambisols were the young soils, luvisols were found in the middle, and Alisols and Nitisols were found at the advanced stage of weathering. The silt/clay ratio of Andosols decreased with increasing the soil depth. The highest Si/Cl ratio of 0.69 was found at the surface layer of Pedons 10, and 11, followed by 0.47 at the subsurface (BC) layers of Pedon 6. This implies that the younger soils were formed at the surface layer of Andosols compared to the subsurface soils. This finding is in line with that of McDaniel, et al, (2012) stated that, unlike other soils, Andisol profiles are usually formed by “upbuilding pedogenesis” since younger volcanic materials are accumulated on top of older ones. Also, in Cambisols, the subsurface soil layers were younger compared to the surface soil layer.

In all surface and subsurface soils, the pH of the soils was acidic in reaction (below 6.5) and the value was in an increasing trend across the soil depth. In the Bako Tibe district, a similar research result was reported by Gezu & Tekalign, (2019) as the mean soil pH in the district was 5.5, and 46% of the soil was strongly acidic while 54% was moderately acidic in reaction. The values of the soil pH increased across the soil depth and this was attributed to the intensive rainfall that leaches down the basic cations to the subsoil layers and the decrease in the OM content of the soil at the subsurface that produces a lower quantity of protons ($H^+$) on decomposition.

Except for the soil bulk density and pH that increased with increasing the soil depth, all the soil parameters such as OC, TN, and available phosphorus, CEC, and exchangeable cations content of the soils and available plant micronutrients such as Fe Mn Cu, and, Zn showed a decreasing trend with increasing the soil depth for all Pedons. This implies that most of the plant nutrients are concentrated in the surface soil compared to the subsurface soil.

The Exchangeable $Ca^{2+}$ was the dominant cation in the soils of the study area. Based on the rating of FAO, (2006), the exchangeable $Ca^{2+}$ content of the soils was in the medium to high range while the highest value was for Andosols and the lowest value was for Alisols. The low values of percent base saturation for Alisols and Nitisols indicated there were considerable leaching losses of basic cation from the soil and the saturation with $H^+$ and $Al^{3+}$. Cambisols and Andosols with higher $Ca^{2+}$ content were the younger and Alisols and Nitisols with lower $Ca^{2+}$ content were at the advanced weathering stage. The ratios of silica/sesquioxide in soil total elemental composition analysis (Appendix Table C) indicated that Andosols were composed of Montmorillonite/Illite clay minerals which are at a less advanced stage of weathering and Alisols, Nitisols, and Luvisols. were more composed of Al oxide (gibbsite) which indicates the soils are at a more advanced stage of weathering.

The cation exchangeable capacity (CEC) of the soil significantly ($P \leq 0.01$) differs across the soil types. Luvisols (48.79 cmol(+)kg$^{-1}$) and Andosols (36.15 cmol(+)kg$^{-1}$) had the highest but Alisols had the lowest (25.02 cmol(+)kg$^{-1}$) CEC content. Based on the rating criteria of CEC by Hazelton and Murphy, (2016), Luvisols was very high (41.56 cmol(+)kg$^{-1}$) while Nitisols, Andosols, and Alisols were high (25.2- 36.15 cmol(+)kg$^{-1}$) in their CEC values which indicates the capacity of the soils to hold nutrients against leaching loss and were satisfactory for agricultural crop production.

The highest (52%) and lowest (28%) value of PBS was recorded under Andosols of Omo Nada and Alisols of Bako Tibe respectively. As rated by Hazelton and Murphy, (2016) the PBS content of Alisols and Nitisols were categorized as low whereas Luvisols and Andosols were categorized as Moderate. As the PBS is an index of the soil's potential fertility, Alisols and Nitsols were low while Luvisols and Andosols were medium in potential fertility. These low values of PBS and relatively higher values of CEC for Alisols indicate the presence of strong to moderate leaching of the basic cations from the soils and replaced by acid-forming ($H^+$ and $Al^{3+}$) cations on the soil's exchange sites which resulted in a strong acidic soil reaction.

Based on the soil profile description, the soil's morphological, physical, and chemical properties were described. Acording to the IUSS Working Group WRB, (2015), the soils of the study area were categorized as: Pedon 1 Dystric Rhodic Nitisols (Humic), Pedon 2 Dystric Nitisols (Humic), Pedon 3 Umbric Nitisols, Pedon 4 Rhodic Alisols (Epidystric), Pedon 5 Rhodic Luvisols Hypereutric), Pedon 6 Leptic Cambisols (Humic), Pedon 7 Chromic Alisols (Hyperdystric, Humic), Pedon 8 Chromic Alisols (Hyperdystric), Pedon 9 Chromic Alisols (Hyperdystric), Pedon 10 Mollic, Silandic Andosols (Clayic), Pedon 11 Dystric, Silandic Andosols (Clayic), and Pedon 12 Eutric, Silandic Andosols (Clayic).

#### *6.1.1.2 Extent of soil acidity*

Concerning the first research question, it was found that acid soils cover a wide area in the highlands of Ethiopia. As mentioned in the literature review, the extent of soil acidity varies from 41% Mesfin (2007) to 47% (Desta et al., 2021) of the Ethiopian total land mass. The soils (Nitisols, Luvisols, cambisols, Alisols, and Andosols) under this study differ in their extent of acidity (in the $pH_{(H2O)}$ range of 5.23-6.44). As indicated in (Table 3.2) the level of exchangeable acidity in the soils of the study area (in an increasing sequence) was 0.17, 0.24, 0.52, 0.61and 1.67 $cmol_{(+)}kg^{-1}$ for Cambisols, Andosols, Nitisols, Luvisols, and Alisols respectively. In line with this study, a previous study by Gezu & Tekalign, (2019) indicated, that the total area of the Bako Tibe district is strongly to moderately acidic in reaction with a mean pH of 5.50. Additionally, this study indicated that the pH of the soil in the Omo Nada district was in the range of very strongly to slightly acidic (4.81 to 6.44). The results lead to the conclusion that all the soils of the study area are acidic in reaction. The acidic soil reaction was because of the high rainfall leaches the basic cations from the soil system and the soil's exchange sites were saturated with acid-forming cations such as $Al^{3+}$ and $H^{+}$. Similarly, Ng et al., (2022), have shown that in Tropical regions, the hot climates and intensive rainfall play a part in the formation of acid sols due to a marked leading of bases such as $Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $Na^{+}$ and after that substitution of the soil exchange site by the acidic cations.

Alisols were very strongly acidic whereas Cambisols and Andosols were slightly acidic in reaction. This implies that in Aliaols, the soil's exchange sites were more saturated with acidic cations such as $Al^{3+}$ and $H^{+}$ and resulted in serious restrictions to crop production due to the toxic levels of Al, Fe, Mn, and low levels of Ca, and P compared to Cambisols and Andisols with the lowest acid saturation levels. In harmony with this finding, the study by Enesi et al., (2023a) indicated that soil acidity decreased the quantity of basic cations that are essential for plant growth and increased solubility of Al in the soil solution to the phytotoxic level.

### *6.1.2 Evaluation of the soils' phosphorus sorption capacity and external phosphorus requirement*

Phosphorus sorption capacity (Pf) is the ability of the soil to tie up (bind) the native and applied phosphorus to it. The soils of the study area varied in their phosphorus sorption capacity. The difference in the soil's phosphorus sorption capacity was due to the variation in their properties such as the pH, the clay content, the OM content, and the quantity of Al and Fe oxides content in the soil. Nitisols had the lowest (280 mg P $kg^{-1}$) and Alisols with the lowest pH of 4.80 and the highest exchangeable acidity of 1.67 $cmol_{(+)}kg^{-1}$ had the highest (413 mg P $kg^{-1}$) phosphorus sorption capacity. Nitisols had the lowest (280 mg P $kg^{-1}$) and Alisols had the highest (413 mg P $kg^{-1}$) phosphorus sorption capacity.

