



DEBREMARKOS UNIVERSITY
COLLEGE OF NATURAL AND COMPUTATIONAL
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DEPARTMENT OF CHEMISTRY

A thesis on:

**Physico-Chemical Properties, And Agricultural Potential of Soils Under
Different Land Uses the Case Gonji Kolela Woreda, North Gojjam Zone,
Amhara Region, Ethiopia**

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October, 2025

Debre Markos University, Ethiopia

DEBRE MARKOS UNIVERSTIY

RESEARCH AND GRADUATE PROGERAMS

PHYSICO-CHEMICAL PROPERTIES AND AGRICULTURAL POTENTIALS OF SOILS, UNDER DIFFERENT LAND USES THE CASE OF GONJI KOLELA WOREDA NORTH GOJJAM ZONE, AMHARA REGION, ETHIOPIA

A Thesis to be submitted to department of Chemistry College of Natural and Computational Sciences, Debre Markos University in partial fulfillment of the requirements for the degree of Master of Science in Analytical Chemistry.

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October, 2025

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Declaration

I hereby declare that, this thesis entitled “Physico-Chemical Properties and Agricultural Potentials of Soils, Under Different Land Uses the case of Gonji kolela woreda North Gojjam zone, Amhara region, Ethiopia” is my original work and is submitted in partial fulfillment of the requirements for a Master of science in Analytical Chemistry at Debre Markos University under the supervision of Adane Abebe (Ph.D.). I also declare that all or part of this work has not been submitted in this or any other university. All the sources of ideas and materials used for this research are honestly and timely acknowledged.

Name: Mehari Solomon Signature _____ Date _____

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APPROVAL OF THESSISS

I hereby certify that I have supervised, read and evaluated this thesis entitled “*Physico-Chemical Properties and Agricultural Potentials of Soils, Under Different Land Uses the case of Gonji kolela woreda North Gojjam zone, Amhara region, Ethiopia*” prepared by Mehari Solomon under my guidance. I recommend the thesis be submitted for oral defense.

Adane Abebe (Ph.D.)
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APPROVAL SHEET

We, the board of examiners hereby certify that the thesis prepared by **Mehari Solomon Tegegne** entitled “*Physico-Chemical Properties and Agricultural Potential of Soils, Under Different Land Uses the case of Gonji Kolela woreda North Gojjam zone, Amhara region, Ethiopia*” and submitted in partial fulfillment of the requirements for the award of Master of Science in Analytical Chemistry complies with the regulation of the university and meets the accepted standards with respect to originality and quality.

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ACKNOWLEDGEMENTS

First of all, I am grateful to the great GOD for providing health, strength, patience, and protection throughout my life and to the completion of this work. Next, I would like to thank my advisor, Adane Abebe (Ph.D.), for his invaluable guidance, valuable comments, corrections, and continuous support, which greatly contributed to the successful completion of this work. I am also grateful to Lihiket Design and Supervision Corporation for their support, as well as to Debre Markos University and all staff members of the Department of Chemistry for their assistance and encouragement throughout my study.

Finally, I want to extend my deepest gratitude to my family and friends for their unreserved support, encouragement, and guidance during my academic journey.

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List of Abbreviations

ATA.....	Agricultural Transformation Agency
ANOVA.....	Analysis of Variance
AV. P.....	Available Phosphorus
BD.....	Bulk Density
CEC.....	Cation Exchange Capacity
EC.....	Electrical Conductivity
EEPA	Ethiopian Environmental Protection Authority
ESP.....	Exchangeable Sodium Percentages
AAS.....	Atomic Absorption Spectroscopy
FAO	Food and Agriculture Organization
GDP.....	Gross Domestic Product
OC.....	Organic Carbon
OM.....	Organic Matter
SOM.....	Soil Organic Matter
TN.....	Total Nitrogen
USDA.....	United States Department of Agriculture
USEPA.....	United States Environmental Protection Agency

Abstract

The quality and fertility of soil are largely governed by its Physico-chemical properties, which include parameters such as texture, structure, pH, electrical conductivity, organic matter content, cation exchange capacity (CEC), total nitrogen, available phosphorus, and exchangeable bases. This study investigated the Physico-chemical characteristics of soils from different land uses in Gongi Zuria, Dim Dengay, and Washera areas, with an emphasis on method validation for multi-elemental analysis. Soil fertility parameters, including texture, bulk density, moisture content, pH, electrical conductivity, organic matter (OM), organic carbon (OC), total nitrogen, available phosphorus (Av. P), and exchangeable bases (Ca, Mg, Na, K), were systematically assessed to determine the effects of land use and management practices on soil quality. Recovery rates ranged between 96.0% and 104.0%, which meet international validation standards, demonstrating the robustness of the analytical procedure. Soil physical analysis revealed that Gongi Zuria and Washera soils were predominantly silty clay loam, whereas Dim Dengay soils were sandy clay loam. Bulk density values ranged from 1.29 to 1.32 g/cm³, and moisture content varied from 3.91% in cultivated Dim Dengay soils to 6.47% in uncultivated Gongi Zuria soils. Chemical analysis indicated that soil pH ranged from moderately acidic (5.84 at Dim Dengay cultivated) to neutral (7.03 at Gongi Zuria uncultivated). Organic matter content was highest at Gongi Zuria cultivated (8.27%) and lowest at Washera cultivated (5.07%). Total nitrogen values were below critical thresholds across all sites, while available phosphorus was generally deficient (<5 ppm), except for Gongi Zuria uncultivated soils. Exchangeable bases varied significantly by land use, with uncultivated soils consistently showing higher nutrient reserves compared to cultivated soils.

Key words: *Atomic Absorption Spectrophotometry, Gonji Kolela, Physico-Chemical parameters, Soil quality, Base Exchange heavy metals*

1. INTRODUCTION

1.1 Background of the study

Soil is one of the most essential natural resources that sustain life on Earth. It serves as a medium for plant growth, a reservoir of water and nutrients, and a habitat for countless organisms. The quality and fertility of soil are largely governed by its Physico-chemical properties, which include parameters such as texture, structure, pH, electrical conductivity, organic matter content, cation exchange capacity (CEC), total nitrogen, available phosphorus, and exchangeable bases (Brady et al., 2008). These properties not only determine the productivity of land but also influence its suitability for various agricultural uses.

Globally, increasing demand for food, fiber, and bioenergy has placed tremendous pressure on soils, making sustainable soil management critical. In many developing countries, including Ethiopia, agriculture remains the backbone of the economy and is heavily reliant on the quality of soil resources. However, land degradation; unsustainable farming practices, deforestation, and climate change have negatively impacted soil health, leading to declining productivity and food insecurity (Hurni et al., 2015).

Ethiopia possesses a diverse agro-ecological system with a wide range of soil types shaped by topography, parent material, climate, and land use patterns. Despite this diversity, a significant portion of Ethiopian soils is characterized by low fertility, high acidity in some regions, nutrient deficiencies, and poor organic matter content (Alemayehu and Bewket, 2016). These challenges are further exacerbated by population pressure and overexploitation of land, especially in highland areas where traditional farming systems dominate. While various studies have been conducted on soil fertility and degradation in different regions of Ethiopia, comprehensive and localized assessments of Physico-chemical soil properties that relate directly to agricultural potential are still limited (Shanko, 2023). Many regions lack detailed data on soil characteristics that are crucial for developing location-specific recommendations for crop production, soil conservation, and land use planning (Abebaw, 2019). Furthermore, there is often insufficient integration of soil property data with agricultural potential evaluation, leading to generalized soil management practices that may not be effective at the local level (Guo et al., 2019). Therefore, this study aims to assess the Physico-chemical properties and agricultural potentials of soils in a Gonji Kolela Woreda in the North Gojjam Zone of the Amhara Region, of Ethiopia.

The findings are expected to fill critical information gaps by providing detailed soil property data that can guide farmers, policymakers, and development planners in making informed decisions. Such data-driven interventions are essential for improving crop productivity, confirming environmental sustainability, and enhancing the flexibility of farming systems in Ethiopia.

1.2. Statement of the Problem

Agriculture remains the backbone of the Ethiopian economy, employing more than 70% of the labor force and contributing significantly to GDP and export earnings (Taffesse et al., 2012). Despite the agricultural significance of Gonji Kolela Woreda, farmers in the region face declining crop yields and inconsistent productivity. These challenges are often linked to poor soil fertility and inadequate knowledge of the soil's Physico-chemical properties. However, there is limited scientific data on the current status of soil quality motivate to conduct the study in the area. Without such information, it is difficult to implement effective soil management strategies or recommend suitable crops. Therefore, a detailed assessment of soil properties is essential to identify fertility constraints and unlock the agricultural potential of the region (Selassie and Ayanna, 2013).

1.3. Objective of the study

1.3.1. General Objective

The main objective of this study was to assess the Physico-chemical properties of soils and evaluate their agricultural potential under Different Land Uses in Gonji Kolela Woreda, North Gojjam Zone, and Amhara Region, Ethiopia.

1.3.2. Specific Objectives

The specific objectives of the study were:

- To determine the key Physico-chemical properties of soils Gonji Kolela Woreda including soil pH, electrical conductivity, organic carbon, organic matter (OM), total nitrogen, available phosphorus (P), and exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ , Na^+) and comparing them with national and *international* soil quality standards.
- To evaluate the agricultural potential of soils based on their Physico-chemical characteristics and their suitability for major crops cultivated in the area.
- To identify soil fertility constraints and recommend appropriate soil management and fertility improvement strategies for sustainable agricultural productivity in Gonji Kolela Woreda

1.4. Significance of the Study

The findings of this study will provide valuable insights into the fertility status and agricultural potential of soils in Gonji Kolela Woreda. It will help farmers, agricultural extension workers, and policymakers make informed decisions about crop selection, soil amendment, and sustainable land management. Moreover, the study contributes to the broader scientific understanding of soil health in Ethiopia's highland regions, supporting efforts to improve food security and rural livelihoods.

