SOIL CHARACTERIZATION AND POTASSIUM NUTRITION FOR WHEAT (*Triticum aestivum* L.) PRODUCTION ALONG THE TOPOSEQUENCE OF QENBERENAWETI SUB-WATERSHED, CENTRAL HIGHLANDS OF ETHIOPIA

PhD DISSERTATION

HAYMANOT AWGCHEW AJERSA

HAWASSA UNIVERSITY
COLLEGE OF AGRICULTURE

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Soil Characterization and Potassium Nutrition for Wheat (*Triticum aestivum* L.) Production along the Toposequence of Qenberenaweti Sub-Watershed, Central Highlands of Ethiopia

Haymanot Awgchew Ajersa

Major Advisor: Sheleme Beyene (PhD, Professor)
Co-Advisors: Alemayehu Kiflu (PhD, Associate Professor)
Asmare Melese (PhD, Associate Professor)

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Sheleme Beyene (PhD, Professor)	______________	__________
Major Advisor	Signature	Date
Alemayehu Kiflu (PhD, Associate Professor)	______________	__________
Co-advisor	Signature	Date
Asmare Melese (PhD, Associate Professor)	______________	__________
Co-advisor	Signature	Date

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Internal Examiner Signature Date

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Chairperson Signature Date

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DEDICATION

This Dissertation is dedicated to my enigmatic Babyboy, Leul.

STATEMENT OF THE AUTHOR

First, I declare that this dissertation is my own work and that all sources of material used in its preparation have been duly acknowledged. The dissertation has been submitted in partial fulfillment of the requirements for the Doctoral Degree in Soil Science at Hawassa University, and I hereby declare that this dissertation has not been submitted to any other institution for the award of any academic degree, diploma, or certificate.

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Name: Haymanot Awgchew Ajersa

Signature: ____________________

Place: Hawassa University, Hawassa

Date of Submission: April 08, 2026 G.C

BIOGRAPHICAL SKETCH

The author was born on 5th November 1987 in Addis Ababa, Ethiopia. He attended his elementary education at the Berhanena Selam Primary School from 1994 to 1999 and joined the Yekatit 23 Junior Secondary School in 2000. After two years, he enrolled at the Kolfe Comprehensive Senior Secondary School, and by 2005, he completed his preparatory session at the Addis Ketema Preparatory School, Addis Ababa. Then, he joined Hawassa University and obtained his BSc degree in Agriculture (Plant Science) on 11th July, 2009; and his MSc degree in Soil Science from Haramaya University on 13th March 2014.

He has been working at Debre Berhan University, College of Agriculture and Natural Resource Science, since 14th September 2009 as an instructor and researcher. Meanwhile, he joined the School of Graduate Studies of Hawassa University in October 2017 to pursue his PhD studies in the field of Soil Science.

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ACRONYMS AND ABBREVIATIONS

AAS	Atomic Absorption Spectro-photometer
ANOVA	Analysis of Variance
ATA	Agricultural Transformation Agency
ATDAO	Angolelana Tera District Agricultural Office
CMA	Cattle Manure Ash
CRD	Completely Randomized Design
CSA	Central Statistics Agency
CV	Coefficient of Variation
DEM	Digital Elevation Model
ESS	Ethiopian Statistics Service
FAO	Food and Agriculture Organization
GPS	Geographic Positioning System
IUSS	International Union of Soil Sciences
LSD	Least Significant Difference
m.a.s.l.	Meters above sea level
MAEE	Mean Absolute Estimation Error
MoARD	Ministry of Agriculture and Rural Development
MOP	Muriate of Potash
PCA	Principal Component Analysis
pH	Power of Hydrogen Ion
RMSE	Root Mean Square Error
RMSSE	Root Mean Square Standardized Error
SAS	Statistical Analysis Software
SD	Standard Deviation
SMU	Soil Mapping Units
SPSS	Statistical Package for Social Science
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WRB	World Reference Base

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MANUSCRIPT TITLES

The dissertation consists of the following manuscripts in chapters from which the first two are published, while the rest are ready for submission to open-access and reputable journals.

1. Haymanot Awgchew, Sheleme Beyene, and Alemayehu Kifilu (2024). Characteristics of Soil Types along the Toposequence in Central Highlands of Ethiopia. *Journal of Science and Development*, 12(1).
2. Haymanot Awgchew, Sheleme Beyene, and Alemayehu Kifilu (2024). Potassium adsorption capacity and desorption kinetics in soils of Qenberenaweti sub-watershed, central highlands of Ethiopia. *Heliyon*, *10*(10). https://doi.org/10.1016/j.heliyon.2024.e31336
3. Haymanot Awgchew, Sheleme Beyene, Alemayehu Kifilu, and Asmare Melese. Potassium forms and relations with selected physicochemical properties in soils of Qenberenaweti sub-watershed, central highlands of Ethiopia.
4. Haymanot Awgchew, Sheleme Beyene, Alemayehu Kifilu, and Asmare Melese. Internal and external potassium requirements of wheat (*Triticum aestivum* L.) on soils of Qenberenaweti sub-watershed, central highlands of Ethiopia.
5. Haymanot Awgchew, Sheleme Beyene, Alemayehu Kifilu, and Asmare Melese. Nature and effects of potassium-containing amendments on selected chemical properties of soils of Qenberenaweti sub-watershed, central highlands of Ethiopia.
6. Haymanot Awgchew, Sheleme Beyene, Alemayehu Kifilu, and Asmare Melese. Responses of wheat (*Triticum aestivum* L.) to integrated potassium fertilizers on soils of Qenberenaweti sub-watershed, central highlands of Ethiopia.

Soil Characterization and Potassium Nutrition for Wheat (*Triticum aestivum* L.) Production along the Toposequence of Qenberenaweti Sub-Watershed, Central Highlands of Ethiopia

By: Haymanot Awgchew[a,b], Sheleme Beyene[a], Alemayehu Kiflu[a], Asmare Melese[b]

[a] College of Agriculture, Hawassa University, Ethiopia

[b] College of Agriculture and Natural Resource Science, Debre Berhan University, Ethiopia

GENERAL ABSTRACT

Topography critically affects soil characteristics through its influence on pedogenesis, nutrient distribution, and crop productivity. Ethiopian agricultural production is constrained by soil degradation (erosion and fertility depletion) as well as by poor fertilization practices (suboptimal and unbalanced) and management (non-integrated and non-sustainable). Despite the nationwide decline in soil potassium (K) reserves (32 kg ha^{-1} yr^{-1}), its use remains neglected due to a historical assumption of soil sufficiency that led to K deficiency, reducing wheat (Triticum aestivum L.) yield far below 5 tons ha^{-1} in the highlands. This study addresses critical gaps in soil fertility management and K dynamics in Ethiopia's highland agriculture, focusing on the Qenberenaweti sub-watershed in the North Shewa Zone of the Amhara Region. The study area exemplifies these challenges: it lacks detailed soil characterization at local topographic scales, underutilizes cattle dung ash (a viable K-rich amendment), and relies on blanket K recommendations (50 kg K ha^{-1}) without considering soil and crop-specific factors. Cattle manure ash, though abundant as a byproduct of fuel use, is discarded by ignoring its potential to improve CEC, reclaim acidity, and supply nutrients (K, Ca, Mg). Therefore, this study was initiated with principal aims to characterize, classify, and map soils along the toposequence; to assess K forms (labile vs. non-labile), adsorption-desorption kinetics, and equilibrium dynamics; to determine optimum external and internal K requirements of wheat across soil types; as well as to evaluate K-containing organic (cattle manure ash, CMA) and inorganic (muriate of potash, MOP) amendments on soil chemical properties and productivity of wheat. The soil sampling followed a topographic approach throughout 317 ha of the watershed (2,808–2,960 m.a.s.l). The research methodology included: the World Reference Base (WRB) system of soil characterization and classification, K fractionation into its diverse forms; mathematical models in the K adsorption-desorption experiment; pot trial to establish critical K concentration for optimum internal and external requirements of wheat; and incubation trials comparing CMA and MOP (0–100% substitution) on soil properties and wheat responses. The findings revealed that topographic positions and slope features have directly shaped the extent of soil variability along the toposequence by determining water movement (drainage and percolation). All the K forms showed significant correlations ($p < 0.01$) among themselves and with soil pH, clay content, and CEC, influencing their availability. The Freundlich isotherm model ($qe = aCe^{b/a}$) performed well for the K-adsorption behavior of the entire soils that are characterized by non-linear increases in the K equilibrium concentration (Ce) and adsorbed amount (qe) due to the rising initial K (Ci) levels. The Power function model best fitted the desorption kinetics, which occurred in three distinct release phases over time: rapid (within 12 hours), gradual decline (72-168 hours), and stabilization (after 288 hours). The addition of K nutrient significantly ($P < 0.001$) improved the growth and yield of wheat, with the quadratic plateau and linear regression models estimating the *optimum external and internal K requirements as 24.48-30.75 mg K L^{-1} and 1.19-1.30%, respectively. The combined application of CMA:MOP at 37.5 to 62.5% ratios achieved the maximum wheat yield, with better N, P, and K harvest indices, owing to their balanced effects on overall soil properties, including pH, OC, exchangeable bases, and CEC. In conclusion, this work articulated the need for site-specific agricultural planning that addresses the localized heterogeneity of soils along the toposequence to sustainably enhance their fertility and productivity. For instance, it is necessary to prioritize CMA in acidic and low-OC soils and KCl blended ratios in high-buffer soils. However, further research on formulating precise fertilization of other essential elements, alongside vital agronomic and soil management practices (develop split fertilization schedules, water requirements, and crop rotation strategies), is needed to maximize profitable wheat production at the experimental site.*

Keywords: Toposequence Variability, Cattle Manure Ash, Muriate of Potash, Nutrient Uptake, Potassium Forms, Adsorption-Desorption Dynamics.

1. GENERAL INTRODUCTION AND DESCRIPTION OF THE STUDY AREA

1.1. General Introduction

1.1.1. Background

Soils are variable in their morphological, physical, and chemical features (Reichert *et al*., 2023; Karuma, 2019), which change laterally across the landscape and vertically down the soil profile (Begna, 2020; Singh, 2018; Yimer, 2017). The variations occur due to the actions of different natural conditions like topography, parent material, climate, biota, and time (Gelybó *et al*., 2018; Singh, 2018). Among these factors, topography is an inherent one that can influence processes of pedogenesis and distribution of soils on the landscape, attributed to slope gradient and soil moisture regime (Pawlik and Šamonil, 2018; Yu *et al*., 2018). It can also influence local and regional climates by changing the pattern of precipitation and temperature (Grose *et al*., 2019). Composition and distribution of vegetation (Ackerly *et al*., 2015), soil formation and organic matter (OM) decomposition (Zhu *et al*., 2019), and soil water relationships (Liang *et al*., 2017; Hu and Si, 2014) are subsequently influenced. Moreover, soil OM accumulation and mineralization, redox chemistry of nutrient availability and toxicity (Fe and Mn), gleying and ferrolysis processes, leaching and lessivage, water infiltration, as well as materials transfer and translocation are linked to hillslope processes (Sharma *et al*., 2023). Topographic features (slope gradient, altitude, form, and aspects) of a given area can influence the soil nutrients via controlling soil water budget, erosion, and deposition (Kumar, 2019; Chadwick and Asner, 2016). These components lead to an alteration in cation exchange capacity (CEC) and percent base saturation (Ma *et al*., 2024; Huntley, 2023). Thus, topography is regarded as a composite factor that combines various effects of crop production (Li *et al*., 2021; Franz *et al*., 2020), which is capable of determining the potential of agricultural land productivity (Kumar *et al*., 2020; Singha and Swain, 2016).