Because of this, the soils had different levels of external P-fertilizer requirements to maintain the standard p-concentration of 0.2 mg P $L^{-1}$ in the soil solution. The external P-fertilizer requirement study suggested 25, 30, 32, and 26 (mg P $kg^{-1}$ soils) or 50 kg P $ha^{-1}$, 60 kg P ha-1, 56 kg P $ha^{-1}$, and 52 kg P ha-1 for Nitisols, Luvisols, Alisols, and Andosols respectively. Therefore, the soils of the study area required a different quantity of P as an external input. This study suggests a soil-specific P-fertilizer recommendation for wise resource utilization and optimum crop production than the formerly used blanket fertilizer recommendation in the southwestern parts of Ethiopia.

### *6.1.3 Lime requirement of acidic soils*

Lime application reduced the level of soil acidity in this study but the quantity of lime required by the soils to ameliorate the acidity of the soils varied as 2.28 t lime $ha^{-1}$ for Nitisols, 3.20 t lime $ha^{-1}$for Luvisols, and 4.22 t lime $ha^{-1}$ for Alisols. The variation in lime requirement among the soils could be based on the level of exchangeable acidity, clay percentage, and OM content of the soils. Compared to Nitisols, Alisols with the highest level of exchangeable acidity (1.76 $cmol_{(+)}kg^{-1}$), the highest percentage (54.7%) of clay particles, and the highest buffering capacity of 471 L $kg^{-1}$ (Table 3.2) required the highest quantity of lime (4.22 t lime $ha^{-1}$) but Nitisols required the lowest quantity of lime of 2.28 t lime $ha^{-1}$ (Table 4.2). The reason for the highest quantity of lime required by Alisols was its clay and organic matter content that gives the soils larger adsorbing surfaces for hydrogen ion ($H^+$) and has more ability to resist a change in soil pH (more buffering capacity). Therefore, Alisls with the highest buffering capacity of 471 L $kg^{-1}$ had the highest lime requirement to neutralize the exchangeable acidity and raise the soil pH to a desired level.

On the other hand, no lime was applied to Andosols with the lowest level of exchangeable acidity (0.12 $cmol_{(+)}kg^{-1}$) since the quantity of exchangeable acidity was lower than the permissible acid saturation for crop production. Similarly, a previous study conducted by Gedefa et al., (2021) suggested about 89% of the soils in Southwestern Ethiopia (Bedeele district) had strongly acidic reactions with a pH of < 5.5 and required the application of 0.09 to 3.6 tons lime $ha^{-1}$. Even though liming is the best strategy to reclaim the soil acidity and its related problems and also increase crop yield, Getachew et al., (2019), many of the farmers in the area may not have the resources to purchase lime, and even the rich farmers who have access to purchase it, the supply of lime is very limited to apply these inputs, which could limit the potential impact of the study.

### *6.1.4 Assessment of the Integrated Effects of Lime and P Fertilizer on Maize Yield Parameters*

The result of the study indicated liming increased maize yields and improved selected soil properties such as pH, Exch $Ca^{2+}$, and Available P but decreased soil acidity. The soil pH was increased with an increasing rate of lime application in turn, the increase in maize yield was proportional to the increase in the level of soil pH that improved the nutrient availability. This result was similar to the finding of Enesi et al., (2023) who indicated the increase in soil pH followed increased rates of lime application since acid soils with more exchangeable acidity require more quantity of lime to correct the acidity.

Another important point that has to be considered here is, that lime application improves the soil properties such as reaction (pH), nutrient solubility, and availability (N, P, and S) through the decomposition of OM due to improved activities of beneficial soil microorganisms. In the long run, unless lime is integrated with organic and inorganic fertilizers, lime application alone causes a serious soil fertility decline since it results in increased nutrient removal without external nutrient inputs. A similar result obtained by Heenus and Karthika (2019) revealed, that liming increases the OC mineralization through increased soil pH detoxifies the harmful effects of $Al^{3+,}$ and enhances the survival of microorganisms by improving the carbon use efficiency.

The low initial P content of the soils (Nitisols, Luvisols, and Alisols) was increased after the addition of both critical P levels plus the recommended lime rates. The lowest increment (2.62 to 15.42 mg P $kg^{-1}$) was recorded for Nitisols, and the highest P increase (5.23 to 40.29 mg P $kg^{-1}$) was for Alisols. The highest P increase for Alisols after the application of the recommended lime and critical P rate implies Alisols released more quantity of P from its highest quantity of adsorbed P compared to the other soil types with lower P reserves. The available P content of the plots treated with recommended lime plus critical P rate was increased from 2.62 to 15.42 mg kg$^{-1}$ in Nitisols, 6.53 to 22.27 mg kg$^{-1}$ in Luvisols, and 5.23 to 40.92 mg kg$^{-1}$ in Alisols.

Also, the yield parameters of maize were significantly varied due to the application of treatments. Compared to the use of conventional N and P fertilizers (treatment 8) and farmers' practices which used only NPSB (treatment 7), the combined application of P fertilizer together with lime improved the growth and development of maize yield since lime ($CaCO_3$) application reduced the soil acidity, Al toxicity and enhanced the solubility and availability of nutrients and created the optimum soil pH and conducive environment for soil microorganisms. The addition of critical P level plus recommended lime rates boosts the maize grain yield by 89.88%, 81.49 %, and 84.38% compared to the control treatment and by 28.35%, 26.53%, and 26.73% over the farmers' practice for Nitisols, Luvisols, and Alisols respectively. The MRR analysis revealed that treatment 3 which received a recommended rate of lime combined with critical P rate (30 kg P ha$^{-1}$) gave the highest MRR of 284.58%, 238.18%, and 325.58% for Nitisols, Luvisols, and Alisols respectively that economically advantageous treatment combination.

### *6.1.5 Wheat Response to Different Rates of P and Fertilizer Recommendation*

There was a positive yield response of wheat to P-fertilization. The P-fertilization significantly increased the wheat yield. The addition of P fertilizer at the levels of 10, 20, 30, 40, and 50 kg P ha$^{-1}$ resulted in a significant linear response with mean grain yield increments of 8.5%, 17.4%, 19%, 28%, and 23.7% respectively, compared to the control treatment received only 46 kg N ha$^{-1}$ (without application of P fertilizer). The farmers' practice treatment (18-36-7-0.71 N-$P_2O_5$-S-B kg ha$^{-1}$) was the recommended P level for wheat production at Omo Nada and gave an 11.2% grain yield advantage over the control treatment.

The addition of P above 40 kg P ha$^{-1}$ did not significantly increase the wheat GYLD (Table 5.2). This level of P (40 kg P ha$^{-1}$) corresponds to the optimum P-uptake for maximum grain yield of wheat. Similar to our finding, Penn & Camberato, (2023) reported overapplication of P above the Olsen critical P resulted in high biomass production rather than the grain yield advantage. The reason behind this fact was that for the addition of P above the critical P, the nutrient was used for luxury consumption by the crop rather than for GYLD increase. Finally, the use of 40 kg P ha$^{-1}$ was used to produce more GYLD while the application of above the critical level of P (50 kg P ha$^{-1}$) was used for the production of more biomass yield such as the application of pasture production.

## 6.2 CONCLUSIONS

The soils vary in their level of acidity, lime requirement, external P requirement, and fertility level. Therefore, different management options were designed for the soils based on their characteristics. The soil's physical properties and most of the soil's chemical characteristics were in the optimum range and did not adversely affect crop production but the soil reaction (pH), available P, available Cu, and B content were below the optimum range and could affect the crop production. The essential plant nutrients were mostly concentrated in the surface soil layers compared to the sub-soil layers. This indicates the surface soil layers are the more fertile part of the soil that supports plant life and it suggests the need for appropriate conservation measures to sustain the soil fertility and the land productivity. The strongly acidic soil reaction affects many of the soil's chemical and biological fertility hence, suggesting the application of lime to correct the acid infertility problems of the soils.