1.5. Scope of the Study

This study focuses on evaluating the Physico-chemical properties of soils in selected agricultural fields across three kebeles within Gonji Kolela Woreda. It includes analysis of soil pH, electrical conductivity, organic carbon, organic matter, total nitrogen, available phosphorus, and exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ , Na^+). Geographically, the study is limited to Gonji Kolela than covering the entire North Gojjam Zone or Amhara Region for several reasons. First, conducting research across a wider geographical scope would require extensive resources in terms of time, finance, and logistics, which were beyond the capacity of this study. Second, Gonji Kolela Woreda was selected purposively because it represents a typical area with agricultural potential and soil conditions relevant to the research objectives, making it a suitable case for study.

2. LITERATURE REVIEW

2.1. Introduction to Soils

Soil is a vital natural resource that plays an essential role in sustaining life on Earth by supporting plant growth, regulating water, recycling nutrients, and serving as a habitat for a wide range of organisms. It is formed through the weathering of rocks and the decomposition of organic matter over long periods, influenced by climatic conditions, topography, biological activity, parent material, and time (Brady and Weil, 2002). The composition and characteristics of soil differ widely across regions, depending on these soil-forming factors. Soils are complex systems made up of minerals, organic matter, water, and air, and their structure and composition significantly influence their physical, chemical, and biological properties

Understanding soil properties is crucial for various applications, particularly in agriculture, environmental management, and land use planning. Soil physicochemical properties such as texture, pH, electrical conductivity, organic carbon, total nitrogen, cation exchange capacity (CEC), and available phosphorus directly affect soil fertility and crop productivity (Agegnehu and Amede, 2017). For instance, soil texture influences water retention and drainage, while pH affects nutrient availability and microbial activity. The degradation or alteration of these properties due to erosion, pollution, or unsustainable land use can lead to declining agricultural productivity and ecological imbalance. In addition to its agricultural importance, soil also plays a critical role in environmental functions such as water filtration, carbon sequestration, and waste decomposition. The ability of soil to buffer pollutants, regulate greenhouse gas emissions, and store organic carbon makes it a key component in global climate regulation (Mukherjee, 2022). Hence, the study of soil properties and their variability is fundamental to promoting sustainable land use and environmental conservation. In Ethiopia, soil degradation is a major concern, particularly due to deforestation, overgrazing, and poor land management practices. Comprehensive assessment of soil properties in different agro ecological zones is essential to inform soil conservation strategies and improve land productivity. Therefore, reviewing the characteristics and dynamics of soil is not only scientifically significant but also practically important for ensuring food security and environmental sustainability.

2.2. Properties of soil

Although soils in general contain the same components, they differ in their properties or characteristics. These differences affect or determine the management of soils.

Soils differ in color, texture, structure, consistence, and fertility and productivity. Many years of proper soil management are required to change soil properties or characteristics. However, agricultural producers can make considerable improvements in the structure, consistence, and fertility and productivity of their soils (Munkholm, 2011).

2.2.1 Soil Physical Properties

Soil is comprised of minerals, soil organic matter (SOM), water, and air. The composition and proportion of these components greatly influence soil physical properties, including texture, structure, and porosity, the fraction of pore space in a soil. In turn, these properties affect air and water movement in the soil, and thus the soil's ability to function.

2.2.1.1. Soil Texture and Structure

Soil texture and soil structure are among the most critical physical properties of soil that directly influence its functionality, fertility, and suitability for agricultural use. Soil texture refers to the relative proportions of mineral particles sand, silt, and clay in a given soil sample. These particles vary significantly in size, with sand being the largest, followed by silt, and clay as the smallest. The texture of the soil influences water retention, drainage, aeration, and root penetration (Brady and Weil, 2002). For instance, sandy soils are known for their high permeability but low water and nutrient-holding capacity, while clayey soils retain water and nutrients well but often suffer from poor drainage and aeration. The classification of soil texture is typically based on the soil textural triangle developed by the United States Department of Agriculture (USDA), which helps determine the textural class by plotting the percentages of sand, silt, and clay.

Loamy soils, which contain a balanced mixture of the three particle types, are generally considered ideal for agriculture because they offer a compromise between water retention and drainage, making them highly fertile and easy to manage (Young, 2012). In contrast to texture, soil structure refers to the arrangement of soil particles into aggregates or peds. These structures can be granular, blocky, platy, prismatic, or columnar, and they influence how easily air and water move through the soil.

Good soil structure promotes root growth and microbial activity by creating a balance of pores that hold air and water. Conversely, poorly structured soils, especially those that are compacted or have massive structure, limit root expansion, reduce infiltration, and increase runoff and erosion risks.

The interaction between soil texture and structure is fundamental to understanding soil behavior. For example, a clayey soil with a strong granular structure may exhibit better permeability than a sandy soil with a compacted or poorly aggregated structure. Management practices such as tillage, organic matter application, and crop rotation significantly affect soil structure by influencing the activity of soil organisms and the formation of stable aggregates. Additionally, soil structure can be severely degraded through erosion, compaction, or continuous monoculture without organic inputs.



Figure.1. Top soil exhibiting granular structure(Salley et al., 2018)

2.2.1. 2.Bulk density

The mass of a unit volume of oven-dry soil is known as bulk density. Soil BD varies depending on the texture, structure, and organic matter content, among other factors. Soil bulk density is highly influenced by soil management practices such as land use type and soil management practices. For example, continuous cultivation raises bulk density resulting in decreasing of total porosity(Shepherd et al., 2016). Soils under cultivated land have much higher bulk density than soils under forest and grazing fields, according to(Gardiner and Miller, 2004). Similarly, found that as the cultivation period increased, the bulk density increased significantly. The advanced bulk density under the cultivated land might be related to the intensive tillage practices which may temporarily loosen the tilled soil layer and in the long term leads to increases in bulk density. In addition, the smallest organic matter (OM) content available in the cultivated land soils also contributes to the highest bulk density.

However, found that bulk density varied quantitatively very slightly between land use types (Table 1). The cause for this could be related to the study area's recent conversion of forest land to grazing and farmed lands.

In general, higher bulk density under cultivated land may be attributable to extensive tillage, constant exposure of the soil surface to direct rain drop impact under fields with long periods of continuous cultivation, and the lowest organic matter (OM) content available in the cultivated area.

2.2.2 Soil Chemical Properties

Soil chemistry is important to study because of its significant effects on crop yields. Obtaining high productivity while at the same time protecting the soil is what good soil stewardship is all about. The relationships among solids, liquids, and air largely determine the productive capacity of the soil. Soil chemistry involves the relationship between the minerals, the water, and other elements in the soil. In soil chemistry, the clay minerals are important (Kekane et al., 2015). Most clay minerals are composed of silicon and oxygen, called silicates. One of the important factors in soil fertility is the quantity and proper balance of nutrient elements.

2.2.2.1. Soil pH

Soil pH is a critical physicochemical property that significantly influences soil fertility, nutrient availability, microbial activity, and overall plant growth. It refers to the concentration of hydrogen ions in the soil solution and is expressed on a logarithmic scale ranging from 0 (highly acidic) to 14 (highly alkaline), with a pH of 7 being neutral. The pH of the soil affects the solubility and mobility of essential nutrients such as nitrogen, phosphorus, potassium, calcium, and magnesium, which are vital for plant development. In acidic soils (pH < 6.0), nutrients like phosphorus become less available due to fixation by iron and aluminum compounds, while in highly alkaline soils (pH > 8.5), micronutrients like iron, zinc, and manganese are rendered less accessible to plants (Oshunsanya, 2018). Soil pH also directly impacts microbial activity and the biological processes that drive organic matter decomposition and nutrient cycling. Many beneficial microorganisms, such as nitrogen-fixing bacteria and decomposers, perform optimally within a near-neutral pH range of 6.0 to 7.5 (EPA, 2004).

Therefore, deviations from this range may suppress microbial populations, hinder nitrogen fixation, and limit organic matter mineralization. This can reduce the soil's capacity to support healthy crop growth and lower agricultural productivity.

Moreover, soil pH influences the toxicity of certain elements; for instance, at low pH levels, toxic metals like aluminum and manganese can become more soluble and harmful to plant roots (Hailu et al., 2015). Various natural and anthropogenic factors affect soil pH, including parent material; rainfall patterns, land use practices, and crop management strategies.

In regions with high rainfall, leaching of basic cations (Ca^{2+} , Mg^{2+} , and K^+) tends to acidify the soil, whereas in arid and semi-arid areas, alkaline conditions may prevail due to limited leaching and accumulation of basic salts. Agricultural activities such as excessive use of ammonium-based fertilizers can also lead to soil acidification over time (Yimer et al., 2008). To manage soil pH, farmers often apply liming materials like calcium carbonate to neutralize acidity or use acid-forming fertilizers and organic matter to reduce alkalinity in calcareous soils. Understanding soil pH is essential for making informed decisions on soil management and crop selection. Regular monitoring and proper amendment practices help maintain a favorable pH range for optimal nutrient availability and plant performance. Consequently, soil pH is widely recognized as a key indicator of soil health and agricultural sustainability.

2.2.2.2. Soil electrical conductivity

Soil electrical conductivity is a key indicator of soil health and productivity, as it reflects the ability of soil to conduct an electrical current, which is primarily influenced by the concentration of soluble salts in the soil solution. EC is widely used as a measure of soil salinity and is affected by factors such as soil texture, moisture content, temperature, organic matter, and cation exchange capacity (CEC) (Zong et al., 2014). High EC values usually indicate saline conditions that can impede plant water uptake due to osmotic stress, potentially reducing crop yield and quality. Conversely, extremely low EC values might suggest nutrient deficiency or poor soil fertility. The EC of soil is typically measured in DeciSiemens per meter (dS/m), and optimal ranges for most crops fall between 0.2 and 1.2 dS/m, though sensitivity to salinity varies among plant species (Lal, 2015).

Elevated EC levels may result from natural processes such as the weathering of minerals or anthropogenic activities like excessive irrigation, use of saline water, and over-application of fertilizers. Furthermore, EC mapping has been employed in precision agriculture to monitor spatial variability and guide management practices such as variable-rate fertilizer application and irrigation scheduling.

2.2.2.3. Soil organic carbon (OC) and organic matter (OM)

Soil organic carbon (OC) and organic matter (OM) play crucial roles in maintaining soil health, fertility, and overall ecosystem functioning. Soil organic matter is a complex mixture of plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population.