Crop production and soil characteristics are critically affected by variation in the physiography of agricultural lands (Abdu *et al*., 2023; Laekemariam *et al*., 2016). Understanding the nature and distribution of soils over an area is a criterion to develop a favorable management plan for efficient use of limited land resources and precise farming practices (Neupane and Guo, 2019; Shah and Wu, 2019), which secures sufficient and sustainable food supplies (Rehman *et al*., 2022; Shah and Wu, 2019). Despite the notable variability of soil types in Ethiopia due to the diversified topographical and ecological conditions (Regassa *et al*., 2023), the act of soil characterization is either limited to some potential areas or done with shallow observations and more generalization (Megarsa, 2023; Nyssen *et al*., 2019). Thus, sustainable soil management practices are not available for most parts of the country (Seifu *et al*., 2023; Debele, 2018).

Ethiopian agriculture is known for its low food productivity per unit area (Asfaw, 2017) that is unable to feed the ever-growing population (Hunde, 2017). The absence of inclusive evidence on the characteristics of soils and their management at the level of local variability is one of the key factors limiting the agricultural development of the country (Seifu and Elias, 2018), so it does particularly in the study area (Cherinet, 2017). Likewise, pressure from the fast-growing population causes overexploitation of soils and severe degradation of other land resources (Kibret *et al*., 2023; Wassie, 2020). Specifically, soils in the highlands of the country are severely degraded and nutrient-depleted (Bayata, 2024; Haile *et al*., 2023), which led to diminished productive capacity through changes in soil characteristics (Bayata, 2024; Kibret *et al*., 2023) and gradually became a serious threat to agricultural production (Haile *et al*., 2023). In addition, these areas are known for sub-optimal fertilization and little culture of using locally available natural inputs and byproducts (Esatu *et al*., 2017). As an indication, the leftover of biomass burning (dung-cake ash) is considered as waste material rather than an alternative source of soil amendment. Though the N content in ash is nil due to its conversion to NH_3, NO_X, and N_2 during the combustion process (Kacprzak *et al*., 2023; Oh *et al*., 2021), it is a good source of K, Ca, Mg, S, P, Mn, and some Fe, Al, Cu, Zn, Na, Si, and B (Maj *et al*., 2022; Szymajda *et al*., 2021). As a result, it improves soil fertility by increasing CEC and reclaiming acidity (Ndzeshala *et al*., 2023). Manure ash also increases the diversity and richness of ectomycorrhizal fungi (Jiang *et al*., 2021) with cellulose-decomposing and N-cycling soil micro-organisms (Davys *et al*., 2023).

The nationwide fertilizer trials indicated that more than 50% and 25% of Ethiopian soils are highly responsive to the addition of N and P, respectively (Kahsay, 2019; Woldekiros, 2018; Abdulkadir *et al*., 2017). Besides, less attention was given to other essential elements, and similar management approaches like blanket and/or suboptimal fertilizer applications have been practiced across the country without considering soil characteristics and related plant factors (Erkossa *et al*., 2022; Demiss *et al*., 2020). Such unbalanced nutrient management reduced both yield and quality of crop production by depleting soil nutrients (AbdelRahman and Metwaly, 2023; Getinet, 2021). For instance, the highest K depletion rate with a negative balance of 32 kg ha^{-1} yr^{-1} was reported on Ethiopian soils (Gadisa, 2021), mainly owing to inadequate and sole use of N and P, continuous and intensive cropping, absence of crop rotation and residue management, severe soil erosion, and excessive loss of OM (Gedamu, 2020; Laekemariam *et al*., 2018). Besides, the use of K-containing fertilizers is not commonly practiced for agricultural crop production in Ethiopia (Laekemariam *et al*., 2018), merely because of the 1968 Murphy's generalization that stated Ethiopian soils are rich in K (Kassa *et al*., 2021; Birhan *et al*., 2017). However, different reports showed that K is gradually declining in soils at many parts of the country, whereby a widespread K-deficiency has been noticed in some recent years (Misskire *et al*., 2019; Laekemariam *et al*., 2018). The deficiency has even been found in soils with optimum exchangeable K due to a very high amount of Ca and/or Mg on the ion exchange complex (Bayle *et al*., 2023; Laekemariam *et al*., 2018). As a case in point, application of K with optimum amounts of N and P increased growth and yield of wheat produced on Vertisols (Assefa *et al*., 2021; Ayele *et al*., 2020), Nitisols (Tesfaye *et al*., 2021; Ayele *et al*., 2020), Cambisols (Gebreslassie and Berhe, 2023), and other soil types in different parts of the country (Dargie *et al*., 2022; Godebo *et al*., 2021).

Improving soil fertility and productivity is very much critical to feed the ever-increasing population in Ethiopia by addressing the issue of balanced fertilization with the optimum rate (Senbeta and Worku, 2023; Zegeye *et al*., 2020). According to Alemu (2024), a maximum yield of 6 to 7 tons ha^{-1} was achieved in the country with a 6.1% productivity increment via the wheat research system. However, the yield in highland areas is still below 5 tons ha^{-1} (Nigus *et al*., 2022; Zegeye *et al*., 2020), owing to the depletion of soil fertility and poor fertilizer management (Asmamaw *et al*., 2023; Kihara *et al*., 2022). Thus, enhancing the production of wheat (*Triticum aestivum* L.) is promising to achieve enough food supply in the country (Mekuriaw, 2023; Zegeye *et al*., 2020), especially in the highlands (Kihara *et al*., 2022).

The concentration of K in the soil determines its use efficiency and yield of crops (White *et al*., 2021; Rawat *et al*., 2016). Hence, a test of soil K status provides valuable information for possible improvement of soil fertility and proper fertilization (Bell *et al*., 2021; Dotaniya *et al*., 2016). There are many standard K extraction methods with different effectiveness in estimating the availability of soil K (Cheng *et al*., 2023; Demiss *et al*., 2020). Fortunately, the use of various techniques to determine the availability of K for crop absorption and production is necessary for proper K management for a given soil type (Sarkar and Patra, 2017). For example, because the labile (exchangeable and water-soluble forms) K fraction is readily available, the majority of K management and recommendation practices are made utilizing the traditional NH_4OAc extraction method (Das *et al*., 2018; Islam *et al*., 2017). However, a substantial role of the non-labile (non-exchangeable and structural) K fraction is evidenced in plant nutrition (Kishore *et al*., 2020; Das *et al*., 2019). That means K availability cannot be explained by the labile contents alone (Rao and Srinivas, 2017; Lalitha and Dhakshinamoorthy, 2014). In this regard, the NH_4OAc method becomes a poor indicator of K supply and uptake during the plant growing season (Charbonnier, 2022; Islam *et al*., 2017). Subsequently, a proper K management strategy should consider the distribution of all K forms and the dynamic equilibrium among them (Aswad *et al*., 2020; Blanchet *et al*., 2017; Chatterjee *et al*., 2015).

The K adsorption-desorption process depends on the level of soil solution K^+, the type of clay minerals, the amount of OM, and soil moisture (Havlin *et al*., 2017; Liao *et al*., 2013). Generally, the fixation of K is faster than the release (Havlin *et al*., 2017; Mouhamad *et al*., 2016) due to the strong binding by the inorganic (clay) and organic (OM) colloids (Ghiri and Abtahi, 2012; Zhang *et al*., 2009). Based on the rate and speed of K removal, the initial adsorption equilibrium in the soil solution phase serves as the K release index (Al-Obaidi *et al*., 2015; Khalil, 2013). The appropriate K nutrient management practice for increasing crop production should consider the adsorption-desorption mechanism (Li *et al*., 2014; Simonsson *et al*., 2009). Assessment of K dynamics in soils under a given watershed is crucial (Akbas *et al*., 2017; Blanchet *et al*., 2017) since it determines the effectiveness of fertilization strategies (Bangroo *et al*., 2012) by predicting the possible fates of the applied K nutrient (Kenyanya *et al*., 2013). Hence, the concept of quantity-intensity has received attention to make better K fertilizer recommendations because of its key information on K availability (AL-Obaidi *et al*., 2020; Bilias and Barbayiannis, 2019).

The adsorption isotherm technique is proven as the most accurate method to predict and evaluate the optimum amount of nutrients required for maximum growth and yield of crops (Palanivell *et al*., 2021; Dunne *et al*., 2020). The approach can also determine the ability of soil to supply K and the exchange of K from the available pool by other ions such as Ca^{2+} (Kassa *et al*., 2019; Kenyanya *et al*., 2014). Since K uptake is affected until it attains its critical concentration (Mengel, 2016; Jatav *et al*., 2012), K optimization for maximum crop production relies on the soil's available K content and the crop's K demand (Aurangzeib *et al*., 2021). Accordingly, an optimized K fertilization calls for the concept of internal and external nutrient requirements, which can be expressed in terms of quantity, intensity, and capacity factors in plant nutrition (Alemayehu, 2019).

A balanced use of organic and inorganic amendments can improve the overall fertility and productivity statuses of Ethiopian soils (Wato *et al*., 2024; Abebe *et al*., 2022). Unfortunately, the majority of farmers in the country do not know how combined fertilization enhances soil physicochemical properties and crop productivity (Wato *et al*., 2024). Despite the relative returns of mineral fertilizer, it is expensive for small-scale farmers and harmful to the soil system (Abebe *et al*., 2022; Reda and Hagos, 2017). Conversely, the organic form optimizes the soil habitat and releases diverse essential nutrients in slow and steady modes to nourish soil organisms (Wato *et al*., 2024; Bhunia *et al*., 2021). For example, cattle manure and its ash increase the efficiency of mineral fertilizers (N, P, and K) by improving the physicochemical properties of soils (Chali and Genati, 2021; Zewide *et al*., 2019).

In general, the efficacy among the amendments varies notably with soil types due to inherent factors like texture, pH, OM, and nutrient buffering capacity (Shao *et al*., 2024; Ndzeshala *et al*., 2023). Understanding such soil-specific interaction is vital for developing sustainable nutrient recommendations for a given area (Meyer *et al*., 2020; Selim, 2020), as their combinational ratio determines the extent of nutrient availability, uptake, and translocation (Gessesew *et al*., 2022; Wajid *et al*., 2020).

1.1.2. Statement of the problem and justification

The detailed nature and distribution of soils along the toposequence of Qenberenaweti sub-watershed are unknown, implying that the soils have not been characterized, classified, and mapped before this work. The study area is recognized for low productivity of field crops, mainly due to poor soil management and unwise utilization practices. Also, less attention has been given to the use of K nutrient; hence, the possible effects of K-containing amendments on the soils and plants are poorly known in the area. Cattle dung-cake is one of the principal fuel sources in the area, but it is not well used as an alternative K amendment in its ash form; it is rather considered as a trash material. Although the soils of the area contain an optimum amount of exchangeable K, applying 50 kg K ha^{-1} was recommended based on the crops' requirements (ATA, 2016) without considering the soils' characteristics and related environmental factors. Generally, the diverse K forms, their adsorption capacity, release kinetics, and critical requirement levels for maximum wheat crop growth, have not yet been studied at the site.

Therefore, this study was initiated with the following set of objectives.

1.1.3. Objectives

General Objective:

- To characterize the soil types and optimize their potassium nutrition for better wheat crop production along the toposequence of Qenberenaweti sub-watershed.

Specific Objectives:

- To characterize, classify, and map the soils along the toposequence of Qenberenaweti sub-watershed;
- To analyze the status of potassium fraction in relation to selected physico-chemical properties and its adsorption-desorption dynamics in soils of the study area;
- To determine the optimum levels of external and internal K requirements of wheat; and
- To evaluate the effects of K-containing amendments on soil chemical properties as well as wheat growth, yield, and K-uptake responses.