From the current research results, it is possible to conclude that different soils with different properties need different management strategies. The morphological, physical, and chemical characteristics of the soils showed variation among the soil types and soil depth. The soils represented by Pedon 6 in the upper slop position were relatively shallow whereas the Pedon s in the middle and lower slope positions were very deep. The clay content in the Bt horizons of all Pedons (except Pedon 6) was higher as compared to the surface horizons. Soil formation in most of the Pedon is characterized by clay illuviation from the surface to the subsurface soil horizons.

Soils varied from strongly acidic (Alisols) to slightly acidic (Andosols) in reaction. The values of exchangeable $Al^{3+}$ for the surface horizons of (Pedons 4, 7, 8, and 9) were not in the desirable range and can adversely influence crop growth Even though lime is superior in ameliorating acid soil-related problems, its limited sources, less availability for rich farmers, and its cost for small-scale resource-poor farmers make the liming program less efficient.

Blanket fertilizer recommendation is still practiced in most parts of Ethiopia. Even the farmers do not know the actual size (area) of their plot of land and they do not apply the actual quantity of fertilizers as per the recommendation. Integrated nutrient management that uses organic and inorganic sources of nutrients in combination with lime can sustain the natural resources (soil) while increasing crop production.

## 6.3 RECOMMENDATIONS

For wise use of soil resources, sustain land productivity, and improve crop yield, the agricultural experts, the land use planners, and the community should use the following recommendations

✓Based on the soil lab analysis data, it is possible to infer that most of the soil's chemical characteristics were in the optimum range but the soil reaction (pH), available P, available Cu, and B content were below the optimum range and affect the crop production. Therefore, the optimum quantity of deficient elements (P, Cu, and B) must be added to the soils by integrating their organic and inorganic fertilizer sources to maintain soil fertility and productivity.

✓Based on their properties, the soils of the study area were categorized under different RSGs. According to their limitations, soils require different management practices. This suggests that:

Soils with Pedons 2, 4, and 12 were within LCC IIs, IIs, and IIe respectively required similar management practices such as counter-cultivation and growing of cover crops and the integrated use of organic and inorganic fertilizers to maintain their fertility status.

✓Particularely, Pedon 6 (Cambisols) had a shallow depth (0.55m). Since it, had limitations for crop production, the farmers should use the land for grazing land or pasture production.

✓The combined use of agronomic (cover crops) and physical conservation measures (graded bands) combined with the integrated use of organic and inorganic fertilizers were recommended for Pedons 1, 3, 5, 6, 7, 8, 9, 10, and 11. to sustain the land productivity.

✓To correct the soil acidity problem, a 2.28 t lime ha$^{-1}$ was for Nitisols; 3.60 t lime ha$^{-1}$ for Luvisols, and 4.20 t lime ha$^{-1}$ was recommended for Alisols.

✓As an alternative, in acid soils, the community has to select crop varieties that are more tolerant to the soil acidity exactly as they selected the crop species for other important agronomic qualities.

✓ The base of lime recommendation to correct soil acidity must be a soil-specific lime requirement determination.

✓From the P-sorption study, the actual quantity of P required (to maintain 0.2 mg P $L^{-1}$) by Nitisols, Luvisols, Alisols, and Andosols were 25, 30, 32, and 26 (mg $kg^{-1}$) respectively. Therefore, 50 kg P $ha^{-1}$, 60 kg P $ha^{-1}$, 56 kg P $ha^{-1}$ and 52 kg P $ha^{-1}$ can be considered to be equivalent values in kg $ha^{-1}$ that can be recommended for optimum crop production on Nitisols, Luvisols, Alisols, and Andosols respectively in the study area.

✓The recommended rate of lime by soil types plus the critical P-rate (30 kg P $ha^{-1}$) gave the highest maize grain yield of 6367, 7062.54, and 6434.47 kg $ha^{-1}$ and MRR of 285%, 238%, and 326% for Nitisols, Luvisols, and Alisols respectively which is economically advantageous for maize production is recommended for optimum maize production in the study area.

✓The study of the soils' external phosphorus requirement (EPR) revealed twice the critical level of P (30 kg P $ha^{-1}$ x2) alone at areas with no serious soil acidity problems or the use of critical P-level (30 kg P $ha^{-1}$) plus the recommended rate of lime by soil types were recommended at areas with more soil acidity problems for maize production on Nitisols, Luvisols, and Aliosols.

✓The use of 40 kg P $ha^{-1}$ that gave the maximum wheat grain yield can be recommended for optimum wheat production in the study area and other Andosols in similar agroecology.

✓Fertilizer recommendation should be based on actual soil test value (not based on soil fertility class ie. L, M, & H).

## 6.4 Future Research Directions

The following research gaps need to be filled in the future:

✔Without an appropriate management practice, the level of soil acidity can change in the long run. Therefore, the farmers are advised to test their soils and apply the recommended rate of lime based on the soil test result.

✔The current study focused on the assessment of P sorption capacity and the external P-fertilizer requirement of the soils but, the percentage (proportion) of the added P that was uptaken by the plants is not quantified. So, future studies can explore the P-uptake and P-level in different crops.

✔ The study on wheat P fertilization has to include the uptake values of phosphorus to come up with a precise fertilizer recommendation for optimum wheat grain production.

✔Fertilizer recommendation should be based on actual soil test value (not based on soil fertility class ie. low, medium, & high).

✔ In the future, It is advisable to conduct research on the selection & breeding of acid-tolerant crop verities as those of high yielding & disease resistant once.

# 7. ANNEXES

## Appendix Tables

**Appendix Table A:** Diagnostic horizons, other features, and FAO-WRB soil names for the studied soils of Bako and Omo Nada

| Ped on No | Diagnostic Horizon | Reference soil group (RSG) | Prefix qualifiers (2nd level quil) | Suffix qualifiers | WRB soil name |
|---|---|---|---|---|---|
| P1 | Umbric, nutic | Nitisols | Dystric | Humic | Hyperdystric Nitisols (Humic) |
| P2 | Umbric, nutic | Nitisols | Dystric | - | Umbric Nitisols |
| P3 | Umbric, nutic | Nitisols | Umbric | Humic | Umbric Nitisols |
| P4 | Umbric | Alisols | Rhodic | Epidystric | Rhodic Alisols (Epidystric) |
| P5 | Umbric | Luvisols | Rhodic | Hypereutric | Rhodic Luvisols (Hypereutric) |
| P6 | Cambic (sub-sur) | Cambisols | Leptic | Humic | Endoleptic Cambisols (Humic) |
| P7 | Argic | Alisols | Chromic | Hyperdystric, Humic | Chromic Alisols (Hyperdystric, Humic) |
| P8 | Argic | Alisols | Rhodic | Hyperdystric, | Rhodic Alisols (Hyperdystric) |
| P9 | Argic | Alisols | Chromic | Hyperdystric, | Chromic Alisols (Hyperdystric) |
| P10 | Mollic & Andic roperties | Andosols | Silandic | Clayic | Mollic, Silandic Andosols (Clayic) |
| P11 | Andic roperties | Andosols | Dystric | Clayic | Dystric, Silandic Andosols (Clayic) |
| P12 | Andic roperties | Andosols | Eutric | Clayic | Eutric, Silandic Andosols (Clayic) |

**Appendix Table B:** Site Characteristics and Profiles Description at Bako –Tibe and Omo Nada Districts.

I. Site Characteristics and Profiles Description at Bako Tibe District

| **Profile/ Pedon ID:** | **BA/SK1/NT (P1)** |
|---|---|
| Date: | 12/03/2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Dystric Nitisols |
| Profile description tatus: | Routine profile description |
| Coordinate (WSG84): | N: $9^0$ 05.196; E: $37^0$8.196 |
| Local soil name: | Biye Dima |
| Location: | Bako Tibe, Seden kitie PA |
| Land form: | Plain |
| Position in land form (Aspect): | West to East |
| Elevation (masl): | 1724m |
| Depth to bedrock: | >200cm |
| Slope gradient: | 8% |
| Slope form: | Straight |
| Position: | Upper slope |
| Climate: | Tepid moist mid highlands |
| Parent material: | Basalt |
| Moisture status: | 0-145 cm dry & moist below |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Slow runoff |
| Land cover: | Harvested field of noog |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 20% of the unit is affected by severe sheet & moderate rill erosion<br>b. Surrounding: About 25% of the unit is affected by moderate rill & severe sheet erosion |