It is broadly classified into active, slow, and passive pools depending on its decomposability and turnover time. Organic carbon, which typically comprises about 58% of soil organic matter, serves as a key indicator of soil organic matter content and is used in calculating OM from OC using a conversion factor (usually 1.724)(Carter, 2002) . Soil organic matter significantly enhances soil structure, water-holding capacity, nutrient availability, and biological activity. The presence of OM improves the aggregation of soil particles, thereby increasing porosity and promoting better aeration and water infiltration(Nelson and Sommers, 1982). It also acts as a buffer against pH fluctuations and toxic elements.

Furthermore, OM serves as a reservoir of nutrients such as nitrogen, phosphorus, and sulfur, which are released slowly to support plant growth through mineralization processes(Brady et al., 2008). Organic carbon, being a major component of OM, plays an essential role in the carbon cycle and contributes to mitigating climate change by sequestering atmospheric CO₂. The levels of OC in soils are influenced by factors such as vegetation type, land use, climate, topography, and soil management practices (Degu et al., 2019). For instance, soils under natural forests generally have higher OC contents compared to those under intensive agricultural use due to the continuous input of organic residues and minimal disturbance (Taffesse et al., 2012).The decline in soil OC and OM due to unsustainable land use and poor agricultural practices has been linked to land degradation, loss of soil fertility, and reduced crop yields(Nelson and Sommers, 1996). Practice such as continuous cropping, deforestation, excessive tillage, and insufficient residue return reduce OM input and enhance its decomposition, leading to depletion of the soil's carbon stock. On the other hand, conservation practices such as cover cropping; reduced tillage, organic amendments, and agroforestry have been shown to enhance soil OC and OM content over time (Six et al., 2004).

2.2.2.4. Total nitrogen

Soil total nitrogen is a fundamental indicator of soil fertility, reflecting the sum of organic and inorganic nitrogen forms that are available to plants and soil microorganisms. In most mineral soils, the bulk of TN exists as organic nitrogen, predominantly within soil organic matter (SOM), which undergoes mineralization to release plant-available ammonium (NH₄⁺) and nitrate (NO₃⁻). The rate and extent of this mineralization are governed by factors such as soil temperature, moisture, pH, and the quality of organic substrates, whereby higher C: N ratios tend to immobilize mineral nitrogen, while lower ratios promote net mineralization (Munkholm, 2011).

Accurate quantification of TN is therefore crucial for understanding nutrient cycling dynamics, predicting crop yield potential, and managing environmental nitrogen losses (Tewolde et al., 2020).

Numerous studies across diverse agro ecosystems have documented soil TN dynamics under different management regimes. For instance, long-term experiments in temperate regions demonstrate that no-till practices and incorporation of cover crops can increase TN stocks by 10–30% over conventional tillage within a decade. In tropical and subtropical soils, however, high rates of organic matter decomposition often result in rapid nitrogen turnover, making maintenance of TN more challenging without continual organic inputs (Ahmed et al., 2019).

Emerging research also underscores the role of soil micro biome composition in modulating TN mineralization rates, suggesting that practices fostering microbial diversity such as reduced chemical input and diversified crop rotations may enhance nitrogen use efficiency and mitigate losses to leaching or denitrification.

2.2.2.5. Available Phosphorus (P)

Phosphorus is one of the essential macronutrients required for plant growth and development, playing a critical role in energy transfer, photosynthesis, and nutrient movement within the plant. However, phosphorus availability in soil is often limited due to its strong fixation and low mobility. Available phosphorus refers to the fraction of total soil phosphorus that is readily accessible for plant uptake, usually measured by chemical extraction methods such as Bray I, Olsen, or Mehlich methods, depending on soil pH and type (Sims, 2000). Soil available phosphorus is influenced by several factors including soil texture, pH, organic matter content, and the presence of iron, aluminum, and calcium compounds which can bind phosphorus and reduce its availability (Ewunetu et al., 2021).

In acidic soils, phosphorus tends to form insoluble complexes with iron and aluminum oxides, whereas in alkaline soils, it precipitates with calcium, making it less available for plants. Organic matter can improve phosphorus availability by competing for sorption sites and through mineralization of organic phosphorus compounds (Maintaining adequate soil available phosphorus levels is crucial for optimal crop production; however, excessive phosphorus application can lead to environmental issues such as eutrophication of water bodies (Hurni et al., 2015, Nyakudya et al., 2005)). Therefore, accurate assessment and management of soil available phosphorus are vital for sustainable agricultural productivity and environmental protection.

2.2.2.6. Exchangeable bases (Ca^{2+} , Mg^{2+} , K^+ , Na^+)

These cations are adsorbed onto soil colloids and are readily available for plant uptake, influencing various physical and chemical soil properties (Brady et al., 2008).

Calcium is essential for cell wall stabilization and membrane function in plants and is also important for soil structure, promoting flocculation of clay particles and enhancing aeration and water movement. Magnesium, a central atom in chlorophyll molecules, is vital for photosynthesis and enzyme activation, and its availability often affects crop yields directly. Potassium is a key nutrient involved in regulating stomata opening, enzyme activation, and osmotic balance in plants; it also enhances drought resistance and disease tolerance (Yimer et al., 2008). Sodium, although not an essential nutrient for most plants, can influence soil physical properties and nutrient balance, particularly in saline and sodic soils where it may displace calcium and magnesium, leading to soil dispersion and reduced permeability.

3. MATERIALS AND METHOD

3.1. Description of the Study Area

The study was conducted in Gonji Kolela Woreda, located in the North Gojjam Zone of the Amhara Region, Ethiopia. It bordered in the east by Huleteju enessie Woreda, in the west by Yilmanadensa Woreda, in the south by Dega Damot Woreda, in the north by south Gondar zone Dera Woreda and in the southwest by Quarit Woreda. The administration seat of Gonji Kolela Woreda is Adis-alem, which is located 69 km far away from BahirDar, the capital city of Amhara national regional state (Kibret and Tulu, 2014). The woreda was selected as the study area due to its significant reliance on agriculture as a primary livelihood, coupled with increasing concerns about declining soil fertility and crop productivity. The woreda has diverse soil types and farming systems, yet lacks of adequate site-specific soil data. Under 29 kebeles three kebeles were purposefully selected to represent variations in topography, land use, and agricultural practices within the woreda, the study being representative of the area. Gonji kolela woreda geographically located between $11^{\circ} 2' 0''$ to $11^{\circ} 16' 0''$ N (latitude), $37^{\circ} 30' 0''$ to $37^{\circ} 53' 0''$ E (longitude) and altitudinal range of 1400-4350m above sea level (GKAO, 2025) . The area climate with a unimodal rainfall pattern, receiving an average annual precipitation of 1,200–1,600 mm and an average temperature ranging from 16°C to 25°C (Sewagegn and Aniley, 2025).

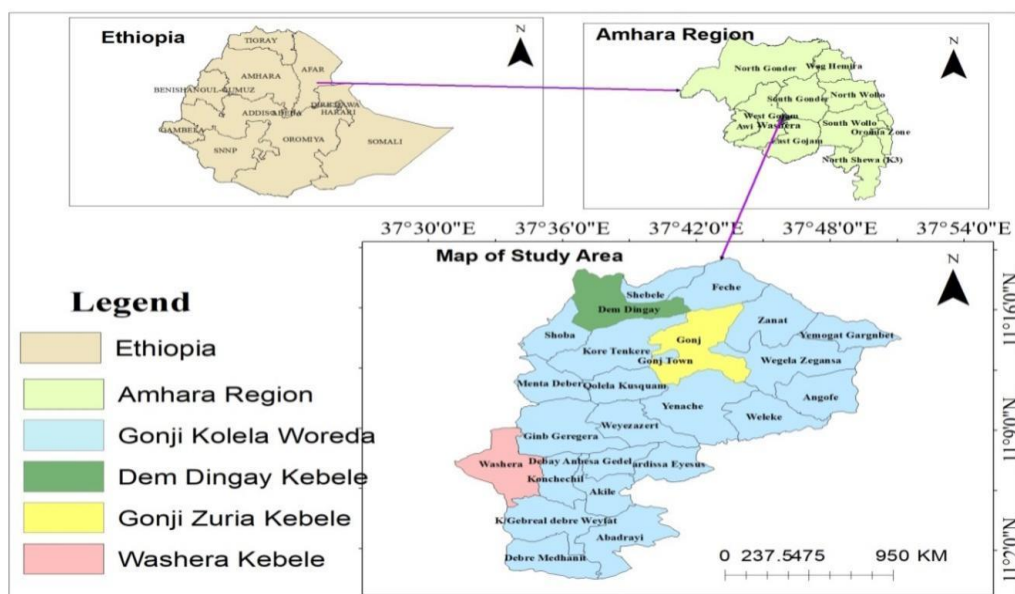


Figure .2. Location map of the study area (Offic, 2025)

3.2. Soil sample collection procedure

A preliminary survey and field observation were conducted to understand landforms, land use, topography, and vegetation. Then two major land use types were selected. Three cultivated (Gonji Zuria, Washera and Dim Dingay represented continuous agriculture and One uncultivated Gonji zuria represented fallow/natural land Sites were adjacent for comparative relevance. The selection was based on land use patterns, accessibility, and agricultural significance. After that sampling sites were identified with support from development agents and local farmers. Surface debris was removed prior to sampling to prevent contamination. From each site top soil samples (20 cm) were collected from four sub-samples in a zigzag pattern over 1 hectare using shovel. Finally, Sub-samples were mixed to form one composite sample per site and placed in clean, labeled plastic bags and transported to the laboratory.



Gongi zuria



Dim Dengay



Washera

Figure.3. Taking soil samples from the fields

3.3 Chemicals

Analytical grade chemicals such as potassium hydroxide, hydrochloric acid, Sulphuric acid, distilled water, acetic acid, Ammonium acetate, Sodium hydroxide solution, bromocresol green and methyl red, Boric acid solution, potassium Chloride solution, phosphoric acid, Digestion mixture (Potassium Sulphate and Copper Sulphate), cesium chloride solution, Calcium Sulphate Magnesium sulfate heptahydraten, Potassium chloride, Sodium chloride and potassium dihydrogen phosphate were used in the research.