1.1.4. Hypothesis of the study

The study area has a unique topographic feature showing the presence of diverse soil groups formed on a parent material with variable geospatial distribution. The different soil types have their own physicochemical properties and K dynamics, which can affect the growth and yield of the wheat crop by determining the optimum internal and external K requirements. Besides, the application of different K-containing amendments can change the chemical properties of the soils, including the K fraction, adsorption capacity, and desorption kinetics of the soils along the toposequence. The growth and K uptake efficiencies of the wheat crop can also vary with the soil type and can be improved with balanced application of K-containing amendments. Thus, the following hypotheses are formulated.

- Soils have unique morphological, physical, and chemical properties due to differences in topographic features.
- Physicochemical properties determine the overall status of soil K fractions.
- Different soil groups vary in K adsorption capacity and desorption kinetics.
- The maximum growth and yield of wheat on different soil types depend on optimum levels of both external and internal K requirements.

- Application of K-containing amendments changes selected soil chemical properties and alters/modifies the availability of K in different soil types.
- Varying rates of K-containing amendments affect the growth and K uptake efficiency of wheat on different soils.

1.2. Description of the Study Area

1.2.1. Geographic location

The study area, Qenberenaweti sub-watershed, is located between 09° 33′ 50″ and 09° 35′ 03″ N latitude and 39° 32′ 50″ and 39° 33′ 54″ E longitude (Figure 1.1). The site is found in Angolelana Tera district, North Shewa zone of Amhara region at 18 km from Chacha town and about 120 km northeast of Addis Ababa. It covers a total area of 317 ha and is situated on a plateau of the central Ethiopian highland system with elevations ranging between 2808 and 2960 meters above sea level (m.a.s.l).

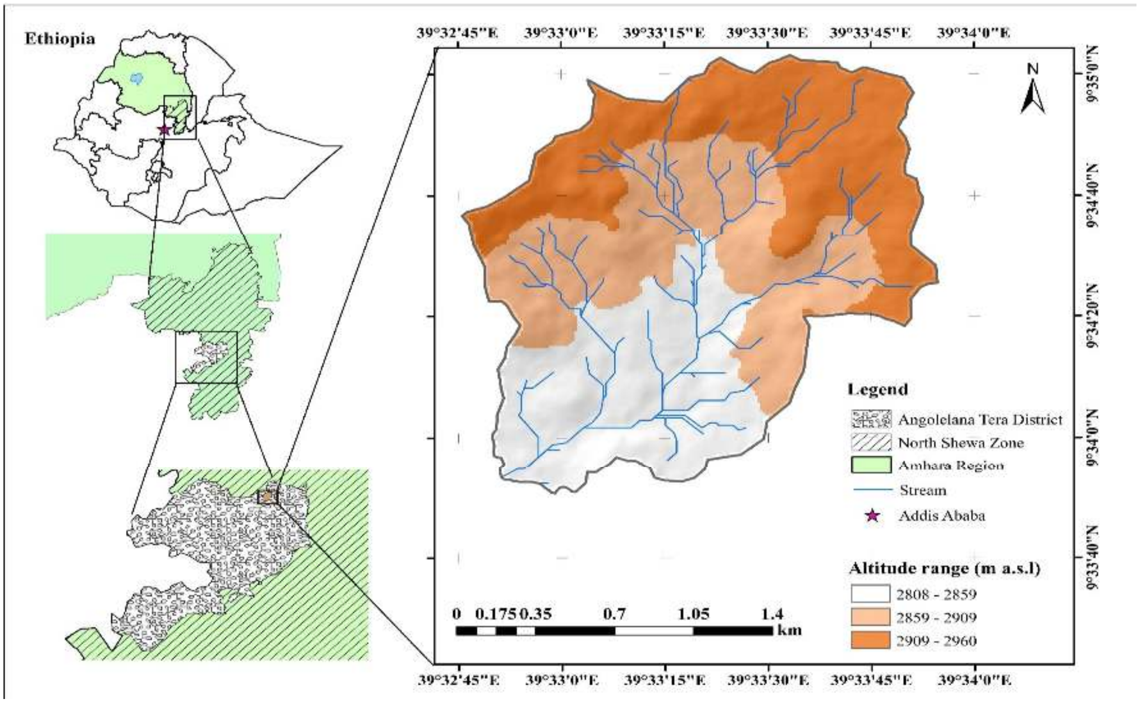

Figure 1. 1. Location map of the study area

1.2.2. Climatic condition

The mean annual temperature of the study area is 14.3 °C with monthly mean value ranging between 15.6 °C in May and 13 °C in October and November. The rainfall distribution is bimodal, having short and long rainy seasons from March to April and June to September, respectively with the mean annual precipitation of 928.5 mm (Figure 1.2).

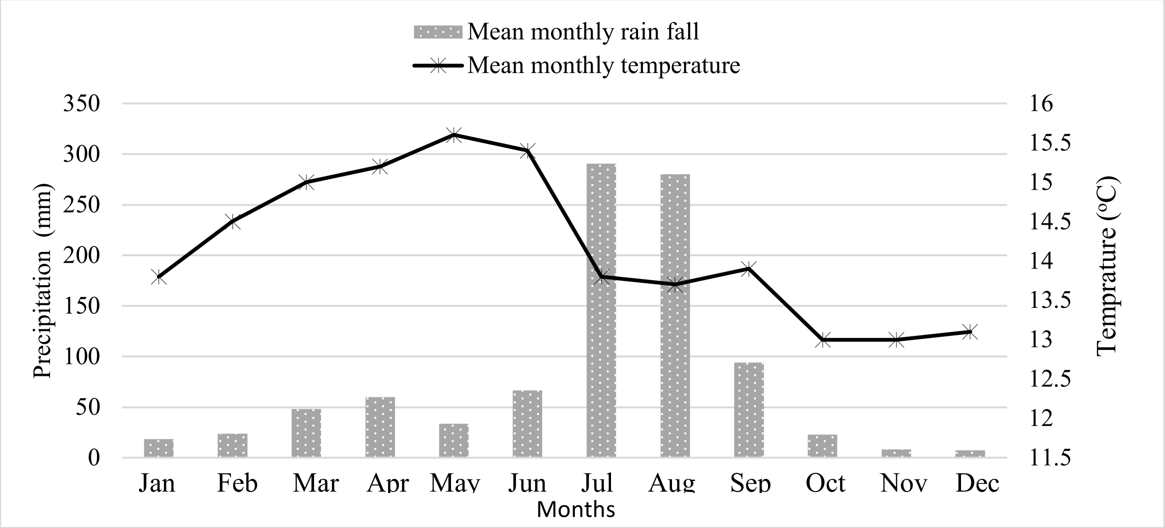

Figure 1. 2. Mean monthly rainfall and temperature of the study area

The short rainy season, though mostly unreliable, initiates plant growth after the long dry season. The long rainy season accounts for more than 70% of the total annual rainfall with peak precipitation (near 300 mm) occurring in July and August (Figure 1.2). Generally, the area falls under the Tepid to Cool Sub-Moist Mid-Highland agro-ecological zone (MoARD, 2005).

1.2.3. Geology and soils

The central Ethiopian plateau is mainly covered with thick tertiary volcanic rocks formed by tectonic activity during the time of weak volcanism (Abbate *et al*., 2015). There are also thin sequences of mesozoic and tertiary sedimentary rocks formed by transgression and regression of the Indian Ocean during triassic to cretaceous (Kassahun *et al*., 2025; Getaneh and Atnafu, 2020). Moreover, the acidic rocks (inter-bedded with some amounts of strati-form basalts) of central-eastern Ethiopian plateau form large and continuous cover extending from Amba Alagae to Debre Berhan and Mugher areas (Mebrahtu *et al*., 2021; Getaneh and Atnafu, 2020). Hence, the geology of the area has transitional and shell-alkaline basalts with minor rhyolite belonging to the Alagae formation of the Oligocene-Miocene era (Mebrahtu *et al*., 2021).

According to the general soil survey of Angolelana Tera district Agricultural Office, the major soil types of the study area are Cambisols, Regosols, and Vertisols. The soils are influenced by topography and mostly have a depth of 100-150 cm with a slight to moderate surface erosion class during the main rainy season (ATDAO, 2017).

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2. CHARACTERIZATION AND CLASSIFICATION OF SOILS ALONG THE TOPOSEQUENCE OF QENBERENAWETI SUB-WATERSHED, CENTRAL HIGHLANDS OF ETHIOPIA

Haymanot Awgchew[1,2], Sheleme Beyene[1], Alemayehu Kifilu[1]

[1]School of Plant and Horticultural Science, Hawassa University, Ethiopia

[2]Department of Plant Science, Debre Berhan University, Ethiopia

ABSTRACT

It is imperative to understand and predict the nature and distribution of soils along a given physiographic position. However, the hitherto practices of collecting basic soil information at a site-specific level seem inadequate to assure sustainable agricultural production via proper utilization and effective management of soil resources. Therefore, this research was conducted to characterize, classify, and map soils along the toposequence of Qenberenaweti sub-watershed, Central Highlands of Ethiopia. A total of 91 auger inspections to a 120 cm depth were made to define soil mapping units with their boundaries using key topographic and morphological features. Six pedons were opened at representative slope positions along the toposequence. The depth of the pedons varied between 135 and 200$^+$ cm, whereas the thickness of A-horizons showed an increasing trend down the slope, except at the back-slope position. All the soils had clayey texture with pH levels ranged from 5.59 to 6.23 and 5.31 to 7.65, respectively at surface and subsurface horizons. The OC contents throughout the entire horizons ranged from 0.22 to 2.03%. The highest CEC values were found at the middle position, followed by pedons at the upper and bottom parts. The exchangeable cations of most pedons were in declining order of Ca, Mg, K, and Na, except for the Mg dominance over Ca at the back slope and depression. Six soil types: Pellic Bathypetroduric Vertisols (Hypereutric, Amphifractic), Hypereutric Vertic Cambisols (Pantoclayic, Humic), Hypereutric Akroskeletic Plinthofractic Cambisols (Pantoclayic, Escalic, Humic, Magnesic), Hypereutric Pisoplinthic Cambisols (Pantoclayic, Profundihumic), Hypereutric Relictistagnic Cambisols (Pantoclayic, Ferric, Humic), and Pisoplinthic Luvisols (Clayic, Hypereutric, Profundihumic, Profondic, Bathyvertic) were identified and their distribution was mapped. The results revealed that the extent of variations in key topographic features brought the formation, development, and distribution of the diversified soils along the toposequence. Consequently, such detailed soil characterization, classification, and mapping work gives a vital clue for proper planning, management, and utilization of the soil resources at the local topographic level. However, further research of topographic impacts on geo-spatial variability of soil properties and fertility implications should be done to enhance crop production at the study area.

Keywords: topography, soil mapping unit, pedon, horizon, soil properties

2.1. Introduction

Soil is a gradually renewable dynamic natural resource (Jenny, 2012) whose extents of proper utilization and effective management determine the sustainability of agricultural production (Adugna, 2016). Generally, soil is classified as a natural body based on its characteristics (Nikiforova *et al*., 2019), and soils in a given group are believed to be homogeneous (Tursina, 2012). Characterization of soils deals with the assessment of their morphological, physical, chemical, and mineralogical properties (Schaetzl and Thompson, 2015) while classification is the systematic categorization of soils into different groups at varying levels of generalization based on their overall properties (Ditzler, 2017; Buol *et al*., 2011). Besides, soil mapping is a process of creating a visual representation of the different soil types and their distribution within a specific geographic area (Wimalasiri *et al*., 2020; Kienast-Brown *et al*., 2017).

The action of characterization and classification is ultimate to all soil studies, as it is a vital tool to reflect the real diversity of soils (Brevik *et al*., 2016; Buol *et al*., 2011). It also links research results and their beneficial extension with field applications (Ayalew *et al*., 2015) by providing key information about soil properties and environmental conditions (Lufega and Msanya, 2017). Hence, it helps in organizing knowledge, ease remembering of soil properties and understanding of relationships, having clear communication, and the best of technology transfer (Lufega and Msanya, 2017; Hartemink, 2015). According to Brevik *et al*. (2016), characterization and classification of soils are done in the application of proper management practices, rehabilitation of degraded soils, and provision of a ready-made map legend for soil surveyors. Whereas, soil mapping aims to unravel lacks in our understanding of soil properties and processes both in time and space (Taha *et al*., 2019; Minasny and McBratney, 2016).