## PROFILE DESCRIPTION

| | |
|---|---|
| AP 0-20cm | Dark reddish brown (2.5YR 3/4) dry and (2.5YR2.5/4) moist; sandy clay; strong coarse sub angular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; none rock fragments; non-cemented and non-compacted; none mineral concentrations; none calcareous; common fine roots; many fine interstitial pores; none biological activities; gradual and smooth boundary. |
| Bt1 20-50cm | Dark red (2.5YR 3/6) dry and dark reddish brown (2.5YR 2.5/4) moist; clay; strong coarse angular blocky structure; none mottles; sticky and plastic wet, friable moist and hard when dry; none surface cracks; none clay coatings; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; common fine roots; many fine interstitial pores; none biological activities; gradual and smooth boundary. |
| Bt2 50-80cm | Dark red (10R3/6) dry and dusky red (10R3/4) moist; clay; strong coarse angular blocky structure; none mottles; sticky and plastic wet, friable moist and hard when dry; none surface cracks; few faint discontinuous irregular clay coatings on pedfaces; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; many fine interstitial pores; none biological activities; clear and smooth boundary. |
| Bt3 80-125cm | Dusky red (10R 3/4) dry and dusky red (10R 3/3) moist; clay; strong coarse subangular blocky; none mottles; sticky and plastic wet, friable moist and hard when dry; none surface cracks; none clay coatings; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; many fine interstitial |

|  |  |  |
|---|---|---|
|  |  | pores; none biological activities; gradual and smooth boundary. |
| Bt4 | 125-145cm | Dusky red (10R 3/4) dry and dusky red (10R 3/3) moist; heavy clay; strong coarse angular blocky structure; many fine faint mottles; sticky and plastic wet, friable moist and hard when dry; none surface cracks; few faint discontinuous irregular clay coatings on pedfaces; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; many fine interstitial pores; none biological activities; gradual and smooth boundary. |
| Bt5 | 145-200+cm | Dark red (10R 3/6) moist; clay; strong coarse angular blocky structure; none mottles; sticky and plastic wet and friable when moist and hard when dry; none surface cracks; none coatings; none rock fragments; non-cemented and non-compacted; common medium hard rounded black manganese mineral concretions; none calcareous; few fine roots; many fine interstitial pores; none biological activities. |

| | |
|---|---|
| Profile ID: | BA/SK2/NT**(P2)** |
| Date: | 13/03/2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Umbric Nitisols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | N: $9^0$ 05.196; E: $37^0$8.196 |
| Local soil name: | Biye Dima |
| Location: | Bako Tibe, Seden kitie PA |
| Landform: | Plain |
| Direction of slope face (Aspect): | West to East |
| Elevation (masl): | 1736m |
| Depth to bedrock: | >200cm |
| Slope gradient: | 6% |
| Slope form: | Straight |
| Position: | Middle slope |
| Climate: | Tepid moist mid-highlands |
| Parent material: | Basalt |
| Moisture status: | 0-110 cm dry & moist below |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Slow runoff |
| Land cover: | Harvested field of maize |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 20% of the unit is affected by severe sheet & moderate rill<br>b. Surrounding: About 25% of the unit is affected by moderate rill & severe sheet erosion |

PROFILE DESCRIPTION

| | |
|---|---|
| AP 0-20cm | Dark reddish brown (2.5YR ¾) dry and dark reddish brown (2.5YR3/3) moist; clay; strong coarse subangular blocky structure; sticky and plastic wet, friable moist hard when dry; fine very closely spaced deep cracks; none mottles; none rock fragments; non-cemented and non-compacted; none mineral concentrations; none calcareous; common fine roots; many fine interstitial pores; none biological activities; clear and smooth boundary. |
| A 20-62cm | Dark red (2.5YR 3/6) dry and dark reddish brown (2.5YR 2.5/4) moist; clay; strong coarse angular blocky structure; none mottles; sticky and plastic wet, friable moist, and hard when dry; fine very closely spaced deep cracks; few faint discontinuous irregular clay coatings on pedfaces; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; many fine interstitial pores; none biological activities; gradual and smooth boundary. |
| B 62-110cm | Dusky red (10R3/4) dry and dusky red (10R3/3) moist; silty clay loam; strong coarse angular blocky structure; no mottles; sticky and plastic wet, friable moist and hard when dry; no surface cracks; none clay coatings; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; many fine interstitial pores; none biological activities; gradual and smooth boundary. |
| Bt1 110-190cm | Very dusky red (7.5R 2.5/4) moist; silty clay loam; strong coarse subangular blocky; none mottles; sticky and plastic wet and friable when moist; none surface cracks; few distinct continuous clay coatings on ped faces; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; none abundance of roots; many fine interstitial pores and none biological activities. |

| **Profile ID:** | **BA/CD1/NT (P3)** |
|---|---|
| Date: | 12/03/2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Dystric Nitisols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | N: $9^0$ 05.391; E: $37^0$08.079 |
| Local soil name: | Biye Dima |
| Location: | Bako Tibe, Cheka dimtu PA |
| Landform: | Plain |
| Direction of slope face (Aspect): | West to East |
| Elevation (masl): | 1710 m |
| Depth to bedrock: | >200cm |
| Slope gradient: | 9% |
| Slope form: | Straight |
| Position: | Middle slope |
| Climate: | Tepid moist mid-highlands |
| Parent material: | Basalt |
| Moisture status: | 0-140 cm dry & moist below |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Slow runoff |
| Land cover: | Harvested field of maize |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 15% of the unit is affected by severe sheet & moderate rill erosion<br>b. Surrounding: About 25% of the unit is affected by moderate rill & severe sheet erosion |

PROFILE DESCRIPTION

AP 0-15cm Dark reddish brown (2.5YR 2.5/4) dry and dark reddish brown (2.5YR2.5/3) moist; clay; strong coarse subangular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; none rock fragments; non-cemented and non-compacted; none mineral concentrations; none calcareous; common fine roots; many fine interstitial pores; none biological activities; gradual and smooth boundary.

A 15-28cm Dark reddish brown (2.5YR 3/3) dry and dark reddish brown (2.5YR 3/4) moist; clay; strong coarse angular blocky structure; none mottles; sticky and plastic wet, friable moist, and hard when dry; none surface cracks; none clay coatings; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; many fine interstitial pores; none biological activities; gradual and smooth boundary.

Bt1 28-60cm Dusky red (10R3/4) dry and dusky red (10R3/3) moist; clay; strong coarse angular blocky structure; none mottles; sticky and plastic wet, friable moist and hard when dry; none surface cracks; few faint discontinuous clay coatings on pedfaces; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; many fine interstitial pores; none biological activities; diffuse and smooth boundary.

Bt2 60-140cm Dark red (10R 3/6) dry, and dusky red (10R3/4) moist; clay; strong coarse angular blocky; none mottles; sticky and plastic wet and friable when moist; none surface cracks; none clay coatings; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; many fine interstitial pores; none biological activities; diffuse and smooth boundary.