3.4. Apparatuses and instruments

Electrical grinder, volumetric flasks, measuring cylinders, digital shaker, different sized test tubes, oven, Whatman filter paper, digital balance, different sized beakers, dropper, sieve, funnels, conical flasks, spatula, , electrical conductivity meter, Plastics bottles , Cooling apparatus, pipette, Kjeldahl apparatus, Burette, Digestion block heater, Magnet stirrer, Mortar and pestle, Automatic distilling device, distillation apparatus, muffle furnace, Thermometer, Spectrophotometer, pH meter, Flame photometer and Atomic Absorption Spectrometer(AAS).

3.5. Sample preparation

In this study, representative soil samples were air-dried, ground, and passed through a 2 mm sieve before analysis. For the determination of exchangeable bases (Ca, Mg, K, and Na), 5 g of the air-dried soil sample was extracted with 50 mL of 1 M ammonium acetate solution at pH 7.0 in a 250 mL Erlenmeyer flask. The suspension was shaken for 1 hour minutes on a mechanical shaker and then filtered through Whatman No. 42 filter paper. The filtrates were transferred into polyethylene bottles and preserved for elemental analysis, where Ca and Mg were determined using an atomic absorption spectrophotometer, while K and Na were measured using a flame photometer.

For available phosphorus, 2.5 g of the prepared soil sample was extracted with 50 ml of 0.5 M sodium bicarbonate (NaHCO_3) at pH 8.5 in a 100 mL Erlenmeyer flask. The suspension was shaken for 30 minutes and filtered through Whatman No. 42 filter paper. The clear extracts were collected in volumetric flasks and used for colorimetric determination of phosphorus by the molybdenum blue method with a spectrophotometer. All prepared extracts were stored in clean, labeled bottles at 4°C until further analysis. These procedures ensured accurate determination of exchangeable bases and available phosphorus in the studied soils (Soremi et al., 2017).

3.6. Preparation of Standard Solutions for exchangeable base and available phosphorus in soil Analysis

In this study, standard solutions of calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and phosphorus (P) were prepared for the determination of available phosphorus using the Olsen method and exchangeable bases using the ammonium acetate method. The procedure was as follows: Standard solutions were prepared by first labeled six 100 mL volumetric flasks for each element. Required volumes of 1000 mg/L stock solutions were calculated using the dilution formula.

The calculated volumes were then pipetted into the respective flasks. After that each flask was filled to the 100 mL mark with distilled water and mixed thoroughly by inverting several times (Buchholz et al., 2004). The prepared solutions were stored in a clean, cool environment until analysis. Subsequently, soil exchangeable Ca and Mg were analyzed by Atomic Absorption Spectrophotometry (AAS), while Na and K were determined by Flame Photometry using the ammonium acetate method (Knudsen et al., 1982). Available phosphorus was measured by Flame Photometry using the Olsen method.

3.7. Soil Physico-Chemical Analysis Method

The collected soil samples were exposed to various analyses to determine their Physico-chemical characteristics and agricultural potential. The methods employed are described below:

3.7.1. Analysis Methods of bulk density of soil

The bulk density of soil was determined using the excavation method. At each sampling point, a trowel was used to carefully excavate a known volume of soil from the surface layer, avoiding contamination from surrounding materials. The excavated wet soil samples from each site were immediately transferred into clean; sealable paper bags to prevent moisture loss during transportation to the laboratory. In the laboratory, the volume of the excavated soil was determined using the water displacement principle. Each soil sample was carefully placed into a graduated cylinder until it reached the 36 mL mark. The volume occupied by the soil was considered equivalent to the volume of water it displaced, taking into account the density of water at room temperature (Al-Shammary et al., 2018). This ensured accurate volume measurement for all four sampling points. After measuring the volume, the soil samples were oven-dried to determine their dry mass. Each sample was placed in a pre-weighed container and dried in an oven at 105 °C for 24 hours, ensuring complete removal of moisture.

The drying process was repeated three times for consistency, and samples were cooled in a desiccator to avoid moisture absorption from the air. The final mass of each dried sample was recorded using a digital balance., and then the bulk density was calculated for each sample using the formula:

$$\text{Bulk Density} = \frac{\text{Dry mass of soil(g)}}{\text{soil volume(cm}^3\text{)}} \text{-----}1$$

3.7.2. Analysis Methods of moisture content of soil

The determination of moisture content in soil by the gravimetric water content method involves a series of careful sampling, handling, and weighing steps to ensure accurate results. First, each soil samples were collected from the desired depth using a soil probe, following standard soil sampling procedures to maintain representativeness. Each sample was immediately placed into a clean, sealable paper bag to minimize moisture loss, properly labeled with the sample code, and transported promptly to the laboratory. 5 g of each field-soil sample (W) was measured using a digital balance. The samples were then placed in a hot-air oven and dried at a constant temperature of 105°C for 24 hours to remove moisture. After drying, the samples were removed from the oven, allowed to cool in a desiccator to prevent moisture absorption from the air, and weighed again to obtain the oven-dry weight (Tola et al., 2025). The moisture content was calculated using the formula:

$$\text{Moisture content (\%)} = [(W - W_d) / W] \times 100 \text{-----}2$$

Where, W = weight of soil before drying,

W_d = weight of dry soil

3.7.3. Analysis Methods of soil texture

The soil texture of the samples was determined using the ribbon method. First, a handful of each soil sample approximately 28 g was taken and moistened with distilled water until the soil became moldable. The soil was then massaged thoroughly by hand to confirm even mixing and to achieve a workable stability. In the second step, the moldable soil from each sample was rolled between the palms to form a ball structure. Afterward, in the third step, the soil balls were pressed between the thumb and index finger to form a ribbon by squeezing the soil upward. The length of the ribbon formed by each sample was measured using a ruler. Finally, in the fourth step, a portion of each sample was further wetted and rubbed between the fingers and palms to evaluate its feel, whether gritty (indicating sand), smooth (indicating silt), or sticky (indicating clay). These observations were used to classify the soil texture of each sample (Salley et al., 2018).

3.7.4. Analysis methods of soil pH

The determination of soil pH was carried out using the standard soil water suspension method. Initially, 10 g of air-dried soil was taken from each of the four sampling sites and placed into separate, clean, and dry plastic bottles.

To each bottle, 40 mL of deionized water was added, maintaining a soil-to-water ratio of 1:4, which is suitable for most agricultural soil pH measurements. The mixture was then vigorously shaken by hand for 30 minute to confirm proper dispersion of soil particles in water and thorough mixing.

The suspensions were allowed to stand for 30 minutes to enable the soil particles to settle and to allow equilibrium between the soil solution and solid phase. Before measurement, the pH meter was calibrated using a KCl standard solution to ensure accuracy. The pH of each soil suspension was then measured directly in the supernatant using the calibrated pH meter, and temperature readings were also recorded, as temperature can influence pH values. The results were noted for each sample in separately labeled beakers to avoid cross-contamination. For improved accuracy, it was advisable to perform the measurements in triplicate and take the average value (Couto, 2018).

3.7.5. Analysis Methods of Soil electrical conductivity

For the determination of electrical conductivity, the same 1:3 soil water suspension used for pH analysis was employed. After thorough stirring and settling, EC was measured directly from the supernatant using a digital EC meter. EC values indicate the concentration of soluble salts in the soil, which can influence plant growth and soil structure (Brown and Rodriguez, 1983).

3.7.6 Analysis methods of soil organic carbon and organic matter

To determine the organic matter and organic carbon content of soil samples, the ignition (loss-on-ignition) method was employed (Brown and Rodriguez, 1983, Robertson, 2011). The procedure began with proper sample preparation. Soil samples were first air-dried and passed through a 2 mm mesh sieve to remove large particles, stones, and visible organic debris. Each crucible was labeled and its empty weight accurately recorded using a digital balance. Then each sieved soil were placed into each crucible and dried in oven set at 105°C for 24 hours to eliminate moisture content. After drying, the crucibles were transferred to a desiccator and allowed to cool to avoid moisture absorption from the air. Once cooled, the crucibles weighed 10 g of oven-dried soil with digital balance. Next, the samples were ignited in a muffle furnace at 550°C for four hours to ensure complete combustion of organic matter. After ignition, the crucibles were cooled in a desiccator at approximately 10°C (Miller et al., 2013).

Finally, the percentage of organic matter was calculated based on the weight loss during ignition.

$$\% \text{ OM} = \frac{W_{\text{dry}} - W_{\text{ignited}}}{W_{\text{dry}}} \times 100 \text{-----} 3$$

Where, W_{dry} = Dry Weight of oven dried soil and W_{ignited} = Weight ignited soil

$$\% \text{ OC} = \frac{\% \text{ OM}}{1.724} \text{-----} 4$$

Where, 1.724 = conversion factor of 100/58

3.7.7. Analysis of Soil Total Nitrogen (Kjeldahl Method)

Total nitrogen was determined using the Kjeldahl digestion method. From each soil sample, 2 g of air-dried soil was first weighed into a digestion tube, after which 10 mL of concentrated sulfuric acid (H_2SO_4) added and heated. Then 2 g of a catalyst mixture (comprising 90% Potassium sulfate and 10% copper sulfate) were added. The mixture was heated until a clear green solution formed, indicating that organic nitrogen had been completely digested and converted into ammonium sulfate. Once digestion was complete, the solution was allowed to cool down to room temperature, and distilled water was added to dilute the digest to 100 mL in a volumetric flask. An aliquot of this digested solution was then transferred into a distillation unit, where 10 mL of sodium hydroxide (NaOH) solution was added to liberate ammonia gas. The released ammonia was trapped by 10 mL of 4% boric acid solution, which had been placed in a 100 mL Erlenmeyer flask. The trapped ammonia was subsequently titrated with standardized sulfuric acid (H_2SO_4), and the volume of acid used was recorded. Finally, the total nitrogen content was calculated using the formula (Bremner, 1996).