Toposequence is a series of soils that vary primarily due to the topography as a soil-forming factor (Alves *et al*., 2024). This means each soil on a toposequence exhibits distinctive characteristics that are directly related to the slope at typical components (crest, shoulder, back slope, foot slope, and toe slope) of a topography (Omokaro, 2023). Moreover, topography is important in pedologic processes via determining the extents of water drainage and runoff, soil thickness and erosion potential, particle size distribution, reaction, and OM content (Omokaro, 2023; Begna, 2020). However, any patterns of soil association along a toposequence is not necessarily repeated with the topography in the landscape (Bonfatti *et al*., 2020; Ogban *et al*., 2019). Soils with identical parent material, existing within a uniform climatic condition, and affected by similar soil-forming factors may still have varied characteristics due to local relief, internal drainage, and/or geomorphic attributes (Tunçay and Dengiz, 2020; Gruber *et al*., 2019). Hence, the concept of toposequence is a useful analytical tool in relating the outline of soil characterization, classification, and mapping for sustainable agricultural production and land use management (Brevik *et al*., 2016).

Soil genesis and distribution (types and characteristics) in Ethiopia are influenced by agro-ecological zones, accompanied by geology, topography, vegetation, and climatic variabilities (Regassa *et al.*, 2023). For instance, different soil units like Acrisols, Cambisols, Fluvisols, Leptosols, Luvisols, Nitisols, Vertisols, and Umbrisols with various qualifiers have been identified in the country (Ali *et al*., 2024; Tufa *et al*., 2021). The country has a long history of collecting basic information on soil characterization, which is either limited to some selected potential areas or done with shallow observations and more generalizations (Megarsa, 2023; Nyssen *et al*., 2019). Moreover, the available soil maps in the country are mostly small-scale and represent scattered areas, which hinder site-specific soil interpretation and utilization (Seifu *et al*., 2023; Debele, 2018). Hence, detailed soil survey and mapping are imperative for a better understanding and prediction of soil types and distribution at the local physiographic variability level (Abdu *et al*., 2023; Megarsa, 2023; Fekadu *et al*., 2018).

Variation in the physiography of agricultural lands has an enormous influence on soil properties and plant production (Abdu *et al*., 2023; Laekemariam *et al*., 2016). Consequently, the absence of inclusive evidence on the nature of soils at the level of local variability is often a key factor limiting the development of Ethiopian agriculture (Seifu and Elias, 2018), as it does particularly around the study area (Cherinet, 2017). Acquiring comprehensive soil information while doing a detailed characterization and classification at a watershed level is important to properly use and manage the soils for sustaining food production, rehabilitating degraded land, and tackling site-specific soil problems (Mathewos and Mesfin, 2024; Bedadi *et al*., 2023). Therefore, this study was conducted to characterize, classify, and map the soils along a toposequence of Qenberenaweti sub-watershed, Central highlands of Ethiopia.

2.2. Materials and Methods

2.2.1. Selection of soil sampling sites and identification of mapping units

Before the field survey, the topographic map (1:50,000) and aerial image (Google Earth Pro) of the study area were interpreted to organize the vital site and land information, namely slope, altitude, drainage patterns, and land configurations. The overall topographic configuration and exact outlet point of the area were recognized during the field visit. Delineation of the sub-watershed and determination of its hydrological components were done using the spatial analysis tools of Arc GIS 10.5 software after retrieving a 12.5 m digital elevation model (DEM) data from the website of the United States Geological Survey (http://www.USGS.gov).

The free-soil surveying method (Dent and Young, 1981) was employed across the north-south facing landscape configuration to identify the soil mapping units (SMU) with their boundaries. A given SMU was defined based on similarity and/or closeness in key topographic and morphological (slope gradient, soil depth, and texture of surface soils) features of each augur sampling point. A total of 91 auger samples to 120 cm depth were collected using the 'Edleman auger' unless limited by the stoniness or compactness of the soils. A toposequence along the major stream flow direction, which has all the typical topographic components and represents the upper, middle, and lower positions, was considered for excavation of a representative pit (1.5 m width by 1.5 m length and up to 2 m depth) and collection of peripheral surface soil samples. Coordinate points of all auger and pedon inspections were taken using a handheld geographic positioning system (GPS) apparatus (Garmin-60) and digitized on the topographic map that was produced using Arc GIS 10.5 software.

2.2.2. Soil sampling and analysis

Both disturbed and undisturbed soils were sampled from every identified genetic horizon of the opened pedons. Additionally, twelve disturbed surface (0-20 cm) soil sub-samples were randomly collected within a 15 m radius surrounding each exhumed pit. Then, the sub-samples were thoroughly mixed and made into three composites per pedon.

The disturbed samples were air-dried and ground to pass through a 2 mm sieve for analyses of most physicochemical properties, except for the organic carbon (OC) and total nitrogen (TN) contents, which were further sieved by a 0.5 mm mesh size. The undisturbed samples were oven-dried at 105 °C for 24 hours to determine bulk density using the core-sampling method (BSI, 1975) while particle density with the pycnometer method (Tan, 1995). Soil particle size distribution was analyzed by the sedimentation hydrometer procedure (Bouyoucos, 1951).

The pH of the soils was determined in a 1:2.5 soil-to-water suspension using a pH meter (Van Reeuwijk, 1995), and the suspension was also used to measure the EC of the soils with a conductivity meter. Soil OC content was determined using the wet digestion method of Walkley and Black (Van Ranst *et al.*, 1999). Soil TN was analyzed by a wet-oxidation procedure of the Kjeldahl method (Bremner and Mulvany, 1982). The soil available P content was extracted following the Olsen method (Van Reeuwijk, 1995), and the concentrations were measured using a spectro-photometer at 882 nm. The exchangeable basic cations (Ca, Mg, K, and Na) and cation exchange capacity (CEC) of the soils were extracted using 1M ammonium acetate (pH 7) as per the percolation tube procedure (Van Reeuwijk, 1995). The concentrations of exchangeable Ca and Mg in the leachate were determined by an Atomic Absorption Spectro-photometer (AAS); whereas the exchangeable K and Na contents were measured by a flame photometer. Available micronutrients (Fe, Mn, Zn, and Cu) were extracted using the diethylene-triamine-penta-acetic acid (DTPA) method (Tan, 1995), and their quantities were determined by AAS. The CEC due to the clay fraction (CEC clay) was computed by subtracting the value of CEC associated with OM from the CEC of soil, with the assumption that OC has a CEC of 200 cmolc kg^{-1} (Landon, 2014):

$$CECclay = \frac{CEC\ soil - (\%\ OM * 200)}{\%\ Clay}$$

2.2.3. Description of the pedons and classification of the soils

The *in-situ* description of soil properties was carried out following the guidelines for soil profile description (FAO, 2006). Furthermore, the soils of the study area were classified according to the World Reference Base (WRB) for soil resources classification system (IUSS, 2022).

2.2.4. Statistical analysis

The data on selected physicochemical properties of the surface soils were interpreted by descriptive statistics. Moreover, Pearson's correlation matrix was used to distinguish the association pattern among variables. All the statistical analyses were performed with the Statistical Package for the Social Sciences (SPSS) software version 26.0 (IBM, 2020).

2.3. Results and Discussion

2.3.1. Description of soil mapping units and site characteristics

After the detailed *in-situ* detection of each soil augering point, 32 different soil mapping units (SMU) were identified in the sub-watershed (Figure 2.1). The upper topographic position occupied SMU-01, 02, 03, 04, 05, 06, 07, 08, 10, and 19, while the middle position had SMU-09, 11, 12, 15, 16, 17, 18, 20, 22, and 23. The rest (SMU-13, 14, 21, 24, 25, 26, 27, 28, 29, 30, 31, and 32) were found at the lower topographic position. A representative pit was dug on SMU-06, 05, 16, 17, 32, and 30 in lieu of the summit, shoulder, back slope, foot slope, toe slope, and bottom depression positions, respectively.

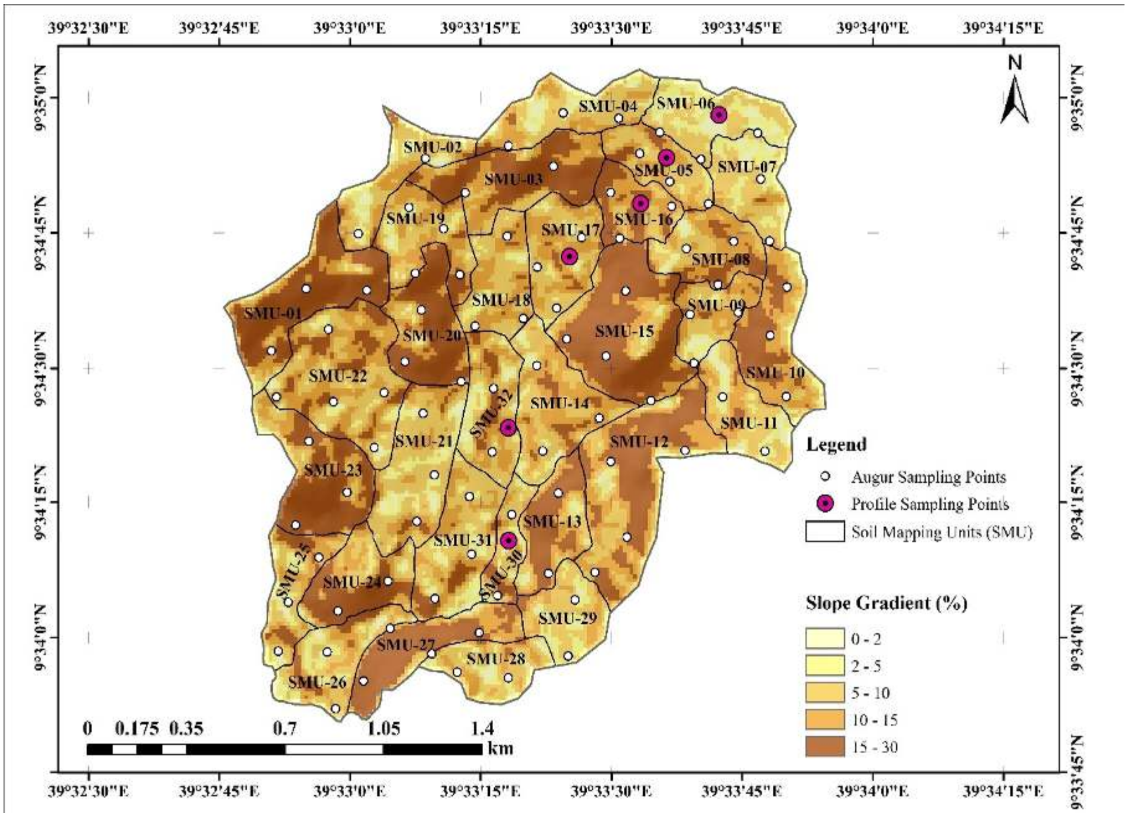

Figure 2. 1. Topographic map of the study area

As shown in Appendix Table 1, the SMU-06, 07, and 30 were very deep soils (>120 cm) with clayey texture (feel method) at the surface of level (0-2%) and gently level (2-5%) lands. Amongst SMUs found on sloping lands (5-10%), SMU-04, 21, 28, 31, and 32 had also very deep profiles, while SMU-02, 18, 26, and 29 were categorized as deep soil (100-120 cm). The soils of SMU-02, 04, 18, 26, 29, 31, and 32 were clayey, while those of SMU-21 and 28 were clay loamy in texture. The strongly sloping land (10-15%) was occupied by SMU-05, 14, 17, 22, and 25, with soils having deep solum and clay loam texture. They were also partly covered by very deep SMU-11 and 19 and deep SMU-08 and 09 solum with clay-textured soils at the surface. Although many of the SMUs (01, 03, 10, 15, 20, 23, 24, and 27) existing on moderately steep slope land (15-30%) had a moderately deep (50-100 cm) solum with clay loam textured surface soils, a few (SMU-12, 13, and 16) were deep soils with a clay texture.