Bt3 140-200+cm Dusky red (7.5R 3/4) moist; clay; strong medium angular blocky; none mottles; sticky and plastic wet and friable when moist; none surface cracks; none clay coatings; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; none abundance of roots; many fine interstitial pores and none biological activities.

| | |
|---|---|
| **Profile ID:** | **BA/TS1/LV (P4)** |
| Date: | 11/03/2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Rhodic Alisols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | $9^0$ 06.23.4N, $37^0$ 07.334 E |
| Local soil name: | Biye Dima |
| Location: | Bako Tibe, Tulu sangota PA |
| Landform: | Plateau |
| Direction of slope face (Aspect): | East to West |
| Elevation (masl): | 1716 m |
| Depth to bedrock: | >200cm |
| Slope gradient: | 3% |
| Slope form: | Terraced |
| Position: | Middle slope |
| Climate: | Tepid moist mid-highlands |
| Parent material: | Basalt |
| Moisture status: | 0-145 cm dry & moist below |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Slow runoff |
| Land cover: | Annual field cropping |
| Land Use | Harvested field of maize |
| Erosion status: | a. Site:About 10% of the unit is affected by slight sheet & erosion<br>b. Surrounding: About 20% of the unit is affected by moderate rill, slight sheet erosion |

## PROFILE DESCRIPTION

| | |
|---|---|
| AP 0-20cm | Dark reddish brown (7.5YR 3/2) dry and (7.5YR2.5/3) moist; clay loam; strong coarse subangular blocky structure; sticky and plastic wet, friable moist and slightly hard dry; none surface cracks; none mottles; none rock fragments; non-cemented and non-compacted; none mineral concentrations; none calcareous; few coarse and many fine roots; many fine interstitial pores and few termite channels; clear and smooth boundary. |
| AB 20-50cm | Dark brown (7.5YR 3/4) dry and very dark brown (7.5YR 2.5/3) moist; clay; strong coarse angular blocky structure; none mottles; sticky and plastic wet, friable when moist and hard when dry; none surface cracks; few faint discontinuous irregular clay coatings on pedfaces; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few coarse and common fine roots; many fine interstitial pores and few termite channels; gradual and smooth boundary. |
| Bt1 50-80cm | Dark brown (7.5YR ¾) dry and (7.5YR3/3) moist; clay; strong medium subangular blocky structure; none mottles; sticky and plastic wet, friable moist and hard when dry; none surface cracks; few distinct discontinuous irregular clay coatings on ped faces; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine and coarse roots; very few fine interstitial pores and few termite channels; clear and smooth boundary. |
| Bt2 80-110cm | Dark reddish brown (5YR 3/3) dry and Dark grayish brown (5YR 3/2) moist; clay; moderate medium angular blocky structure; none mottles; sticky and plastic wet, friable moist and hard when dry; no surface cracks; many prominent continuous clay coatings on ped faces; |

none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few coarse roots; few fine interstitial pores and few termite channels; clear and smooth boundary.

Bt3 110-153cm Dark reddish brown (5YR 3/4) dry and dark reddish brown (5YR 3/3) moist; clay loam; moderate medium subangular blocky structure; none mottles; sticky and plastic wet, friable moist and slightly hard when dry; none surface cracks; many prominent continuous clay coatings on ped faces; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few coarse roots; few fine interstitial pores; none biological activities; abrupt and smooth boundary.

Bt4 153-200+cm Dark reddish brown (2.5YR 3/4) dry and dark reddish brown (2.5YR 3/3) moist; clay; moderate medium subangular blocky structure; none mottles; sticky and plastic wet, friable moist and hard when dry; none surface cracks; none coatings; none rock fragments; non-cemented and non-compacted; none mineral concretions; none calcareous; few fine roots; few fine interstitial pores and none biological activities.

| | |
|---|---|
| **Profile ID:** | **BA/CD2/LV (P5)** |
| Date: | 12/03/2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Chromic Luvisols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | $9^0$ 06.23.4N, $37^0$ 07.334 E |
| Local soil name: | Biye Dima |
| Location: | Bako Tibe, Cheka Dimtu PA |
| Landform: | Plain |
| Direction of slope face (Aspect): | West to East |
| Elevation (masl): | 1735 m |
| Depth to bedrock: | >102 cm |
| Effective soil depth: | > 102 cm |
| Slope gradient: | 10% |
| Slope form: | Straight |
| Position: | Lower slope |
| Climate: | Tepid moist mid-highlands |
| Surface coarse fragments: | Dominant stones and boulders |
| Parent material: | Basalt |
| Moisture status: | 0-50cm dry & moist below |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Slow runoff |
| Land cover: | Harvested field of maize |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 25% of the unit is affected by severe sheet & moderate rill<br>b. Surrounding: About 30% of the unit is affected by moderate rill & severe sheet erosion |

PROFILE DESCRIPTION

| | |
|---|---|
| AP 0-18cm | Dark brown (7.5YR 3/4) dry and dark brown (7.5YR3/2) moist; clay; strong coarse subangular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; none clay coatings; few irregular shaped fresh stones; non-cemented and non-compacted; none mineral concentrations; none calcareous; many fine roots; many fine interstitial pores and few termite channels; clear and smooth boundary. |
| Bt 18-50cm | Dark reddish brown (5YR3/2) dry and dark reddish brown (5YR2.5/2) moist; clay; strong coarse angular blocky structure; none mottles; sticky and plastic wet, friable moist and hard when dry; none surface cracks; few faint discontinuous clay coatings on ped faces; few irregularly shaped fresh stones; non-cemented and non-compacted; none mineral concretions; none calcareous; common fine roots; many fine interstitial pores and few termite channels; clear and smooth boundary. |
| B 50-102cm | Dark reddish brown (5YR3/4) moist; clay; strong coarse angular blocky; none mottles; sticky and plastic wet and friable when moist; none surface cracks; none clay coatings; none rock fragments; common hard medium rounded black manganese mineral concretions; none calcareous; few fine roots; many fine interstitial pores and few termite channels; abrupt and smooth boundary; Below 102cm highly weathered rock. |

| | |
|---|---|
| **Profile ID:** | **BA/CD3/CA (P6)** |
| Date: | 12/03/2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Chromic Cambisols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | $9^0$ 05.074'N, $37^0$ 07.70 E |
| Local soil name: | Biye Dima |
| Location: | Bako Tibe, Cheka Dimtu PA |
| Landform: | Plateau |
| Direction of slope face (Aspect): | West to East |
| Elevation (masl): | 1791 m |
| Depth to bedrock: | >200 cm |
| Effective soil depth: | > 200 cm |
| Slope gradient: | 19% |
| Slope form: | Irregular |
| Position: | Upper slope |
| Climate: | Tepid moist mid-highlands |
| Surface coarse fragments: | Dominant gravels, Stones & boulders |
| Parent material: | Basalt |
| Moisture status: | Dry throughout |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Slow runoff |
| Land cover: | Harvested field of pepper |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 25% of the unit is affected by severe sheet & moderate rill erosion.<br>b. Surrounding: About 40% of the unit is affected by moderate rill, severe sheet and slight gully erosion |

PROFILE DESCRIPTION

| | |
|---|---|
| AP 0-10cm | Very dark gray (7.5YR 3/1) dry and very dark brown (2.5YR2.5/3) moist; clay loam; strong medium subangular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; common irregular shaped fresh gravels and few irregular shaped fresh stones; non-cemented and non-compacted; none mineral concentrations; none calcareous; many fine roots; many fine interstitial pores; none biological activities; clear and smooth boundary. |
| B 10-28cm | Dark brown (7.5YR 3/3) dry and very dark gray (7.5YR 3/1) moist; clay; strong coarse angular blocky structure; no mottles; sticky and plastic wet, friable moist and hard when dry; no surface cracks; few distinct discontinuous clay coatings on pedfaces; common irregular shaped fresh gravels; non-cemented and non-compacted; none mineral concretions; none calcareous; Common fine roots; many fine interstitial pores; none biological activities; clear and smooth boundary. |
| BC 28-55cm | Dark brown (7.5YR3/4) dry and dark brown (7.5YR3/3) moist; clay; strong medium angular blocky structure; none mottles; sticky and plastic wet, friable moist and hard when dry; none surface cracks; none clay coatings; many irregularly shaped weathered gravels; non-cemented and non-compacted; none mineral concretions; none calcareous; Few fine roots; many fine interstitial pores; none biological activities; abrupt and smooth boundary. |