Analysis Methods of Soil Total Nitrogen

$$\% \text{ N} = \frac{(V_s - V_b) \times N_{\text{acid}} \times 14.007 \times 100}{\text{sample mass (mg)}} \text{-----} 5$$

Where, V_s = volume of acid used for the sample (ml), V_b = volume of acid used for the blank (ml), N_{acid} = normality of the acid, 14.007 = atomic mass of nitrogen

3.7.8. Procedure for analysis of soil available phosphorus (Olsen method)

To determine available phosphorus in soil, 2.5 g of air-dried soil was weighed into a 250 mL Erlenmeyer flask, and 50 mL of 0.5 M sodium bicarbonate (NaHCO_3 , pH 8.5) was added. The mixture was shaken for 30 minutes, allowing the phosphorus to be extracted into the solution. Following shaking, the suspension was filtered through filter paper, and an aliquot of the filtrate was taken for colorimetric analysis.

To this aliquot, ammonium molybdate and antimony potassium tartrate solutions were added to form a phosphomolybdate complex. Subsequently, ascorbic acid was added as a reducing agent to develop a blue color, which was then measured at 880 nm using a flame photometry (Olsen, 1954). Finally, the concentration of available phosphorus was determined by comparing the absorbance value with a standard calibration curve.

$$\text{Available P (mg/kg)} = C \times V/W \dots\dots\dots 6$$

Where, C = concentration of the element in mg/L

V = volume of extract ant used, in millilitres (mL) and

W = weight of soil sample, in grams (g)

3.7.9. Analysis methods of soil exchangeable bases (Ca²⁺, Mg²⁺, K⁺, Na⁺)

To determine the exchangeable bases (Ca²⁺, Mg²⁺, K⁺, and Na⁺), the ammonium acetate method at pH 7.0 is commonly used. Added about 5 g of air-dried and sieved (<2 mm) different soil sample in to each prepared bottles. Then shaken with 1 M neutral ammonium acetate solution in a 1:10 soil-to-solution ratio for 1 hour. The suspension was filtered, and the filtrate is analyzed. Exchangeable calcium (Ca²⁺) and magnesium (Mg²⁺) were measured using atomic absorption spectrophotometry (AAS), while potassium (K⁺) and sodium (Na⁺) were determined by flame photometry. This method ensures accurate quantification of the basic cations that are essential for soil fertility and plant nutrition (Yimer et al., 2008). Finally calculated exchangeable base

$$\text{Exchangeable base (cmol (+)/Kg)} = [(C \times V) / (E_w \times W)] \times 0.1 \dots\dots\dots 7$$

Where, C = concentration of the element in mg/L

V = volume of extract ant used, in millilitres (mL)

W = weight of soil sample, in grams (g)

0.1 = unit conversion factor (to adjust for mL and g to get cmol (+)/kg)

E_w = Equivalent weight of the element

3.8. Optimal validation method

To ensure the accuracy and reliability of the analytical results in assessing the Physico-chemical properties and agricultural potential of soils in Gonji Kolela Woreda, appropriate validation methods were employed.

The optimal validation approach incorporated both calibration coefficient determination and recovery testing.

Calibration curves were prepared for each soil parameter using standard solutions with known concentrations.

The correlation coefficients (R^2) of the calibration curves were calculated to assess the linearity of the instrument response, and values exceeding 0.995 were considered acceptable, indicating excellent analytical performance and precision. Calibration was performed routinely before sample analysis to ensure instrument stability (García-Alegría et al., 2015). In addition to calibration, recovery tests were conducted by spiking known quantities of standard solutions into pre-analyzed soil samples. The percentage recovery was calculated to evaluate the accuracy of the analytical method. Acceptable recovery rates ranged between 80% and 120%, confirming the method's capability to quantify analytes accurately in real soil matrices (Knudsen et al., 1982).

This combination of high correlation coefficients and acceptable recovery rates validated the analytical procedures used for determining key soil properties such as pH, electrical conductivity, total nitrogen, organic carbon, available phosphorus, cation exchange capacity (CEC), and exchangeable bases. Together, these validation techniques confirmed the reliability and scientific credibility of the results, supporting the study's conclusions on soil fertility and agricultural suitability in the study area.

$$\% R = \frac{CM \text{ spiked} - CM \text{ unspiked}}{CM \text{ added for spiking}} \times 100 \text{ -----}8$$

Where, Unspiked Conc = concentration found in the original (Unspiked) sample
Spiked Conc = concentration found after adding a known amount sample
Amount Added = the known concentration of the spike added and
% R = Percentage recovery

3.9. Data Analysis

Descriptive statistics (mean, and standard deviation) were used to summarize soil properties.

The

results were interpreted using standard ratings from literature such as national and international agricultural soil fertility guidelines to assess the suitability of the soils for agricultural production.

Relationships between soil parameters were evaluated using correlation analysis in SPSS software (version 26).

4. RESULTS AND DISCUSSION

4.1. Method validation

Table 1: The correlation coefficient, Slope intercept equation and recovery test to confirm analytical method validation

Metals	Concentrations of standard solutions (mg/L)	Correlation coefficient (R ²)	Slope intercept equation	Unspiked Conc (mg/L)	Spiked Conc (mg/L)	Amount added (mg/L)	%Recovery
Ca	0, 5, 10, 15,20,25	0.999	Y=0.038X + 0.011	5.20	7.18	2.0	99.0
Mg	0, 0.5, 1 ,1.5, 2, 2.5	0.997	Y= 0.055X - 0.001	2.49	2.48	2.0	98.0
Na	0,4, 8, 12, 16, 20	0.996	Y= 0.106X - 0.007	0.14	0.62	0.5	96.0
K	0,2, 4,6, 8, 10	0.995	Y= 0.113X -0.001	0.41	0.93	0.5	104.0
P	0, 0.4, 0.8, 1.2, 1.6, 2	0.998	Y= 0.288X +0.007	0.60	1.09	0.5	98.0

4.1.1. Calibration curves of standard solution

The concentrations of the standard solutions for Ca, Mg, Na, K, and P were chosen to ensure the calibration curve is accurate within the working concentration range. The correlation coefficient (R²) and regression equations obtained from the calibration curves of calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and phosphorus (P) indicate excellent linearity between the Atomic Absorption Spectroscopy (AAS). The correlation coefficients for all the metals were above 0.99, with Ca showing the highest R² value of 0.999, followed by P (0.998), Mg (0.997), Na (0.996), and K (0.995). An R² value greater than 0.995 is considered acceptable for analytical method validation as it demonstrates a strong linear relationship between analyte concentration and instrument response (Shabir, 2005). Thus, the results obtained in this study confirm that the calibration models used for the metal analysis were highly reliable and precise. The regression equations of the calibration curves also indicate sensitivity differences among the studied metals. For instance, potassium (K) and sodium (Na) showed relatively higher slope values (0.113 and 0.106, respectively), reflecting greater instrument sensitivity toward these elements compared to calcium (0.038) and magnesium (0.055).

Phosphorus (P) had the highest slope (0.288), indicating the strongest response per unit concentration, which is consistent with previous findings that certain non-metallic elements such as phosphorus yield higher absorption signals in spectrophotometric analysis (Bremner, 1996).

The presence of small positive or negative intercepts in the regression equations suggests minimal systematic errors, which can be attributed to instrument background noise or matrix interferences. However, the intercepts were relatively small compared to the concentration range, confirming that they did not significantly affect the accuracy of quantification.

4.1.2 Recovery test

Table 1: Recovery test for analytical method of exchangeable base and available phosphorus taken from different soil samples. The accuracy of the analytical method confirmed by spiked known amount of metal concentrations in to Unspiked analyzed concentration of metals of each soil samples. The recovery test of each metal and phosphorus concentration result calculated by the using equation (8). High accuracy and dependability of the process were shown by the recovery test results for calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), and phosphorus (P) in the examined soil water samples (Table 1). All tested metals had recovery percentages ranging from 96.0% to 104.0%, which is within the U.S. Environmental Protection Agency's recommended range of 80–120% for analytical and environmental investigations (Brereton et al., 2017). With recovery rates of 99.0% and 98.0% for calcium and magnesium, respectively, the technique demonstrated remarkable effectiveness in identifying alkaline earth metals without significant matrix interferences. Similarly, acceptable recoveries for salt (96.0%) and phosphorus (98.0%) demonstrated the procedure's dependability for trace mineral analysis in complicated soil water matrices. It's interesting to note that potassium showed a marginally greater recovery of 104.0%, which is still within the acceptable analytical recovery range despite being above 100%. Deviations exceeding 100% could be caused by minor changes in sample preparation and spiking procedures, matrix enhancement effects, or instrument sensitivity.

The recovery values' consistency indicates that the improved approach for multi elemental analysis is accurate and exact. Furthermore, the outcomes meet international validation standards like which mandate that analytical techniques show a satisfactory level of accuracy through recovery tests.

4.2. Soil physical properties

These characteristics are qualitative indicators and provide supportive evidence for the texture class designation. For instance, the smooth consistency and longer. Soil physical properties such as texture, bulk density, and moisture content are crucial for determining soil quality, fertility, and productivity. In the present study, texture was determined using the ribbon method, where ribbon length and the moistening and feel test were applied to classify soil texture classes (Brady et al., 2008). The ribbon length and smooth feel in Gongi Zuria and Washera soils corresponded to a silty clay loam texture, while the gritty feel and shorter ribbon length in Dim Dengay indicated a sandy clay loam texture. This difference is significant because sandy clay loam soils typically have lower water-holding capacity and reduced organic matter compared to silty clay loam soils, which are generally more fertile and better at retaining moisture. Bulk density values ranged from 1.29 to 1.32 g/cm³, while soil moisture content varied considerably across land uses, with the highest value (6.47%) in Gongi Zuria uncultivated land and the lowest (3.91%) in Dim Dengay cultivated soils. These variations reflect differences in soil management, organic matter input, compaction, and characteristic soil properties.