The variations in the depth of the solum and soil texture at the surface might be related to the shape and length of the slope, which determine the degree of soil material translocation and accumulation via the action of water flowing down the slope. The depth of the solum and soil texture at the surface are ascribed to slope features (Mwendwa, 2021; Subhatu *et al*., 2018) that erode, move, and deposit finer soil materials via the action of the running water from upper to bottom topographic positions (Debele *et al*., 2018). Consequently, the nature of the slope in a given landscape can influence the rate of soil formation and development at different topographic positions (Deressa *et al*., 2018; Mulugeta and Sheleme, 2010).

All pedons were opened on grazing and fallow land uses that had distinctive parent materials of the basaltic igneous rock (Appendix Table 2). The pedons have existed on diverse landforms and slope gradients with straight slope forms and straight plus concave surface flow pathways. Rill and sheet soil erosion were observed at the shoulder, back-slope, and foot-slope positions, whereas soil material deposition was prevalent on the toe-slope and bottom depression areas. Also, the surface of the eroded topographic components was covered by different amounts and sizes of coarse fragments. However, there are no rock outcrop and sign of surface sealing in the area. The data from auger inspection and site characteristics of the study area revealed the presence of variations in key topographic features that determine the nature (morphological, physical, and chemical properties) and distribution of soils along the toposequence.

2.3.1.1. Soil morphological properties

The pedons had A and B sequence of horizons with their depth varying between 135 and 200^+ cm (Table 2.1). In general, the thickness of A-horizons showed an increasing trend down the slope, except for the horizon at the back-slope. The thinnest (25 cm) and thickest (70 cm) A horizons existed at the summit and toe slope, respectively (Table 2.1). The disparity in thickness of surface horizons could be ascribed to the steepness and form of the slope at a given topographic position, which might have influenced the soil formation and development through their direct influence on lateral (erosion and deposition) and vertical (eluviation and illuviation) translocation of soil materials. According to Sheleme (2017); Alemayehu *et al*. (2016); Dessalegn *et al*. (2014), an increase in the depth of the surface horizon along toposequences largely occurs due to water erosion that takes soil materials from the summit to the bottom depression. The relatively gentler slope at the lower topographic positions aids the deposition of materials eroded from the upper part (Chaplot, 2013; Ali *et al*., 2010).

Table 2. 1. Morphological properties of soils along the toposequence of the sub-watershed

Profile	Horizon	Depth (cm)	Boundary	Soil Color (Munsell Code)		Soil Structure (Grade/ Size/ Shape)	Soil Consistency				Texture (Feel)
				Dry	Moist		Dry	Moist	Wet		
									Plasticity	Stickiness	
Summit	A	0-25	CW	10YR 3/3	7.5YR 2.5/2	Mo/ Me/ Gr	HA	VFR	PL	VST	Clay
	Bt1	25-70	AS	10YR 4/1	7.5YR 3/1	St/ Co/ Ab	VHA	FI	VPL	VST	Clay
	Bt2	70-105	CW	10YR 4/2	10YR 3/2	St/ Co/ Pr	EHA	FI	VPL	VST	Clay
	Btk1	105-135	AS	10YR 4/3	7.5YR 3/3	MS/ Co/ Ab	VHA	VFI	PL	VST	Clay
	Btk2	135-165	AW	10YR 4/3	7.5YR 3/2	MS/ Me/ Sb	HA	FI	VPL	ST	Clay
	Btkm	165-200	-	10YR 4/4	7.5YR 4/2	MS/ Me/ Cr	HA	FR	PL	ST	Clay
Shoulder	A	0-30	AS	10YR 3/4	7.5YR 2.5/3	MS/ Me/ Gr	SHA	VFR	VPL	ST	Clay loam
	AB	30-65	CS	10YR 3/3	7.5YR 2.5/2	Mo/ Fi/ Cr	SHA	VFR	VPL	VST	Clay loam
	Bt1	65-100	AW	10YR 3/1	7.5YR 2.5/1	St/ Me/ Pr	VHA	FR	VPL	VST	Clay
	Bt2	100-120	GW	10YR 4/1	7.5YR 3/1	St/ Me/ Pl	HA	VFI	VPL	VST	Clay
	BC	120-135	-	10YR 4/2	7.5YR 3/2	MS/ Fi/ Cr	SHA	FR	PL	ST	Clay loam
Back slope	Ac1	0-25	AS	7.5YR 3/3	5YR 3/3	Mo/ Me/ Sb	SHA	VFR	PL	ST	Loam
	Ac2	25-40	CW	7.5YR 3/4	5YR 3/3	Mo/ Me/ Sb	HA	FR	PL	ST	Loam
	Bwv	40-60	CS	7.5YR 3/2	5YR 3/2	MS/ Me/ Sb	VHA	FI	PL	ST	Clay loam
	Bhsm	60-110	CW	7.5YR 3/2	7.5YR 2.5/2	St/ Me/ Ab	VHA	VFI	VPL	VST	Clay loam
	Btx	110-125	AW	7.5YR 4/4	7.5YR 3/3	MS/ Me/ Cr	HA	FI	VPL	VST	Clay loam
	B/C	125-155	-	7.5YR 4/3	7.5YR 3/3	St/ Me/ Cr	HA	FR	PL	ST	Clay loam
Foot slope	Ac1	0-35	AS	7.5YR 3/4	5YR 3/3	Mo/ Co/ Sb	SHA	VFR	PL	ST	Clay loam
	ABc2	35-70	CS	7.5YR 3/2	5YR 3/2	Mo/ Me/ Sb	HA	FR	PL	ST	Clay
	Btc3	70-95	CW	7.5YR 3/3	7.5YR 2.5/2	Mo/ Me/ Ab	HA	FR	PL	VST	Clay
	2Bti1	95-150	AS	10YR 3/1	7.5YR 2.5/1	St/ VC/ Cl	SHA	VFR	VPL	VST	Clay
	2Bti2	150-200^{+}	-	10YR 2/1	7.5YR 2.5/1	St/ Co/ Cl	VHA	FI	VPL	VST	Clay
Toe slope	Ac1	0-20	AS	7.5YR 3/3	5YR 2.5/2	Mo/ Me/ Gr	SHA	VFR	PL	ST	Clay loam
	Ac2	20-45	AS	7.5YR 3/4	5YR 3/2	Mo/ Fi/ Gr	SHA	FR	PL	ST	Clay loam
	Ac3	45-70	CS	7.5YR 4/4	5YR 3/2	Mo/ Fi/ Cr	HA	FI	VPL	ST	Clay
	Bhc4	70-105	CW	7.5YR 3/2	7.5YR 2.5/2	Mo/ Me/ Cr	HA	VFI	VPL	VST	Clay
	B/C	105-165^{+}	-	7.5YR 4/2	5YR 2.5/2	WM/ Me/ Cr	HA	FR	PL	ST	Clay loam
Bottom depression	Ag1	0-30	AW	7.5YR 3/4	5YR 2.5/2	Mo/ Fi/ Gr	HA	FR	VPL	ST	Clay loam
	Aqg2	30-65	GW	7.5YR 3/3	5YR 3/2	Mo/ Me/ Sb	SHA	VFR	VPL	VST	Clay loam
	Bg3	65-110	CW	7.5YR 3/3	5YR 3/2	Mo/ Me/ Ab	HA	FR	VPL	ST	Clay
	Bhg4	110-140	CW	7.5YR 3/2	5YR 3/2	Mo/ Fi/ Ab	SHA	FR	VPL	VST	Clay
	BCg5	140-190	-	7.5YR 4/3	7.5YR 2.5/2	WM/ Fi/ Cr	HA	FR	PL	ST	Clay loam

Where: AS-Abrupt Smooth; CS-Clear Smooth; AW-Abrupt Wavy; CW-Clear Wavy; GW- Gradual Wavy; St-strong; Mo-moderate; We-weak; MS-moderate to strong; WM-weak to moderate; VC-very coarse; Co-coarse; Me-medium; Fi-fine; Cr-crumbly; Ab-angular blocky; Sb-subangular blocky; Gr-granular; Pr-prismatic; Cl-columnar; Pl-platy; HA-hard; VHA-very hard; SHA-Slightly hard; FI-firm; FR-friable; VFR-very friable; PL-plastic; VPL-very plastic; ST-sticky; VST-very sticky

In line with the present findings, Mulugeta and Sheleme (2010) also found a reduction in the depth of surface soils with increasing slope along the toposequences of Kindo Koye sub-watershed in southern Ethiopia, whereby the thinner and thicker A-horizons appeared at the steep (shoulder and back) and gentle (foot and toe) slopes, respectively.

The distinctness and topography of horizon boundaries between the surface and sub-surface horizons were abrupt and smooth, except for the clear-wavy and abrupt-wavy boundaries for the pedons at the summit and bottom depression areas (Table 2.1). The variations in the appearance of horizon boundaries indicate that the soils were formed through different soil-forming processes (Ayalew *et al.*, 2015) while they also partly reflect anthropogenic impacts (Cools and De Vos, 2010). The boundary changes between surface and subsurface horizons of cultivated land-use have occurred because of repeated human activities like plowing (Hagos *et al.*, 2015). Moreover, the changes in grazing land use could be due to gradual transformation, homogenization, and/or erosional-depositional processes (Ande, 2010).

The color of the surface soils ranged from very dark brown (7.5YR 2.5/2 or /3) at the upper to dark reddish brown at the middle (5YR 3/3), and lower (5YR 2.5/2) slope positions (Table 2.1). The surface soil colors of the pedons were darker than their subsurface counterparts, except for the pedons at the summit and shoulder (Table 2.1). The observed color variations within and among the pedons might be the reflection of differences in chemical and mineralogical composition, topographic positions, OM content, and moisture regimes. Dengiz *et al.* (2012) confirmed that soil color is related to OM and carbonate accumulations, redoximorphic features, drainage condition, and physiographic position.

Concurrent with the findings of this study, several authors reported that the surface horizons have darker colors than the corresponding subsurface horizons as a result of relatively higher soil OM contents in the surface layers (Dessalegn *et al.*, 2014; Ali *et al.*, 2010; Mulugeta and Sheleme, 2010). Mulugeta and Sheleme (2010) also reported that soils on slopes that have never been saturated with water had reddish and brownish subsoil colors, while soils on poorly drained locations tended to have grey-colored B-horizons. However, the greyish subsurface soil color at the summit could be due to the limited weathering of smectite clays that remain stable as long as the pH is above neutral, resulting in subsoils with a lower red hue and weaker chroma because of less free ferric ions (Driessen *et al.*, 2001). Moreover, the blackish/greyish subsurfaces at the shoulder could be because of the leaching and accumulation of weathered smectitic clays that impede internal drainage upon cementation of subsoil particles, providing reddish color due to Fe^{3+} compounds left behind in the surface horizon (Driessen *et al*., 2001).

The structures of the soils at the surface layers were granular and sub-angular blocky with grades ranging from moderate and moderate to strong and fine to coarse sizes (Table 2.1). On the other hand, the subsurface horizons had different structures (angular blocky, sub-angular blocky, prismatic, columnar, platy, and crumbly) with weak to moderate and strong grades, and fine to very coarse sizes. The presence of granular structure at the surface could be attributed to the OM content (Gebrekidan and Negassa, 2006), whereas the well-developed structure in the subsurface is due to increasing clay content (Khormali *et al*., 2003). The results corroborate with Mesfin *et al*. (2017); Teshome *et al*. (2016) who found granular soil structure in the surface horizons that changed to angular and sub-angular structures in the subsurface horizons.