II. Site Characteristics and Profiles Description at Omo Nada District

| | |
|---|---|
| **Profile ID:** | ON/Wak1/AL **(P7)** |
| Date: | 02/ 05/ 2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Clayic Chromic Alisols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | $7^0$ 43.808 N, $37^0$ 12.153 E |
| Location: | Omo Nada,Waktola PA |
| Local soil name: | Biye Dima |
| Landform: | Plateau |
| Direction of slope face (Aspect): | West to East |
| Elevation (masl): | 1791 m |
| Depth to bedrock: | >200 cm |
| Effective soil depth: | > 200 cm |
| Slope gradient: | 19% |
| Slope form: | Irregular |
| Position: | Upper slope |
| Climate: | Tepid moist mid-highlands |
| Parent material: | Volcanic rocks |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Slow runoff |
| Land cover: | Harvested field of pepper |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 25% of the unit is affected by severe sheet & moderate rill erosion.<br>b. Surrounding: About 40% of the unit is affected by moderate rill, severe sheet and slight gully erosion |

## PROFILE DESCRIPTION ON/Wak1/AL

| | |
|---|---|
| AP 0-10cm | Dark reddish brown (2.5YR 3/4) dry and dark reddish brown (2.5YR2.5/3) moist; clay; moderate medium granular structure; sticky and plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; none mineral concentrations; none calcareous; many medium roots; common medium interstitial pores; few termite channels; abrupt and smooth boundary. |
| AB 10-30cm | Dark reddish brown (5YR 3/4) dry and dark reddish brown (2.5YR3/4) moist; clay; moderate medium angular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; none mineral concentrations; none calcareous; few coarse roots; few medium pores; few termite channels; abrupt and smooth boundary. |
| Bt1 30-110cm | Red (2.5YR 4/6) dry and red (2.5YR4/6) moist; clay; moderate medium angular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; many distinct continuous clay coatings on pedfaces; non-cemented and non-compacted; none mineral concentrations; none calcareous; few fine roots; few medium interstitial pores; none biological activities; gradual and smooth boundary. |
| Bt2 110-200$^+$ | Red (2.5YR 4/6) dry and dark reddish brown (2.5YR3/4) moist; heavy clay; moderate coarse angular blocky structure; sticky and very plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; many distinct continuous clay coatings on pedfaces; non-cemented and non-compacted; none mineral concentrations; none calcareous; few fine roots. |

| | |
|---|---|
| **Profile ID:** | ON/Wak2/AL **(P8)** |
| Date: | 02/ 05/ 2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Chromic Alisols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | $7^0$ 42.970 N, $37^0$ 12.506 E |
| Location: | Omo Nada,Waktola PA |
| Local soil name: | Biye Dima |
| Landform: | Terraced |
| Direction of slope face (Aspect): | East to West |
| Elevation (masl): | 1762 m |
| Depth to bedrock: | >200 cm |
| Effective soil depth: | > 200 cm |
| Slope gradient: | 10% |
| Slope form: | Concave |
| Position: | Lower slope |
| Climate: | Tepid moist mid-highlands |
| Parent material: | volcanic rocks |
| Moisture status: | Dry throughout |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Slow runoff |
| Land cover: | Harvested field of pepper |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 25% of the unit is affected by severe sheet & moderate rill.<br>b. Surrounding: About 30% of the unit is affected by moderate rill, severe sheet and slight gully erosion |

PROFILE DESCRIPTION ON/Wak2/AL

| | |
|---|---|
| AP 0-15cm | Dark reddish brown (5YR 3/3) dry and dark reddish brown (5YR3/2) moist; clay; Moderate medium granular structure; less sticky and less plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; none calcareous; common medium roots; common fine interstitial pores; few termite channels; abrupt and smooth boundary. |
| A 15-80cm | Reddish brown (2.5YR 4/4) dry and dark reddish brown (2.5YR3/4) moist; clay; moderate coarse subangular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; none mineral concentrations; none calcareous; many fine roots; few fine interstitial pores; abrupt and smooth boundary. |
| Bt1 80-120cm | Yellow red (5YR 4/6) dry and dark reddish brown (2.5YR2.3/4) moist; clay; weak medium angular blocky structure; sticky and plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; many distinct discontinuous irregular clay coatings on vertical ped faces; non-cemented and non-compacted; common black manganese nodules; none calcareous; common fine roots; none biological activities; abrupt and smooth boundary. |
| Bt2 120-200$^{+}$ | Dark reddish brown (2.5YR 3/4) dry and dark reddish brown (2.5YR3/3) moist; clay; weak medium angular blocky structure; sticky and plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; many distinct discontinuous irregular clay coatings on vertical ped faces; non-cemented and non-compacted; common black manganese nodules; none calcareous; very few fine roots; none biological activities. |

| | |
|---|---|
| **Profile ID:** | ON/Wak3/AL **(P9)** |
| Date: | 02/ 05/ 2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Chromic Alisols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | $7^0$ 44.248 N, $37^0$ 12.442 E |
| Location: | Omo Nada,Waktola PA |
| Local soil name: | Biye Dima |
| Landform: | Terraced |
| Direction of slope face (Aspect): | East to West |
| Elevation (masl): | 1762 m |
| Depth to bedrock: | >200 cm |
| Effective soil depth: | > 200 cm |
| Slope gradient: | 15% |
| Slope form: | Convex |
| Position: | middle slope |
| Climate: | Tepid moist mid-highlands |
| Parent material: | volcanic rocks |
| Moisture status: | Dry throughout |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Rapid runoff |
| Land cover: | Harvested field of pepper |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 26% of the unit is affected by severe sheet & moderate<br>b. Surrounding: About 30% of the unit is affected by moderate rill, severe sheet and slight gully erosion |

PROFILE DESCRIPTION ON/Wak3/AL

| | |
|---|---|
| AP 0-16cm | Dark reddish brown (2.5YR 3/4) dry and dark reddish brown (2.5YR3/3) moist; clay; moderate medium granular structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; none mineral concentrations; none calcareous; many medium roots; few fine interstitial pores; few termite channels; abrupt and smooth boundary. |
| A 16-40cm | Dark reddish brown (2.5YR 3/3) dry and dark reddish brown (2.5YR3/4) moist; clay; strong medium subangular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; none mineral concentrations; none calcareous; few fine roots; few fine interstitial pores; few termite channels; abrupt and smooth boundary. |
| Bt1 40-120cm | Dark reddish brown (2.5YR 3/4) dry and red (2.5YR4/6) moist; clay; strong medium subangular blocky structure; sticky and plastic wet, friable moist very hard when dry; none surface cracks; none mottles; few distinct continuous irregular clay coatings on vertical ped faces; non-cemented and non-compacted; none mineral concentrations; none calcareous; few fine roots; few coarse interstitial pores; abrupt and smooth boundary. |
| Bt2 120-200$^+$ | Red (2.5YR 4/6) dry and dark red (2.5YR3/6) moist; clay; strong coarse angular blocky structure; sticky and plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; few distinct continuous irregular clay coatings on vertical ped faces non-cemented and non-compacted; none mineral concentrations; none calcareous; very few fine roots |

| | |
|---|---|
| **Profile ID:** | ON/CD1/AN **(P10)** |
| Date: | 01/ 05/ 2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Mollic Andosols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | $7^0$ 17.739 N, $37^0$37.·739E |
| Location: | Omo Nada, Chalalaka Donga PA |
| Local soil name: | Biye Guracha |
| Landform: | Terraced |
| Direction of slope face (Aspect): | South to North |
| Elevation (masl): | 2406 m |
| Depth to bedrock: | >200 cm |
| Effective soil depth: | > 200 cm |
| Slope gradient: | 13% |
| Slope form: | Convex |
| Position: | upper slope |
| Climate: | cool highland |
| Parent material: | Tertiary volcanic rocks |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Rapid runoff |
| Land cover: | Harvested field of pea |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 40% of the unit is affected by severe sheet & high rill erosion<br>b. Surrounding: About 45% of the unit is affected by moderate rill, severe sheet and slight gully erosion |