Table 2: Soil Physical properties influenced by different land uses

Soil sample	Soil physical properties					
	Texture			Bulk density	Moisture content (%)	
	Ribbon length(cm)	Moisten and feel	Texture class			
Gongi zuria with cultivated	4.25	Smooth	Silty Clay loam	1.32±0.000	5.57±0.86	
Gongi zuria with uncultivated	4.18	Smooth	Silty Clay loam	1.31±0.009	6.47±0.85	
Dim Dengay with cultivated	3.46	Gritty	Sandy Clay loam	1.29±0.039	3.91±0.087	
Washera with cultivated	3.87	Smooth	Silty Clay loam	1.32±0.000	5.22±0.084	
International guideline (FAO/USDA)	2.5-5	Smooth	Silty Clay Loam	1.1-1.4	5-10	
National guideline (ATA, 2014)	2.5 – 5	Smooth	Silty Clay loam	1.1 – 1.4	5-10	
Hazelton and Murphy (2007)	2.5-5	Smooth	Silty Clay Loam	1.1–1.4	5-10	

Uncertainty Values in the Results Table 2: The bulk density of Gongi Zuria cultivated soils was $1.32 \pm 0.000 \text{ g/cm}^3$, indicating no variation among replicates and reflecting highly uniform soil compaction with relatively low uncertainty of moisture content (5.57 ± 0.86) due to consistent of measurement. Similarly, Washera cultivated soils showed the same bulk density value and zero uncertainty, confirming consistent compaction and the moisture content was lowest uncertainty.

In contrast, Gongi Zuria uncultivated soils exhibited a slightly higher uncertainty of ± 0.009 around a mean bulk density of 1.31 g/cm^3 , suggesting minor natural variability in undisturbed soil structure with *moderate variability; possibly due to organic matter or structure*. The highest uncertainty of bulk density ($1.29 \pm 0.039 \text{ g/cm}^3$, and moisture content (3.91 ± 0.087) was observed in Dim Dengay cultivated soils, with a bulk density of $1.29 \pm 0.039 \text{ g/cm}^3$, indicating greater variability likely due to the gritty texture and less compact sandy clay loam soil (Fang and Katchova, 2023). Overall, the integration of both qualitative texture indicators (ribbon length, feel test) and quantitative measures (bulk density and moisture content with uncertainty values) provides an inclusive assessment of the soil physical properties. These findings highlight the effect of land use on soil structure, compaction, and water holding, which are critical for sustainable land management and crop productivity.

4.2.1. Soil texture

The amount of clay, silt, and sand particles determines the permanent feature of soil texture (FAO, 2019). The majority of the soils in this study were categorized as silty clay loam, which denotes a comparatively fine texture with moderate to low permeability and an excellent water-holding capacity. Because it efficiently holds moisture and nutrients, this texture type is frequently appropriate for crop cultivation when maintained appropriately (USDA, 2006, ATA, 2014). The silty clay loam textures found in the cultivated soils of Gongi Zuria and Washera were consistent with soils that are continuously farmed and frequently retain better particles as a result of thicker materials being worn. On the other hand, the sandy clay loam soils used for cultivation in Dim Dengay had a rougher texture and a larger sand concentration, which improved ventilation while decreasing water holding.

Both anthropogenic and natural soil-forming processes are responsible for the variations in texture between sites. In Gongi Zuria, for instance, uncultivated areas resembled farmed ones in texture, but their physical structure was better conserved, which improved their ability to retain moisture.

According to research done in Ethiopia, cultivated soils typically lose finer fractions as a result of cultivating and erosion, which results in coarser surface textures than uncultivated soils. (Safanelli et al., 2025). This is consistent with the finding in Dim Dengay, where greater exposure to the sand fraction was probably caused by farming.

4.2.2. Bulk density

Bulk density is a critical indicator of soil compaction and porosity. The values in this investigation fall within the permissible range for agricultural soils, ranging from 1.29 to 1.32 g/cm³. For loamy soils, the ideal bulk density for plant root growth usually falls between 1.1 and 1.4 g/cm³ (USDA, 2006). More than 1.6 g/cm³ frequently limits root penetration, lowers water infiltration, and lowers crop yield. Therefore, based on the reported data, it appears that the soils in these locations are not overly compacted and are still suitable for growing crops. However, some variations were noted between land users. Dim Dengay farmed soil has the lowest BD (1.29 g/cm³), but Washera and Gongi Zuria cultivated soils had the highest (1.32 g/cm³). The bulk density of Gongi Zuria cultivated soils showed no variation (1.32 ± 0.000 g/cm³), indicating highly uniform compaction, possibly due to consistent farming practices. Similarly, Washera cultivated soils recorded the same bulk density with zero uncertainty, reflecting stable soil structure. In contrast, Gongi Zuria uncultivated soils exhibited slightly higher uncertainty (1.31 ± 0.009 g/cm³), suggesting minor heterogeneity in undisturbed conditions. The highest uncertainty was recorded in Dim Dengay cultivated soils (1.29 ± 0.039 g/cm³), likely due to the sandy clay loam texture, which promotes less uniform compaction.

The sandy clay loam texture of Dim Dengay, which typically has bigger pore spaces and lower packing density than silty clay loam soils, may be the cause of the slightly lower BD. However, the finer particles and fewer macro pores in silty clay loam soils may be the cause of their greater BD. Ethiopia's national soil quality assessments (ATA, 2020) highlight that clay loam soils with BD above 1.4 g/cm³ frequently experience compaction issues, which lowers their agricultural output.

Given that the current study values fall below this cutoff; the soils can be regarded as reasonably advantageous. However, these values may ultimately rise as a result of management techniques including excessive cultivation, overgrazing, and decreased organic matter inputs. Thus, to preserve soil structure, organic matter addition and soil conservation are required.

4.2.3. Moisture content

Soil moisture content is an important determinant of crop productivity since it influences plant water availability, soil microbial activity, and nutrient cycling. Significant differences in moisture content between the various land uses were found by the study.

The lowest uncertainty in moisture content was observed in Washera cultivated soils ($5.22 \pm 0.084\%$), followed closely by Gongi Zuria cultivated ($5.57 \pm 0.86\%$). These values suggest consistent water retention capacity in silty clay loam soils under cultivation. Gongi Zuria uncultivated soils showed slightly higher variability ($6.47 \pm 0.85\%$), likely reflecting better-preserved soil structure and organic matter. Dim Dengay cultivated soils showed the highest uncertainty ($3.91 \pm 0.087\%$), attributed to the coarser texture and lower water-holding capacity of sandy clay loam soils. The uncultivated Gongi Zuria soil had the maximum moisture content (6.47 ± 0.85), while the farmed soils of Dim Dengay had the lowest (3.91 ± 0.087). These findings demonstrate how land use management affects soil water retention. Uncultivated soils generally retain higher moisture due to better organic matter buildup, undisturbed structure, and reduced evaporation rates. In contrast, cultivated soils are often subject to cultivation, which can disturb aggregates and increase evaporation, leading to reduced water retention (Tola et al., 2025). This claim is supported by the data from Gongi Zuria's uncultivated land, which, although having the same texture as its farmed equivalent, displayed higher moisture content. The soils grown in dim Dengay, which have a sandy clay loam texture, have the lowest moisture content. Due to the predominance of wide pores that drain rapidly under gravity, sandy soils are infamous for having a low capacity to hold water. The recorded figure in this study is consistent with soil water retention criteria, which state that sandy clay loam soils typically hold 3–6% moisture under field circumstances (USDA, 2006). Conversely, silty clay loam soils tend to hold 5–10% moisture, which is in line with the values seen in soils grown in Washera and Gongi Zuria (5.57 ± 0.86 and 5.22 ± 0.084) respectively.

4.3. Soil Chemical properties

The soil chemical properties across the studied sites Gongi Zuria (cultivated and uncultivated), Dim Dengay (cultivated), and Washera (cultivated) show clear variations influenced by land use and management practices. The major parameters assessed include soil pH, electrical conductivity, organic matter (OM), organic carbon (OC), total nitrogen, and available phosphorus (Av. P)(Young, 2012).

These parameters are critical indicators of soil fertility and agricultural productivity, and their values need to be interpreted in light of both national and international soil quality standards.

Table 3: Soil chemical properties influenced by different Land uses by related with standards

Soil samples	Soil Chemical properties					
	pH	EC(dS/m)	OM (%)	OC (%)	Total nitrogen (%) or (mg/kg)	AV. P (ppm)
Gongi zuria with cultivated	6.81±0.016	1.27±0.013	8.27±0.026	4.79±0.01	0.112±0.003	4.48±0.34
Gongi zuria with uncultivated	7.03±0.043	1.26±0.007	7.99±0.023	4.63±0.016	0.103±0.005	5.38±0.13
Dim Dengay with cultivated	5.84±0.019	1.22±0.006	7.06±0.016	4.09±0.008	0.091±0.001	3.94±0.36
Washera with cultivated	6.04±0.050	1.25±0.013	5.07±0.017	2.94±0.012	0.073±0.004	2.13±0.19
FAO,2006	6.0-7.5	< 2	> 3	> 2.4	> 0.5	5-15
National guideline (ATA, 2014)	5.6 – 6.5	< 2	> 2.6	> 1.5	> 0.2	5-15
Hazelton and Murphy (2007)	5.6 – 6.5	< 2	2.6 – 5.2	> 2.4	0.1 – 0.15	3.03 – 14.79

4.3.1. Soil pH

The pH of the soil varied from 5.84 in the farmed Dim Dengay to 7.03 at the uncultivated Gongi Zuria. While Washera (6.04) and Dim Dengay (5.84) displayed moderately acidic conditions, the cultivated (6.81) and uncultivated (7.03) soils of Gongi Zuria are in the slightly acidic to neutral range. The ideal soil pH range for the majority of crops is between 6.0 to 7.5, where microbial activity and nutrient availability are maximum, soil categorization (USDA, 2006). With a pH of 7.03, the uncultivated Gongi Zuria site fits in nicely with this ideal, indicating little disturbance and balanced soil chemical reactions. On the other hand, the lower pH of 5.84 in the cultivated soil of Dim Dengay suggests that the soil may have become acidic as a result of ongoing cultivation, the loss of organic matter, and possibly basic cation leaching (Ca^{2+} , Mg^{2+} , K^+ , and Na^+). Ethiopian soils are generally acidic in highland regions due to high rainfall and intensive cultivation. The relatively small uncertainty values (\pm) indicate that the measurements were consistent across the samples, suggesting uniformity of soil properties within each sampling site. For instance, the pH value of 6.81 ± 0.016 in Gongi Zuria cultivated soil shows minimal variation among samples. Dime Dingaye and Gonji zuria uncultivated moderately uncertain. Conversely, Washera with cultivated (6.04 ± 0.050) larger uncertainties would imply greater variability or lower measurement of precision. However, in the present study, uncertainties are generally small compared to the mean values, demonstrating good precision in measurements and reliable sampling methods. Acidic conditions, particularly below pH 6, can reduce phosphorus availability and increase the solubility of toxic elements like Al^{3+} and Mn^{2+} (Barrow, 2017). Thus, the relatively low pH at Washera and Dim Dengay suggests constraints for crop production unless amelioration practices such as liming are applied.