The soils along the toposequence had consistence ranging from hard to slightly hard, friable to very friable, and plastic/sticky to very plastic/very sticky at the surface horizons, while the soil consistence in the subsurface horizons varied from hard to extremely hard, very friable to firm, and plastic/sticky to very plastic/very sticky (Table 2.1). The variations in soil consistence could result from the differences in particle size distribution, OM content, and amount and nature of clay particles (Paltseva, 2024; Ayalew *et al*., 2015; Moradi, 2013). Very friable and friable consistencies were observed in the surface soils as a result of higher OM contents compared to their subsurface counterparts (Debele *et al*., 2018; Mulugeta and Sheleme, 2010) and this impacted the better workability of clayey soils by reducing their stickiness (Ali *et al*., 2010). In contrast, sticky/very sticky and plastic/very plastic consistencies show the existence of high clay and low organic carbon contents, with difficulty in soil till (Ayalew *et al*., 2015). Besides, Ali *et al*. (2010) pointed out that very sticky and very plastic appearances could be best indicative of the presence of smectitic clays in the soils.

2.3.1.2. Soil physical properties

The textural classes of all soils at the surface and subsurface horizons were clay with a different distribution of the three soil separates (Table 2.2). The proportion of the separates is determined by slope steepness, form, and topographic laying position of the excavated pedons (Ofori *et al*., 2013). The sand fraction in the surface layer increased from 18% at the summit to 32% at the back-slope, and then decreased to 24% at the bottom depression position, whereas the clay decreased from 48% to 40%, and then increased to 48% at the respective topographic positions

(Table 2.2). The coarser texture in the surface horizons at the middle part of the toposequences might be due to the selective removal of fine (clay) and medium (silt) sized soil particles by the action of erosion due to the steeper slope at this topographic position and their deposition at lower parts. Silt proportion would likely be raised on foot and toe slopes as compared to the surface soils on the shoulder and back slopes when erosion left coarse particles on the hilly part (Mulugeta and Sheleme, 2010). The highest amount of clay particles at the surface of the bottom depression position could be attributed to their translocation and deposition from the upper and adjacent profiles (Babalola *et al*., 2007).

Table 2. 2. Physical properties of soils along the toposequence of the sub-watershed

Profile	Horizon	Depth	Particle Size (%)			Silt to	Textural	Density (g cm^{-1})		Total
		(cm)	Sand	Silt	Clay	Clay Ratio	Class	Bulk	Particle	Porosity (%)
Summit	A	0-25	18	34	48	0.71	Clay	1.22	2.35	47.97
	Bt1	25-70	14	14	72	0.19	Clay	1.24	2.39	48.33
	Bt2	70-105	12	14	74	0.19	Clay	1.30	2.43	46.50
	Btk1	105-135	18	14	68	0.21	Clay	1.35	2.42	44.10
	Btk2	135-165	14	24	62	0.39	Clay	1.29	2.51	48.50
	Btkm	165-200	10	18	72	0.25	Clay	1.41	2.56	45.12
Shoulder	A	0-30	26	28	46	0.61	Clay	1.19	2.43	51.03
	AB	30-65	22	26	52	0.50	Clay	1.21	2.42	50.00
	Bt1	65-100	18	16	66	0.24	Clay	1.29	2.50	48.30
	Bt2	100-120	12	16	72	0.22	Clay	1.40	2.58	45.63
	BC	120-135	26	22	52	0.42	Clay	1.31	2.56	48.73
Back slope	Ac1	0-25	32	28	40	0.70	Clay	1.19	2.41	50.62
	Ac2	25-40	28	28	44	0.64	Clay	1.23	2.44	49.59
	Bwv	40-60	30	24	46	0.52	Clay	1.28	2.56	49.90
	Bhsm	60-110	20	34	46	0.74	Clay	1.30	2.53	48.62
	Btx	110-125	18	20	62	0.32	Clay	1.29	2.47	47.87
	B/C	125-155	24	28	48	0.58	Clay	1.40	2.57	45.72
Foot slope	Ac1	0-35	30	28	42	0.67	Clay	1.19	2.35	49.36
	ABc2	35-70	24	38	38	1.00	Clay Loam	1.16	2.39	51.67
	Btc3	70-95	18	26	56	0.43	Clay	1.26	2.49	49.40
	2Bti1	95-150	14	16	70	0.23	Clay	1.36	2.64	48.39
	2Bti2	150-200^+	14	16	70	0.23	Clay	1.42	2.60	45.58
Toe slope	Ac1	0-20	26	32	42	0.76	Clay	1.15	2.37	51.37
	Ac2	20-45	26	30	44	0.68	Clay	1.20	2.43	50.82
	Ac3	45-70	24	32	44	0.73	Clay	1.19	2.41	50.62
	Bhc4	70-105	22	28	50	0.56	Clay	1.24	2.48	50.10
	B/C	105-165^+	36	18	46	0.39	Clay	1.28	2.61	50.96
Bottom depression	Ag1	0-30	24	28	48	0.58	Clay	1.18	2.43	51.34
	Aqg2	30-65	34	16	50	0.32	Clay	1.20	2.50	51.90
	Bg3	65-110	20	26	54	0.48	Clay	1.19	2.45	51.33
	Bhg4	110-140	20	28	52	0.54	Clay	1.23	2.59	52.51
	BCg5	140-190	34	20	46	0.43	Clay	1.29	2.55	49.31

On the other hand, the subsurface horizons of most pedons were finer in texture than their respective surface horizons due to the downward translocation of clay particles and *in-situ* clay synthesis in the subsurface layers (Table 2.2). Accordingly, the higher clay content in the B horizon of soils was reported as a result of illuviation, predominant *in-situ* pedogenetic formation in the subsoil, destruction in the surface horizon, upward movement of coarser particles due to swelling and shrinking, biological activity, and a combination of two or more of these different processes (Fekadu *et al*., 2018; Yitbarek *et al*., 2018; Mesfin *et al*., 2017). The presence of clay illuviation is the main factor in the formation of the argillic horizon in the subsurface soils of the upper and middle slope profiles (Mulugeta and Sheleme, 2010). In line with this finding, Adhanom and Toshome (2016) as well as Mulugeta and Sheleme (2010) found an increasing trend of clay content down the soil profile. The highly significant ($P \leq 0.01$) correlations between clay and sand ($r = -0.82$) and silt ($r = -0.80$) also confirm the translocation and illuvial accumulation of clay in the subsurface horizons (Appendix Table 3).

The silt to clay ratio of the soils across the profiles ranged from 0.19 to 1.00 (Table 2.2), implying that the soils are at a relatively advanced stage of development, with significant leaching of clay particles (Wambeke, 1962). Soils having a silt-to-clay ratio below a unity are considered to be at an advanced stage of development and have undergone a feralitic pedogenesis process (Debele *et al*., 2018; Abayneh, 2005). The lower silt-to-clay ratios in the subsoil layers, as compared to their surface counterparts, also confirm the existence of clay migration in the pedons (Nahusenay *et al*., 2014; Beyene, 2011). The presence of an appreciable amount of silt in the surface soils could increase the water-absorbing ability of the soils and facilitate longer soil-water retention for plant use (Saha *et al*., 2020; Beyene, 2011).

The bulk and particle densities of the surface horizons ranged from 1.15 to 1.22 and 2.35 to 2.43 g cm^{-3}, respectively, whereas their corresponding values in the subsurface horizons ranged from 1.16 to 1.42 and 2.39 to 2.64 g cm^{-3} (Table 2.2). The bulk density values of the soils in the surface horizons were under the normal ranges (1.0-1.5 g cm^{-3}) of fine-textured soils (Wogi *et al*., 2021). Both the particle and bulk densities of the soils increased with soil depth at all topographic positions, which could be due to the relatively higher OM content in the surface than the subsurface layers; while the increase in bulk density could also result from natural compaction of the subsurface soils by a load of surface soils (Abayneh, 2005). According to Mulugeta and Sheleme (2010), soils that are loose, porous, or well-aggregated may have lower bulk densities than soils that are compacted or non-aggregated.

The total pore space in the surface layers was between 47.97 and 51.37%, showing a decreasing trend with soil depth (Table 2.2). According to Michael (2009), the total pore spaces in the clayey textured soils may vary between 40 and 60%. Besides, Shahab *et al*. (2013) stated that the optimum total pore space value for crop production is about 50%. Hence, the studied soils could be considered convenient for better crop production as there is a conducive situation for free aeration and water movement within the soil structure that is also capable of determining the number, diversity, and activity of important soil organisms (Mulugeta *et al*., 2019).

Table 2. 3. Mean values of particle-size distribution of the soils around excavated pedons

	Percent sand			Percent silt			Percent clay			Textural class
Pedon	Mean	SD	CV (%)	Mean	SD	CV (%)	Mean	SD	CV (%)	
SU	19	1	5.26	33	1	3.03	49	1	2.04	Clay
SH	23	3	13.04	29	1	3.45	49	3	6.12	Clay
BS	30	2	6.67	31	3	9.68	39	1	2.57	Clay loam
FS	28	2	7.14	31	2	6.45	41	1	2.40	Clay
TS	27	1	3.71	29	1	3.45	43	1	2.33	Clay
BD	25	1	0.04	29	1	3.45	46	2	4.35	Clay

Where: SU = Summit, SH = Shoulder, BS = Back-slope, FS = Foot-slope, TS = Toe-slope,
BD = Bottom depression, SD = Standard deviation, CV = Coefficient of variation

The surface soil samples collected from all directions of the opened pedon had more or less similar texture with the corresponding soils of the surface horizons of the respective pedons, except for a slight difference at the back-slope. However, the proportion of clay, silt, and sand fractions at a given physiographic position deviated by ±1-3% between the soils of the surface horizons of the pedons and the respective surface soils around the pedons (Table 2.3). The descriptive statistical analysis revealed the presence of very close values (CV < 15%) within the three soil separates of the samples around the opened pedons (Wilding and Drees, 1978).

2.3.1.3. Soil chemical properties

The pH values of surface and sub-surface soils ranged from 5.59 to 6.32 and from 5.31 to 7.65, respectively (Table 2.4). According to Wogi *et al*. (2021), the surface soils at the shoulder and toe slope parts were slightly acidic, while the others were moderately acidic. The higher pH at the surface of the shoulder site might be allied with the substantial deposition of grayish-white dust particles that are blown up from the nearby main paved road of dolomitic [$CaMg(CO_3)_2$] stone source. Because the dolostone samples have not fizzed as treated by 1M HCl, but did weakly only in their powdered form (Haluschak, 2006). Conversely, the high pH at the surface of the toe-slope could be related to the effects of water moving down the toposequence, causing erosion and deposition of materials rich in basic cations on the surface layer. In general, the low-lying topographic positions had higher pH values than the uphills, which could be due to excessive accumulation of exchangeable bases that are laterally removed from uphills and subsequently deposited at the lower slopes (Hagos *et al*., 2015; Nahusenay *et al*., 2014).