PROFILE DESCRIPTION ON/CD1/AN

| | |
|---|---|
| AP 0-20cm | Very dusky red (2.5YR 2.5/2) dry and black (5YR2.5/1) moist; sandy clay loam; weak medium granular structure; friable moist slightly hard when dry; no surface cracks; none mottles; non-cemented and non-compacted; none mineral concentrations; none calcareous; common medium roots; few medium termite channels; abrupt and smooth boundary. |
| Bt1 20-60cm | Very dark grey (2.5YR 3/1) dry and black (2.5YR2.5/1) moist; clay loam; moderate medium angular blocky structure; friable moist slightly hard when dry; none surface cracks; none mottles; few distinct continuous clay coatings on vertical pedfaces; non-cemented and non-compacted; none mineral concentrations; none calcareous; common fine roots; few medium interstitial pores; abrupt and smooth boundary. |
| Bt2 60-120cm | Dark reddish brown (2.5YR 3/2) dry and dark reddish brown (2.5YR2.5/2) moist; clay; moderate medium subangular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; many distinct continuous irregular clay coatings on vertical ped faces; non-cemented and non-compacted; none mineral concentrations; none calcareous; few fine roots; gradual and smooth boundary. |
| BC 120-$200^+$ | Dark reddish brown (2.5YR 3/3) dry and dark reddish brown (2.5YR2.5/3) moist; clay; moderate coarse angular blocky structure; sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; many black manganese nodules; none calcareous and very few fine roots. |

|  |  |
|---|---|
| **Profile ID:** | ON/CD2/AN **(P11)** |
| Date: | 01/ 05/ 2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Umbric Andosols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | $7^0$ 17.997 N, $37^0$ 34.571 E |
| Location: | Omo Nada, Chalalaka Donga PA |
| Local soil name: | Biye Guracha |
| Landform: | Plateau |
| Direction of slope face (Aspect): | South to North |
| Elevation (masl): | 2530 m |
| Depth to bedrock: | >200 cm |
| Effective soil depth: | > 200 cm |
| Slope gradient: | 10% |
| Slope form: | Concave |
| Position: | upper slope |
| Climate: | cool highland |
| Parent material: | Tertiary volcanic rocks |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Rapid runoff |
| Land cover: | Harvested field of maize |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 35% of the unit is affected by severe sheet & moderate rill<br>b. Surrounding: About 40% of the unit is affected by high rill, severe sheet and slight gully erosion |

PROFILE DESCRIPTION ON/CD2/AN

AP 0-15cm Dusky red (2.5YR 3/2) dry and dusk reddish grey (2.5YR3/1) moist; sandy clay loam; weak medium granular structure; sticky and plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; none mineral concentrations; none calcareous; few fine roots; many medium interstitial pores; many termite channels; abrupt and smooth boundary.

AB 15-60cm Dark red (2.5YR 3/2) dry and dusk reddish gray (2.5YR3/1) moist; clay loam; moderate medium granular blocky structure; sticky and plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; none mineral concentrations; none calcareous; few fine roots; many medium interstitial pores; few termite channels; clear and smooth boundary.

Bt1 60-100cm Dark reddish brown (5YR 2.5/2) dry and dark (5YR2.5/1) moist; clay; moderate coarse subangular blocky structure; sticky and plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; much distinct continuous clays; coatings on vertical ped faces; non-cemented and non-compacted; none mineral concentrations; none calcareous; few fine roots; abrupt and smooth boundary.

Bt2 100-200$^+$ Yellowish red (2.5YR 4/4) dry and dark reddish brown (2.5YR3/4) moist; clay; moderate coarse angular blocky structure; very sticky and plastic wet, friable moist hard when dry; none surface cracks; none mottles; many distinct continuous clay coatings on vertical ped faces and discontinuous circular manganese coatings on voids; non-cemented and non-compacted; none mineral concentrations; none calcareous; very few fine roots; none biological activities.

| **Profile ID:** | ON/CD3/AN **(P12)** |
|---|---|
| Date: | 30/ 04/ 2017/18 |
| Author(s): | Berhanu Dinssa |
| Soil classification (FAO): | Mollic Andosols |
| Profile description status: | Routine profile description |
| Coordinate (WSG84): | $7^0$ 17.723 N, $37^0$ 17.195 E |
| Location: | Omo Nada, Chalalaka Donga PA |
| Local soil name: | Biye Guracha |
| Landform: | Plateau |
| Direction of slope face (Aspect): | South to North |
| Elevation (masl): | 2670 m |
| Depth to bedrock: | >200 cm |
| Effective soil depth: | > 200 cm |
| Slope gradient: | 7% |
| Slope form: | Concave |
| Position: | upper slope |
| Climate: | cool highland |
| Parent material: | Tertiary volcanic rocks |
| Soil drainage class: | Well drained |
| Human influence: | Ploughing |
| Surface drainage: | Rapid runoff |
| Land cover: | Harvested field of pea |
| Land use: | Annual field cropping |
| Erosion status: | a. Site: About 30% of the unit is affected by severe sheet & moderate rill erosion<br>b. Surrounding: About 40% of the unit is affected by moderate rill, severe sheet and slight gully erosion |

## PROFILE DESCRIPTION ON/CD3/AN

AP 0-17cm Dusk reddish gray (2.5YR 3/1) dry and dusky red (2.5YR2.5/2) moist; sandy clay; weak medium granular structure; sticky and plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; non-cemented and non-compacted; none mineral concentrations; none calcareous; many medium roots; many fine interstitial pores; many burrows; abrupt and smooth boundary.

Bt1 17-23cm Black (5YR 2.5/1) dry and reddish black (2.5YR2.5/1) moist; clay; moderate medium angular blocky structure; sticky and plastic wet, friable moist very hard when dry; none surface cracks; none mottles; few faint continuous clay coatings on vertical ped faces; non-cemented and non-compacted; none mineral concentrations; none calcareous; common fine roots; many fine interstitial pores; many large burrows; continues and smooth boundary.

Bt2 23-65cm Dusk reddish gray (2.5YR 3/1) dry and reddish black (2.5YR2.5/1) moist; clay; strong medium angular blocky structure; sticky and plastic wet, friable moist very hard when dry; none surface cracks; many distinct continuous irregular clay coatings on vertical ped faces; none mottles; non-cemented and non-compacted; common hard medium rounded black manganese coatings; none calcareous; few fine roots; abrupt and smooth boundary.

Bt3 65-105cm Dusk reddish brown (2.5YR 3/3) dry and dark Very dusky red reddish brown (2.5YR2.5/2) moist; clay; strong medium angular blocky structure; sticky and very plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; many distinct continuous irregular clay coatings on vertical ped faces and manganese coatings on voids; non-cemented and non-compacted; common black manganese nodules; none calcareous; few fine roots; abrupt and smooth boundary.

Bt4 105-200$^+$ Dark reddish brown (5YR 3/4) dry and dark reddish brown (5YR2.3/3) moist; clay; moderate coarse subangular blocky structure; sticky and plastic wet, friable moist slightly hard when dry; none surface cracks; none mottles; many distinct continuous irregular manganese coatings; abundant black manganese nodules; none calcareous; few fine roots.