4.3.2. Electrical conductivity

The EC values showed non-saline conditions at all sites, ranging narrowly from 1.22 dS/m at Dim Dengay cultivated to 1.27 dS/m at Gongi Zuria cultivated. Soil Salinity Laboratory criteria state that soils with an EC of less than 2 dS/m are considered non-saline, meaning that crop growth should not be disadvantaged.

At an average of 1.25 dS/m, these values fall well below the salinity danger threshold. The absence of salinity problems reflects favorable conditions for agriculture.

However, the slight differences observed could be attributed to differences in land use intensity and organic matter levels, which influence ion retention and exchange. Compared with soil EC ranges reported by (FAO, 2006a).

The lowest uncertainty EC value of ± 0.006 Dim Dengay with cultivated and Gongi Zuria un cultivated soil shows minimal variation among samples. Conversely, larger uncertainties in Gongi zuria with cultivated and Washera with cultivated (± 0.013) would imply greater variability or lower measurement precision. However, in the present study, uncertainties are generally small compared to the mean values, demonstrating good precision in measurements and reliable. The studied soils are typical for highland areas, confirming their suitability for both cereal and leguminous plant cultivation without risk of salinity stress.

4.3.3. Organic matter (OM) and organic carbon (OC)

Organic matter (OM) ranged from $5.07 \pm 0.017\%$ at Washera cultivated to $8.27 \pm 0.026\%$ at Gongi Zuria cultivated, while organic carbon (OC) followed a similar trend, ranging from $2.94 \pm 0.012\%$ to $4.79 \pm 0.009\%$. According to (USDA, 2006, FAO, 2006a), soils with OM $> 3\%$ are considered fertile, supporting sustainable crop productivity. Despite land-use differences, all sites exhibited OM levels above this threshold, indicating generally good organic matter status. Among the samples, Gongi Zuria cultivated soils showed the highest OM ($8.27 \pm 0.026\%$) with relatively low uncertainty, suggesting a consistent organic input or management. Gongi Zuria uncultivated soil also showed high OM ($7.99 \pm 0.023\%$), with similarly low uncertainty, possibly due to stable vegetative cover and minimal disturbance. Dim Dengay cultivated soils reported moderate OM ($7.06 \pm 0.016\%$) with the lowest uncertainty, indicating uniformity in replicated measurements. Washera, with the lowest OM ($5.07 \pm 0.017\%$), also had low uncertainty, reflecting a consistent but depleted organic status likely a result of ongoing intensive cultivation, residue removal, and limited organic input. This is in line with research from Ethiopia (Dessie et al., 2022), which found that intensive management causes cultivated soils to lose up to 25–40% of their organic matter in comparison to uncultivated soils. Internationally, SOM is a key soil health indicator, influencing cation exchange capacity, soil structure, and water-holding capacity (Six et al., 2004, FAO, 2006b). The relatively high OM values ($> 5\%$) across the study sites suggest that the soils retain moderate to good fertility potential, though declining trends under intensive cultivation are evident.

4.3.4. Total nitrogen

At Gongi Zuria cultivated land, the total nitrogen content was $0.112 \pm 0.003\%$, while in Washera cultivated soils, it was lower at $0.073 \pm 0.004\%$.

According to (FAO, 2006b), soils with TN levels below 0.1% (1000 mg/kg) are considered nitrogen-deficient. Although the cultivated Gongi Zuria soil showed comparatively higher TN, it still falls below the optimal threshold required for high-yield crop production. This deficiency is consistent with widespread nitrogen depletion in Ethiopian highland soils, often attributed to continuous cereal cultivation, removal of crop residues, and limited application of both organic and inorganic fertilizers (ATA, 2014). The slightly higher TN in cultivated Gongi Zuria soils may result from periodic fertilizer or manure application (Asfaw et al., 2020). However, TN uncertainty ($\pm 0.003\%$) suggests a relatively stable estimate compared to Washera ($\pm 0.004\%$), where the lower mean value also coincides with higher uncertainty. This indicates a more variable nitrogen condition in Washera soils, likely due to intensified farming without adequate nutrient replenishment. Dim Dengay cultivated soils presented a TN of $0.091 \pm 0.001\%$, indicating lower nitrogen content with minimal uncertainty, suggesting consistent nitrogen depletion across sampled plots. Gongi Zuria uncultivated land showed $0.103 \pm 0.005\%$ TN, slightly below the threshold, with the highest uncertainty among all samples, possibly reflecting spatial variation in organic matter decomposition. Overall, the TN data not only reflect spatial variability in nitrogen status but also highlight differing levels of certainty in nitrogen estimation across sites. This suggests the need for more site-specific soil fertility management, especially in areas with both low nitrogen and high variability.

4.3.5. Available phosphorus (Av. P)

Available phosphorus ranged from 2.13 ± 0.19 ppm at Washera cultivated to 5.38 ± 0.13 ppm at Gongi Zuria uncultivated. Based on Olsen's classification, only the uncultivated Gongi Zuria soil (5.38 ppm) falls within the medium range (5–15 ppm), while the rest are considered phosphorus-deficient (< 5 ppm) (FAO, 2006b). The lowest available phosphate (Av. P) at Washera (2.13 ppm) is coupled with relatively high uncertainty (± 0.19), indicating variability likely due to strong P fixation under acidic conditions.

Dim Dengay (3.94 ± 0.36 ppm) also shows low availability with the highest uncertainty among all sites, suggesting inconsistent phosphorus levels, possibly from uneven nutrient depletion or fixation. Gongi Zuria cultivated soil (4.48 ± 0.34 ppm) shows moderate uncertainty and remains below the sufficiency threshold, reflecting nutrient mining from continued cultivation (ATA, 2014).

In contrast, the uncultivated Gongi Zuria soil not only has the highest Av. P but also the lowest uncertainty (± 0.13), indicating more stable phosphorus conditions due to limited nutrient disturbance. These findings align with international reports highlighting P limitation as a major factor reducing productivity in tropical soils (Sims, 2000). Overall, the variability in Av. P values across sites points to both deficiency and uncertainty in phosphorus availability, reinforcing the need for targeted soil fertility interventions.

4.3.6. Exchangeable bases

Table 4: Exchangeable bases influenced by the land uses by related with standards.

Soil samples	Exchangeable bases			
	Ca(cmol(+)/kg)	Mg(cmol(+)/kg)	Na(cmol(+)/kg)	K(cmol(+)/kg)
Gongi zuria with cultivated	10.74 \pm 0.16	2.35 \pm 0.10	0.15 \pm 0.01	0.37 \pm 0.03
Gongi zuria with uncultivated	12.93 \pm 0.38	2.32 \pm 0.19	0.13 \pm 0.03	0.46 \pm 0.07
Dim Dengay with cultivated	8.97 \pm 0.21	2.25 \pm 0.11	0.11 \pm 0.02	0.28 \pm 0.03
Washera with cultivated	5.23 \pm 0.08	1.76 \pm 0.18	0.09 \pm 0.01	0.19 \pm 0.03
International guideline (FAO/USDA)	5-20	0.5-8.0	0.1 – 0.3	0.2-2.0
National guideline (ATA, 2014)	6-15	1.0-5.0	0.05-0.20	0.2-0.8
Hazelton and Murphy (2007)	5-25	1.0-6.0	0.05-1.5	0.1-1.2

4.3.6.1. Exchangeable calcium (Ca)

Calcium is the dominant exchangeable base in most soils and plays a vital role in soil aggregation, root penetration, and neutralization of soil acidity. In this study, exchangeable Ca ranged from 5.23 ± 0.08 cmol (+)/kg in cultivated Washera soils to 12.93 ± 0.38 cmol (+)/kg in uncultivated Gongi Zuria soils.

Ca show higher concentrations in uncultivated soils likely due to minimal crop uptake and reduced leaching compared to cultivated soils, where these nutrients are frequently removed by harvest and may be lost through erosion or intensive farming practices.

The highest uncertainty was observed in uncultivated Gongi Zuria (± 0.38), indicating more variability in less disturbed soils, possibly due to natural heterogeneity. In contrast, Washera cultivated soils showed the least uncertainty (± 0.08), reflecting more uniform but depleted Ca status, likely due to prolonged land use. All values fall within the range reported for moderately fertile soils in Ethiopia (ATA, 2014). The lowest Ca concentration in Washera is just above the critical limit, suggesting deteriorating fertility. The high Ca in uncultivated Gongi Zuria reflects nutrient preservation. According to (USDA, 2006) soils with >10 cmol(+)/kg Ca are very fertile, and those <5 cmol(+)/kg may require amendment. Thus, while uncultivated lands retain high Ca with greater variability, cultivated sites show depletion with tighter distribution, emphasizing the need for Ca management.

4.3.6.2. Exchangeable Magnesium (Mg)

Exchangeable Mg levels ranged from 1.76 ± 0.18 cmol (+)/kg in Washera to 2.35 ± 0.10 cmol (+)/kg in cultivated Gongi Zuria. The uncertainty was highest in Washera (± 0.18), suggesting greater inconsistency possibly due to uneven depletion under cultivation. Gongi Zuria cultivated land showed lower variability (± 0.10), implying a relatively stable Mg status. According to (Keenan et al., 2015). (FAO, 2006a)), indicating balanced cation interactions. Therefore, although Mg concentrations are within acceptable ranges, higher uncertainty in Washera underlines the need for more consistent nutrient management in cultivated lands.