Apart from the toe slope, the pH values in the subsurface horizons were higher than the surface horizons of the rest pedons (Table 2.4). The escalations in pH values in the subsoils could be due to the illuvial accumulation of basic cations, i.e., leaching and downward translocation of basic cations (Fekadu *et al*., 2018; Nahusenay *et al*., 2014). Additionally, it might also be due to less H^+ released from the poor decomposition of the lower OM content in the subsoils (Ayalew and Beyene, 2012). However, the more acidic reaction in the sub-surface horizons of the toe-slope has most likely been caused by the hydrogeological and geochemical processes that vary with groundwater flow patterns. The groundwater dynamics contribute to the lower pH in subsurface layers at the toe-slope position through enhancing the generation and distribution of acidic substances (Seibert *et al*., 2016; Cervi, 2015). This effect is particularly marked under limited OM decomposition and clay-rich conditions (Awoonor and Dogbey, 2021). The primary geochemical processes responsible for lower pH occurrences at subsurface layers of toe-slope positions include eluviation-accumulation of dissolved OC, dissolution of carbonate minerals, and redox reactions (Ha *et al*., 2017). Buildup of dissolved OC leaching from the surface layer could lower the pH of the subsoils due to excessive occurrence of the humic and fluvic acids, protonation via carboxylic and phenolic functional groups, and complexation of acidifying metal (Fe and Al) ions (Neupane and Datta, 2020; Bailey *et al*., 2019). The dissolution of carbonate minerals, such as ankerite [$Ca(Fe, Mg, Mn)(CO_3)_2$], could also cause the release of more Fe/Mn ions (Wu *et al*., 2020; Ha *et al*., 2017). According to Jun *et al*. (2013), the reduction of ferric to ferrous iron in anaerobic conditions can lead to increased acidity as iron oxides are reduced. Pyrite (FeS_2) oxidation produces sulfuric acid because of its exposure to oxygen and water, leading to a decrease in pH levels (Ha *et al*., 2017).

The findings of this study agreed with the work of Fekadu *et al*. (2018) and Ali *et al*. (2010) whereby the pH-H_2O showed a general rise with soil depth in the pedons at the upper and middle slopes than those at the bottom and toe slope positions. The pH showed negative correlations with OC ($r = -0.45$, $P \leq 0.01$), av. Fe ($r = -0.69$, $P \leq 0.001$) and av. Mn ($r = -0.50$, $P \leq 0.01$) contents while having positive correlations with the ex. Na ($r = 0.71$, $P \leq 0.001$), ex. K ($r = 0.39$, $P \leq 0.05$) and ex. Ca ($r = 0.39$, $P \leq 0.05$) concentrations (Appendix Table 3).

Irrespective of the topographic positions, the surface horizons of all pedons had relatively low soil electrical conductivity (EC) values (0.087 to 0.273 dS m^{-1}) than the subsurface horizons

(0.058 to 0.457 dS m^{-1}). All soils of the study area were non-saline (Havlin *et al*., 2017; Richards *et al*., 1954) with a very low EC rate (Shaw, 1999). In general, poor soil salinity is related to the high rainfall incidence of the study area. The increased rainfall resulted in the movement of Na and other salts over the soil surface (Budak *et al*., 2022)Hence, reducing salinity via diluting their concentration and cause leaching in soil profiles. High precipitation can also lead to the leaching of salts from the soil surface to deeper layers, thereby altering the salinity profile of the soils (Budak *et al*., 2022). This process can have varying impacts depending on soil types (Isidoro and Grattan, 2011), landscape positions (Budak *et al*., 2022), and existing salinity levels (Eltarabily *et al*., 2024). Although most crops' growth and productivity are unaffected by the current levels of soluble salts (Landon, 2014; Richards *et al*., 1954), this incidence shows how crucial it is to monitor soil salinity in relation to rainfall as a means to effectively manage agricultural practices (Eltarabily *et al*., 2024).

The organic carbon (OC) and total nitrogen (TN) contents across the horizons varied from 0.22 to 2.03% and from 0.02 to 0.18%, respectively (Table 2.4), while the carbon to nitrogen (C:N) ratio was between 6.0 and 20.0. The OC and TN contents decreased with the soil depth, except for a substantial accumulation of illuviated OM in some subsurface horizons of the back slope and bottom depression parts (Table 2.4). Additionally, the OC and TN contents of surface soils declined from the summit to the shoulder and back slope, and then increased down the toposequence with almost equal amounts at the toe slope and the bottom depression. The surface soils were rated as medium (1.5-3.0%) in OC (Wogi *et al*., 2021) and low (0.10-0.20%) in TN contents (Landon, 2014), whereby their C:N ratio is found under the low (10-15) category (Newey, 2006). According to Hartz (2007), soils with less than 0.07% TN are believed to have a limited N mineralization potential, while those above 0.15% are expected to mineralize a significant amount of N during the next crop cycle, showing that most of the studied soils have a good potential of N mineralization. In general, the C:N ratios were within the common range (8:1 to 15:1) for arable soils (Brady and Weil, 2008), implying that OM was fully decomposed and N loss was apprehended. The similar distribution pattern of OC and TN with soil depth was also evident from the positive ($r = 0.93$) and very highly significant ($P \leq 0.001$) correlation between the two parameters (Appendix Table 3).

The variations in OC and TN contents of the soils might be due to repeated tillage with poor management practices, including complete removal of crop residues and/or reduced usage of organic amendments (Sheleme, 2023). The relatively lower content of OC in the surface layers of the shoulder and back slope positions could be attributed to the erosion effects (Juřicová *et al*., 2022) and the rapid OM decomposition and mineralization processes (Beyene, 2011; Dengiz, 2010), which result in a reduction of TN (Adhanom and Toshome, 2016). The better level of OC in the surface horizon of the summit parts might be due to biomass turnover of grasses on the grazing land use (Fekadu *et al*., 2018); whereas it might have been because of depositional effects at the foot-slope to the bottom depression positions (Capoane *et al*., 2016). However, the slight decline of OC in the surface horizon at the bottom depression could be due to interrelated effects of colluvial sediments on the distribution and retention of soil OC. In addition to the younger soil development stage (Azam *et al*., 2020), the erosion-induced rearrangement of colluvial sediments can alter the overall OC storage in surface layers of soils at the bottom depression position (Kołodyńska-Gawrysiak *et al*., 2023). Despite the loss of labile OC fraction from mid-slope areas during aggregate breakdown (Zhu *et al*., 2021), accumulation of OC in this topographic part also decreases owing to its potential dilution by deposited fine sediment (Yang *et al*., 2022).

The exceptional accumulations of OC in some subsurface horizons at the back-slope and bottom depression positions are certainly attributed to topographically driven anthropogenic and natural processes that affect the soil erosion-deposition dynamics. Hence, play a crucial role in the redistribution and stabilization of OC. For instance, the built terrace structures of stone-bunds throughout the back-slope of the study area could control the translocation of eroded soil and the associated OC-containing materials from upslopes. This process results in a progressive accumulation (Juřicová *et al*., 2022) and stabilization of OC (Wang, 2014) in the subsurface layers at the back-slope position. The differences in decomposition rates of OC-rich soil materials further contribute to the storage of OC in the subsurfaces (Liu *et al*., 2015). The topography-induced heterogeneity significantly affects the distribution and burial deposition of OC-rich materials at this slope position (Zhu *et al*., 2019). A human factor, such as terracing, could enhance the potential for heterotrophic distribution and accumulation of dissolved and particulate OC materials in some subsurface layers (Creed *et al*., 2013) via modifying the topographically regulated hydrologic and geomorphological processes (Novák *et al*., 2018). Besides, the contents of OC in subsurface horizons of the bottom depression might be ascribed to the frequent deposition of OC-rich soil materials and slower rates of OM decomposition compared to eroding slopes at the middle topographic parts. The soil OC amasses in subsurface layers at the bottom depression primarily due to the stabilization and humification processes by finer soil particles (Akitwine, 2021). According to Moreland *et al.* (2024), OC can resist biological degradation in subsurface soils at such topographic positions owing to its intimate association with secondary hydrous Fe/Al minerals.

The available P (Av. P) concentrations in surface and subsurface soils oscillated from 8.43 to 23.96 and from 0.48 to 24.27 mg kg^{-1}, respectively (Table 2.4). The surface soils had low to high Av. P contents while the subsoils were under very low to high ranges (Wogi *et al*., 2021). The content of Av. P was increased from the surface to the immediate subsurface horizon but declined with further depths, except for the pedon at the toe-slope, which was probably due to leaching accumulation. Though its availability is determined by the P adsorption capacity (Deressa *et al*., 2018), soils with a near-neutral pH have the highest Av. P than those under acidic reaction (Yitbarek *et al*., 2018; Beyene, 2011). The extent of microbially mediated P mineralization and immobilization processes could also determine its availability to plants (Zhu *et al*., 2018). Generally, there were variations in the availability of P along the toposequence with an alternative decrease-increase trend from the summit to the bottom depression, perhaps due to the differences in the soil types, topography, level of inherent P content, use of P-containing fertilizers, and soil management practices in the area (Debele *et al*., 2018; Mulugeta and Sheleme, 2010).

The lowest Av. P in the two top soil horizons of the bottom depression could be evidence of P sensitivity to waterlogged and redox conditions (Ruhl, 2015). The labile P fraction declines mainly because of its binding to iron oxides upon soil dryness after a prolonged waterlogging at the depression part (Gérard, 2016; Ruhl, 2015). Thus, P becomes less available in the soils as it reprecipitates with iron mottling and concretions (Deressa *et al*., 2018). However, the depression area often has diverse P dynamics that critically influence distribution and forms of P compared to the other topographic positions. For instance, erosion and runoff from Gleyic Cambisols and Luvisols on the surrounding hillslopes can lead to the deposition of "legacy P" at the bottom depression (Rode *et al*., 2023) but readily unavailable form like P bound to Fe/Al oxides (Mumbi *et al*., 2024).

Similar to this finding, different scholars confirmed that the Av. P content decreases with increasing soil depth because of a decline in soil OM and/or a rise in clay contents (Yitbarek *et al*., 2018; Nahusenay *et al*., 2014; Mulugeta and Sheleme, 2010). Besides, Deressa *et al*. (2018) reported differential P distribution along a toposequence in mountainous topography and undulating landforms of humid western Ethiopia due to lateral and vertical movements of soil materials via the action of water. Mulugeta and Sheleme (2010) found a general increase in the distribution of Av. P down the slope because of the strong association between slope position and soil properties such as pH, OC, clay, etc. This was also confirmed by the positive correlations of Av. P with OC ($r = 0.42$, $P \leq 0.05$), Av. Fe ($r= 0.54$, $P \leq 0.01$) and Av. Mn ($r = 0.44$, $P \leq 0.001$) contents, whereas it was negatively correlated with pH ($r = -0.42$, $P \leq 0.05$) and clay ($r = -0.51$, $P \leq 0.01$) content (Appendix Table 3).

The amounts of exchangeable Ca, Mg, K, and Na ranged from 10.80 to 32.26, 2.86 to 26.84, 0.36 to 0.92, and 0.14 to 0.37 cmol$_c$ kg^{-1} (Table 2.4), which were under high to very high, medium to very high, medium to high, and low to medium ranges, respectively (Wogi *et al*., 2021). All the cations had an irregular pattern across the soil depth, but both the divalent cations showed systematic trends of increase-decrease along the toposequence. Moreover, Ca was the abundant cation on exchange sites, which was followed by Mg, K, and Na in decreasing order, except for the Mg dominance over Ca at the surface layer of the back slope and depression pedons. The cationic swarming of soil colloidal surface is often reported as $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$ (Fekadu *et al*., 2018; Yitbarek *et al*., 2018; Adhanom and Toshome, 2016); and was considered an ideal for normal plant growth and development (Havlin *et al*., 2017).

Apart from the soils in the summit position, the surface soils in all pedons had Ca:Mg ratios below the approximate optimum (3:1 to 4:1) range for most crops to face a Mg-induced Ca deficiency (Landon, 2014). Besides, the Ca:Mg ratios of the surface soils at the back slope and bottom depression positions were below the suggested lowest acceptable (1:1) limit, whereby Ca availability is curtailed by Mg (Landon, 2014). The existing variabilities in relative concentration and distribution of the basic cations could be attributed to differences in the soil type (parent material), stage of weathering and development, erosion and deposition, translocation and leaching, and mining by cropping systems (Hailu *et al*., 2015; Nahusenay *et al*., 2014; Ali *et al*., 2010). In addition to the presence of Mg-bearing minerals (dolomite, olivine, and serpentine), the dominance of Mg over Ca could be ascribed to its primary release after a relatively greater degree of weathering and a strong adsorption nature with certain clay minerals (especially smectites) under lower pH and high water content conditions (Tardif *et al*., 2019; Gardner, 2017; Senbayram *et al*., 2015; Gransee and Führs, 2013).