**Appendix Table C:** Ratios of Silica /sesquioxide in elemental composition as an indicator of weathering stage for selected pedons at Bako Tibe and Omo Nada Districts

| **Pedon ID and depth(**cm) | **%$SiO_2$** | **%$Al_2O_3$** | **%$Fe_2O_3$** | **%$K_2O$** | **%$SiO_2$/ % $Al_2O_3$** | **% $SiO_2$ / % $Al_2O_3$ + %$Fe_2O_3$** | **Type of Clay minerals Present** |
|---|---|---|---|---|---|---|---|
| BA/SK1/NT 0-20cm **(P1)** | 37.07 | 27.04 | 16.14 | 0.63 | 1.37 | 0.86 | Al Oxide (gibbsite) |
| BA/SK1/NT 80-125 cm **(P1)** | 36.68 | 26.33 | 15.86 | 0.59 | 1.39 | 0.87 | Al Oxide (gibbsite) |
| BA/TS1/LV 0-20cm **(P4)** | 35.42 | 24.76 | 15.67 | 0.58 | 1.43 | 0.88 | Al Oxide (gibbsite) |
| BA/TS1/LV 80-110cm **(P4)** | 36.31 | 23.01 | 16.23 | 0.66 | 1.58 | 0.93 | Al Oxide (gibbsite) |
| ON/WAK1/AL 0-10cm **(P7)** | 44.03 | 21.45 | 12.81 | 0.92 | 2.05 | 1.29 | Al Oxide (gibbsite) |
| ON/WAK1/AL 110-200cm **(P7)** | 41.71 | 25.01 | 14.27 | 0.73 | 1.67 | 1.06 | Al Oxide (gibbsite) |
| ON/CD1/AN 0-20cm **(P10)** | 56.88 | 12.96 | 8.43 | 1.39 | 4.39 | 2.66 | Montmorillonite/Illite and Koalinite |
| ON/CD1/AN 60-120cm **(P10)** | 52.73 | 15.15 | 10.04 | 1.39 | 3.48 | 2.09 | Montmorillonite/Illite and Koalinite |

**Note:**

BA/SK1/NT 0-20 cm = Bako Tibe District, Sadan Kite PA, Pedon 1, Nitisols, 0-20cm (Surface soil)

BA/SK1/NT 80-125 cm = Bako Tibe District, Sadan Kite PA, Pedon 1, Nitisols, 80-125 cm (Subsurface soil)

BA/TS1/LV 0-20cm = Bako Tibe District, Tulu Sangota PA, Pedon 4, Luvisols, 0-20cm (Surface soil)

BA/TS1/LV 80-110cm = Bako Tibe District, Tulu Sangota PA, Pedon 4, Luvisols, 80-110cm (Subsurface soil)

ON/WAK1/AL 0-10cm = Omo Nada District, Waktola PA, Pedon 7, Alisols, 0-10cm (Surface soil)

ON/WAK1/AL 0-10cm = Omo Nada District, Waktola PA, Pedon 7, Alisols, 110-200cm (Subsurface soil)

ON/CD1/AN 0-20cm = Omo Nada District, Chalalaka Donga PA, Pedon 10, Andosols, 0-20cm (Surface soil)

ON/CD1/AN 0-20cm = Omo Nada District, Chalalaka Donga PA, Pedon 10, Andosols, 60-120cm (Surface soil)

**Appendix Table D:** Functional characteristics of chemical fertility

| Description | LCC | pH | | PBS | | $CaCO_3$ | | total CEC | | ESP |
|---|---|---|---|---|---|---|---|---|---|---|
| good | I | 6.6-8.4 | and | > 50 | And | < 40% | and | >10 | and | < 8 |
| Partly good | II | 5.6-6.5 | Or | 35-50 | Or | > 40% | or | 5-10 | or | < 8 |
| Moderate | III | 4.5-5.5 or > 8.4 | Or | < 35 | Or | Any | or | <10 | or | < 8 & 8-15 within 1 m |
| Low | IV | < 4.5 | and | Any | And | Any | and | Any | and | < 15 and any within 1 m |
| from good to low | V | Any | and | Any | And | Any | and | Any | and | < 8 and any within 1 m |
| from good to low | VI | Any | and | Any | And | Any | and | Any | and | < 8 and any within 1 m |
| very low | VII | Any | and | Any | And | Any | and | Any | and | > 15 |
| Any | VIII | Any | and | Any | And | Any | and | Any | and | Any |

*PBS = base saturation*

Source: (Costantini, 2009)

## Appendix Figures

## Appendix Figure A: Selected Field and Laboratory Photos

Appendix Figure A: Discussion with farmers during site selection

Appendix Figure B: Surface soil samples collection at Omo Nada Districts

Appendix Figure C: Surface Soil sample collection at Bako -Tibe District

Appendix Figure D: Soil sample collection

Appendix Figure E: Undisturbed Sample collection

Appendix Figure F: Soil profile description at Omo Nada of Jimma Zone

Appendix Figure G: Soil lab analysis at DZ Horticoop, Ethiopia

Appendix Figure H:  Lime application before maize planting at the farmers’ field

Appendix Figure I: The farmer at Bako Tibe comparing the cobe of maize and suggesting the best treatment

Above dround biomass data colllectiuon

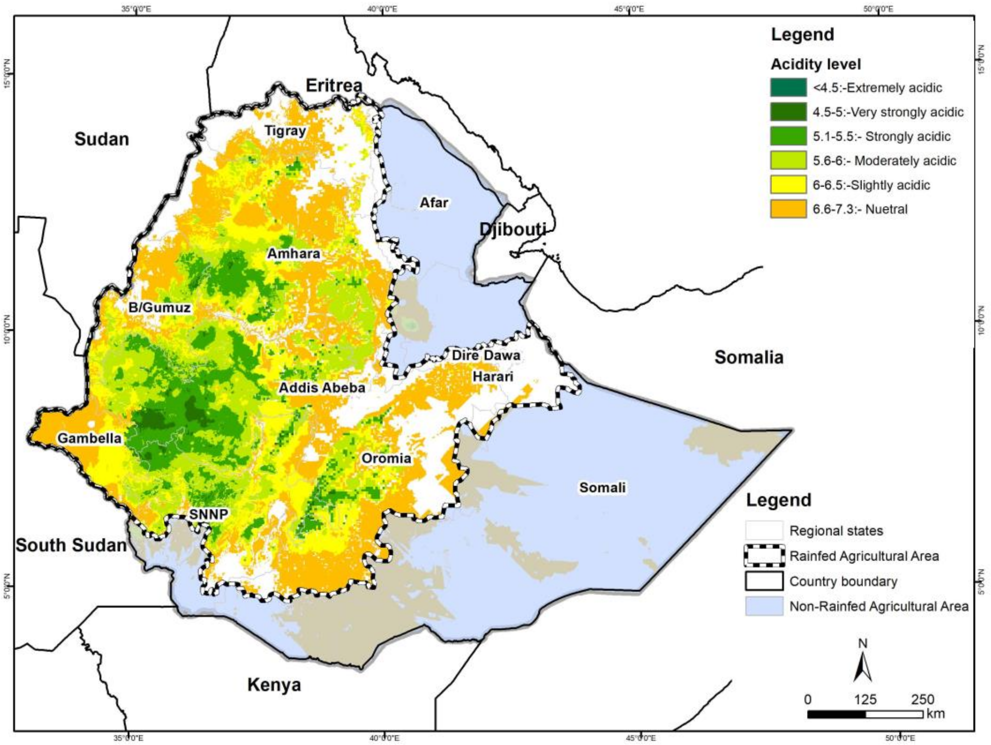
Appendix Figure J: The farmer (Sharafu Shebadiru) evaluating the best treatment resulted in the highest yield.

Appendix Figure K: Effect of Recomm. Lime + critical P rate on maize yield for Alfisols on farmer’s field, Mamado Abafita of Omo Nada, Jimma

I remember the saying of this farmer (Mamado Abafita) at Waktola kebele of Omo Nada district at the end of the fieldwork “Thank you Gashe for what you have done for the past 2 years. If you want my family to eat bread and improve their livelihood, before you leave Jimma, please convince the woreda’s agricultural officials to supply the required quantity of lime for our field on time”

Appendix Figure L: Wheat experimental plot (Andosols at Omo Nada of Jimma) that received 40 kg P ha $^{-1}$ + 46 kg N ha$^{-1}$

Appendix Figure M: Wheat P rate field experiment on Andosols, Omo Nada of Jimma Zone.



Appendix Figure N; The current extent of soil acidity (45%) in the rainfed agricultural land of Ethiopia**.** Source: Desta et al., 2021