4.3.6.3. Exchangeable Sodium (Na)

Sodium values were low across all sites, from 0.09 ± 0.01 cmol (+)/kg in cultivated Washera to 0.15 ± 0.01 cmol (+)/kg in cultivated Gongi Zuria. The uncertainties were uniformly low (± 0.01 to ± 0.03), suggesting stable Na levels across samples.

The slightly higher standard deviation in uncultivated Gongi Zuria (± 0.03) may indicate slight natural variability, but still well within the safe range. According to USDA (USDA, 2006) all values fall within the non-sodic category (0.05–0.20 cmol(+)/kg).

Though Na levels are low and non-problematic, the marginally higher values in cultivated Gongi Zuria suggest potential accumulation from fertilizers or irrigation. Continued monitoring is recommended, especially where anthropogenic inputs might raise Na over time.

4.3.6.4. Exchangeable Potassium (K)

Exchangeable K ranged from 0.19 ± 0.03 cmol (+)/kg in cultivated Washera to 0.46 ± 0.07 cmol (+)/kg in uncultivated Gongi Zuria. K show higher concentrations in uncultivated soils likely due to minimal crop uptake and reduced leaching compared to cultivated soils, where these nutrients are frequently removed by harvest and may be lost through erosion or intensive farming practices. The highest uncertainty was observed in uncultivated Gongi Zuria (± 0.07), suggesting more spatial variability in K reserves in less disturbed soil. Cultivated soils such as Washera and Dim Dengay showed lower uncertainties (± 0.03), reflecting consistent depletion due to cropping. According to (Roy et al., 2006) , K below 0.2 cmol(+)/kg is deficient; hence, Washera is at the deficiency threshold. Ethiopian guidelines (ATA, 2014) similarly note K depletion in cultivated zones. The K:Mg ratios were within the optimal 0.2–0.5 range (Hazelton, 2007)), indicating balanced nutrient dynamics. However, the decline in cultivated soils, despite stable uncertainties, underscores the need for K replenishment through fertilization or organic inputs

5. CONCLUSIONS AND RECOMMENDATION

5.1. Conclusions

The present study evaluated soil quality parameters through recovery tests and assessment of physical and chemical properties across different land uses in Gongi Zuria, Dim Dengay, and Washera areas. The method validation results demonstrated excellent linearity and reliability of the calibration curves for Ca, Mg, Na, K, and P, with correlation coefficients (R^2) above 0.99, fulfilling international validation standards. Recovery tests further confirmed the accuracy and precision of the analytical procedure, with recovery values ranging between 96.0% and 104.0%, well within USEPA guidelines. Soil physical properties revealed that most sites had silty clay loam textures with favorable bulk density (1.29–1.32 g/cm³) and variable moisture content, strongly influenced by land use. Uncultivated Gongi Zuria soils retained higher moisture compared to cultivated sites, highlighting the role of management practices in soil water conservation. Chemical properties showed marked differences across sites: soils ranged from moderately acidic to neutral in pH (5.84 – 7.03), with non-saline EC values, generally good organic matter levels (>5%), but relatively low total nitrogen and available phosphorus compared to international fertility standards. Exchangeable bases (Ca, Mg, Na, and K) were adequate in uncultivated soils but showed depletion in intensively cultivated areas, particularly at Washera, where Ca and K approached deficiency thresholds. Overall, the findings indicate that while the studied soils possess moderate fertility and remain suitable for crop production, continuous cultivation without adequate replenishment of organic matter and nutrients is driving a gradual decline in soil quality. Sustainable land management strategies such as organic matter incorporation, balanced fertilizer application, and soil conservation practices are therefore essential to maintain soil health and agricultural productivity in the study areas.

5.2. Recommendation

Based on the findings of this study, several recommendations can be made to enhance soil fertility, sustain agricultural productivity, and ensure proper environmental management in the study areas:

- ✓ Falling fertility in cultivated soils, especially in Washera and Dim Dengay, farmers should apply integrated soil fertility management (ISFM) strategies, including the use of organic modifications (compost, dung, crop residues) along with balanced inorganic fertilizers.

- ✓ Exchangeable calcium and potassium levels were lower in cultivated Washera and Dim Dengay soils compared to uncultivated sites, suggesting nutrient depletion due to continuous cropping. Regular soil testing should be implemented, and where deficiencies are observed, site-specific fertilization or organic amendments should be applied to replenish these nutrients.
- ✓ To minimize soil moisture loss, mulching, terracing, contour plowing, and agroforestry practices should be promoted, particularly in sandy clay loam soils like Dim Dengay where water-holding capacity is low.

Further research is needed to assess the long-term impacts of land use changes on soil nutrient dynamics, heavy metal accumulation, and crop productivity in the area.

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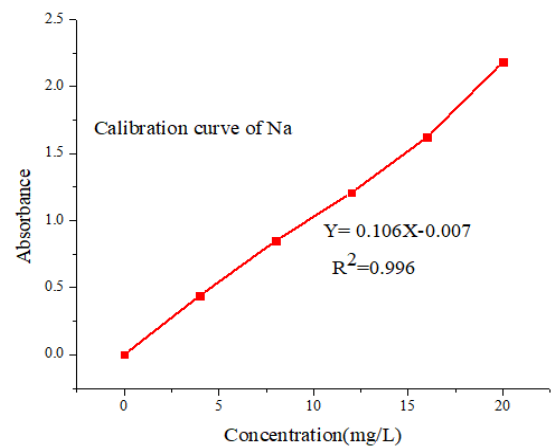
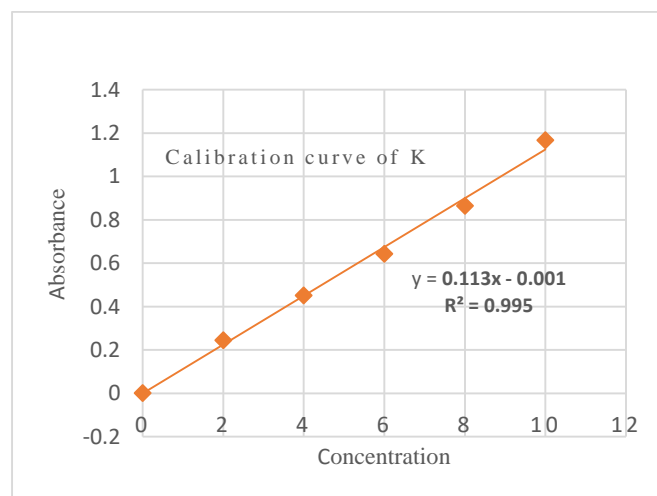
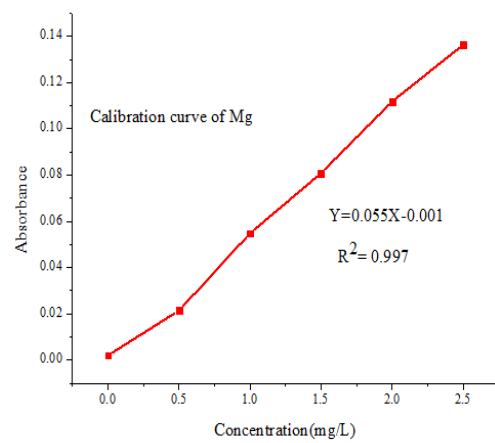
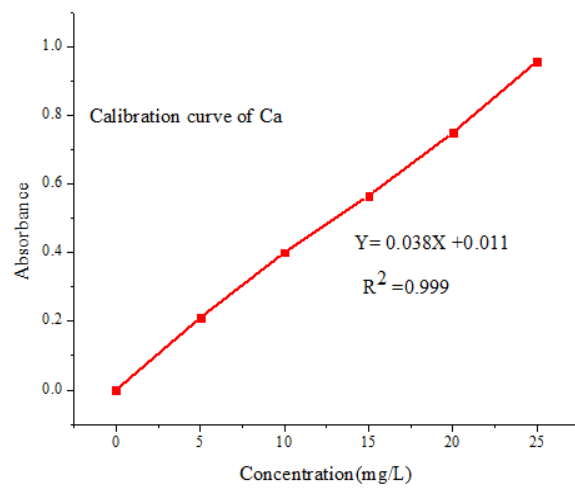
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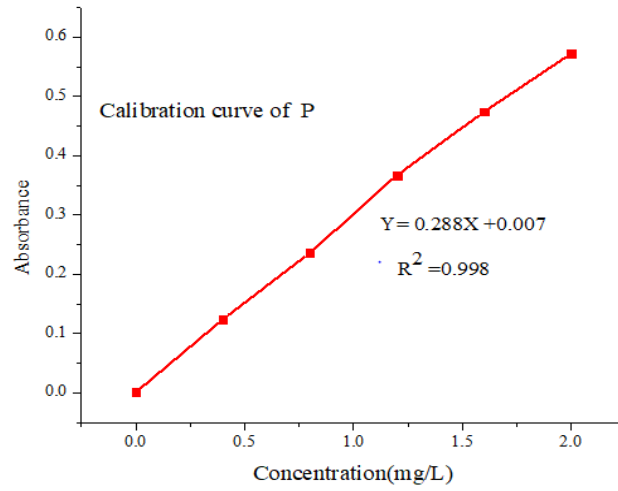
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APPENDIX

Appendix-1. Calibration curve of standard solutions metals in exchangeable base of soil analysis



Appendix-2. Calibration curve of standard solution phosphorus used in analysis of available phosphorus of soil



Appendix-3. Photo taken during soil sample analysis



Appendix- 4. The formula to describe recovery, accuracy and precision

$$\%R = \frac{\text{CM spiked} - \text{CM unspiked}}{\text{CM added for spiking}} \times 100\%$$

$$\bar{x} = \frac{\sum x_i}{n} = \frac{1}{n} \sum x_i$$

$$s = \sqrt{\frac{1}{n-1} \sum (x_i - \bar{x})^2}$$

$$\text{SE} = S/\sqrt{n}$$

Where: x_i = individual sample value

\bar{x} = mean value n = number of replicates

S = standard deviation and SE = standard error or uncertainty