Table 2. 4. Chemical properties of soils along the toposequence of the sub-watershed

Profile	Horizon	Depth	pH	EC	OC	TN	Av. P	Ex. Ca	Ex. Mg	Ex. K	Ex. Na	CEC	CEC clay	BS	Av. Fe	Av. Mn	Av. Zn	Av. Cu
		(cm)	(H_2O)	(ds/m)	%		mg kg^{-1}	(cmol$_c$ kg^{-1})						(%)	(mg kg^{-1})			
Summit	A	0-25	5.59	0.155	1.83	0.17	18.82	29.38	6.14	0.91	0.16	41.20	72.72	90.27	2.17	1.63	0.41	0.08
	Bt1	25-70	6.23	0.358	0.43	0.07	22.74	23.08	11.92	0.84	0.21	40.76	54.55	90.28	1.45	1.36	0.19	0.11
	Bt2	70-105	7.17	0.293	0.51	0.08	15.32	23.14	11.76	0.81	0.25	40.80	52.74	90.29	0.18	0.57	0.33	0.08
	Btk1	105-135	7.18	0.391	0.38	0.04	4.24	28.40	13.02	0.78	0.32	48.59	70.05	89.90	0.10	0.36	0.45	0.05
	Btk2	135-165	6.97	0.452	0.76	0.04	10.39	32.26	7.50	0.73	0.36	46.84	71.29	89.97	0.17	0.37	0.01	0.13
	Btkm	165-200	7.65	0.280	0.29	0.03	6.33	18.46	21.30	0.86	0.37	47.03	64.96	89.99	0.17	0.27	0.23	0.05
Shoulder	A	0-30	6.23	0.087	1.67	0.16	15.69	22.72	11.08	0.66	0.15	39.45	73.26	89.05	3.22	5.95	0.12	0.17
	AB	30-65	6.52	0.096	1.04	0.12	20.62	19.78	11.12	0.92	0.17	36.55	63.42	89.25	3.82	2.00	0.36	0.12
	Bt1	65-100	6.06	0.287	0.78	0.09	13.25	18.63	12.67	0.91	0.20	37.15	52.23	89.21	1.28	1.56	0.30	0.09
	Bt2	100-120	6.38	0.395	0.27	0.03	4.92	22.15	12.26	0.81	0.24	40.82	55.42	89.00	0.37	1.03	0.18	0.07
	BC	120-135	6.77	0.145	0.31	0.02	3.35	23.55	7.62	0.54	0.28	36.99	69.10	89.24	0.48	1.01	0.16	0.08
Back slope	Ac1	0-25	5.97	0.259	1.69	0.14	22.89	14.37	23.14	0.41	0.19	40.77	83.16	95.14	4.50	5.92	0.22	0.16
	Ac2	25-40	5.95	0.198	1.52	0.13	24.27	13.01	24.46	0.37	0.17	40.59	80.30	95.15	3.99	1.55	0.03	0.14
	Bwv	40-60	5.31	0.409	0.22	0.02	12.28	11.35	20.81	0.52	0.20	35.19	74.83	95.51	4.53	2.16	0.40	0.12
	Bhsm	60-110	6.35	0.117	1.46	0.17	18.46	13.62	21.19	0.51	0.19	37.99	71.64	95.31	3.31	2.59	0.10	0.16
	Btx	110-125	5.93	0.346	0.86	0.08	10.08	19.24	21.57	0.60	0.19	44.56	67.07	94.93	1.84	1.81	0.27	0.12
	B/C	125-155	6.17	0.363	0.40	0.02	16.73	20.93	20.85	0.46	0.24	45.69	92.30	94.88	2.29	4.56	0.43	0.10
Foot slope	Ac1	0-35	5.63	0.143	1.80	0.18	11.49	19.78	18.58	0.42	0.16	42.44	86.30	93.07	2.89	4.32	0.18	0.18
	ABc2	35-70	6.41	0.187	1.71	0.17	13.57	20.94	19.36	0.41	0.18	43.71	99.47	95.08	5.09	3.86	0.64	0.15
	Btc3	70-95	5.94	0.165	1.56	0.15	11.61	19.64	18.12	0.54	0.21	42.17	65.72	93.10	4.27	3.30	0.95	0.14
	2Bti1	95-150	6.51	0.249	1.19	0.09	1.86	22.26	21.79	0.36	0.16	48.69	63.71	92.77	1.18	1.31	0.53	0.12
	2Bti2	150-200$^+$	7.24	0.374	0.88	0.05	0.48	26.13	17.08	0.68	0.31	48.84	65.46	92.75	0.34	0.56	0.70	0.12
Toe slope	Ac1	0-20	6.32	0.143	2.03	0.18	23.96	20.96	8.04	0.72	0.18	31.45	58.24	97.14	3.37	5.82	0.21	0.15
	Ac2	20-45	5.61	0.091	1.53	0.13	16.38	28.01	2.86	0.45	0.16	33.07	63.17	97.01	3.42	5.51	0.75	0.11
	Ac3	45-70	5.87	0.243	1.69	0.17	19.20	10.80	16.20	0.58	0.16	29.07	52.80	97.42	5.36	4.58	0.01	0.25
	Bhc4	70-105	5.42	0.435	1.47	0.17	16.43	23.34	5.56	0.66	0.22	31.47	52.80	97.11	5.33	2.49	0.27	0.13
	B/C	105-165$^+$	5.73	0.457	1.04	0.08	12.82	12.70	26.84	0.78	0.19	42.78	85.20	96.28	2.97	1.76	0.01	0.14
Bottom depression	Ag1	0-30	5.61	0.273	1.98	0.17	8.43	13.46	22.98	0.58	0.15	42.99	75.34	87.67	2.91	6.55	0.28	0.13
	Aqg2	30-65	6.69	0.119	1.43	0.16	8.53	21.78	17.44	0.72	0.14	46.38	82.93	87.52	2.24	4.94	0.38	0.15
	Bg3	65-110	6.16	0.058	0.84	0.14	15.64	26.12	5.86	0.49	0.18	37.86	64.73	88.01	3.82	2.71	0.21	0.11
	Bhg4	110-140	5.31	0.218	1.56	0.15	15.79	21.26	17.14	0.46	0.16	45.25	76.70	87.56	3.83	3.71	0.42	0.11
	BCg5	140-190	5.49	0.356	0.81	0.06	11.77	14.70	12.38	0.47	0.17	32.05	63.59	88.46	2.71	3.19	0.36	0.09

The overall cation exchange capacity (CEC) of soils in the study area ranged between 29.07 and 48.84 cmolc kg^{-1} (Table 2.4), which is under high and very high categories (Wogi *et al*., 2021). The CEC of surface horizons inconsistently varied along the toposequence, whereby the highest CEC value was obtained from the bottom depression part, followed by the foot slope, summit, back slope, shoulder, and toe slope positions. Though the CEC of the soils did not show any regular pattern with soil depth, relatively higher CEC values were recorded in the subsurface horizons of the pedons than their surface counterparts (Table 2.4).

The differing values of CEC down the soil depth and topographic positions could be linked with soil OC and clay contents (Debele *et al*., 2018). The highest CEC in the bottom layers of pedons at the lower (bottom depression) and middle (foot slope) topographic positions could be the result of the relatively high clay accumulation (Table 2.4), whilst the lowest CEC at the surface layers of the pedon at the upper (shoulder) topographic position could be due to lateral and/or vertical movements of clay particles (Deekor *et al*., 2012; Nega and Heluf, 2009). In line with the present findings, Abate and Kibret (2016) found higher CEC in subsurface layers as compared to the surface layers in pedons at different topographic positions.

With respect to the decreasing trend of CEC along the slope, Debele *et al*. (2018) also reported that pedons at upper and middle slope positions had relatively higher CEC than the lower part. Cation exchange capacity had a highly significant positive correlation with clay ($r = 0.46$) and pH ($r = 0.48$), while it was insignificant and negative ($r = -0.21$) with OC (Appendix Table 3). Hereby, the unusual interaction between CEC and OC has been implied for the pH dependence of surface charges (Van Ranst, 2006) and/or incomplete decomposition state of the OM bulk (Akpoveta *et al*., 2014). The ionizable functional groups on organic colloids and clay edge sites are pH dependent; acidification can reduce the negative charge contributed by OM or eliminate mineral sites, that changing the OC-CEC strength (Curtin *et al*., 2015; Mosayeb Heshmati *et al*., 2011). Besides, OM-CEC correlations can be weak or negative when OM is coarse and concentrated on sandy fractions (Zro *et al*., 2023; Khaledian *et al*., 2017).

The CEC clay varied between 52.23 and 99.47 cmolc kg^{-1} whereby higher results were recorded on subsurface horizons of all pedons except for those at the summit and shoulder. Moreover, it increased from the summit to the foot slope and then showed a fall and rise in values at the toe slope and bottom depression pedons, respectively (Table 2.4). Since CEC depends on the nature and amount of soil colloidal particles (Brady and Weil, 2008), the CEC of the clay fraction can be used as a sign for the type of clay mineralogy (Buol *et al*., 2011). Consequently, all soils are assumed to have smectite (60-100 cmolc kg^{-1}) clay group (Fekadu *et al*., 2018). Also, soils with a high proportion of 2:1 expanding clay mineral, dominantly the montmorillonite (80-100 cmolc kg^{-1}), are expected to reserve more Mg, K, and Fe nutrients (Landon, 2014).

The percent base saturation (PBS) of the soils throughout the profiles ranged between 87.52 and 97.42 (Table 2.4). As per the rating of (Hazelton and Murphy, 2021), the PBS is under a very high (>80%) category. The PBS values were higher in subsurface horizons than in the surface, and the values in the surface horizons showed inconsistent decreasing and increasing trends along the toposequence (Table 2.4). High PBS values are in line with the high amount of exchangeable Ca^{2+} ions occupying the exchange sites on the colloidal sites (Sekhar *et al*., 2014). The variation in PBS also indicates the degree of leaching, which could be used as a diagnostic character for classifying soils (Meena *et al*., 2014).

The concentrations of DTPA extractable Fe, Mn, Zn, and Cu in the whole horizons varied from 0.1 to 5.36, 0.27 to 6.55, 0.01 to 0.95, and 0.05 to 0.25 mg kg^{-1}, respectively, with inconsistent patterns along the toposequence and soil depth (Table 2.4). Generally, the highest Fe, Mn, Zn, and Cu concentrations were recorded at the surfaces of back-slope, bottom depression, summit, and foot-slope positions, respectively. Whereas, the lowest contents of the rest micro-nutrients existed at the surface of the summit, except for Zn at the shoulder part. The availability of Mn was followed by Fe, and both were the dominant micronutrients in the surface soil horizons, except for the summit position (Table 2.4). As per the rating set by Wogi *et al*. (2021), the surface soils of the study area are under low to medium and medium to very high ranges in available Fe and Mn contents, respectively, but very low to low in available Zn and Cu contents.

The quantities of soil Fe, Mn, Zn, and Cu could be attributed to the most vital factors such as soil reaction (pH), OM content, clay amount and type, cation proportion, and drainage condition (Havlin *et al*., 2017). For instance, the solubility and availability of Fe^{+3} in soil solution decrease a thousand-fold while that of Fe^{+2} and Mn^{+2} by a hundred-fold for each unit increase in soil pH. Soluble Fe^{+2} and Mn^{+2} ions are complexed by organic compounds in the soil solution, which improves their availability through chelation reaction. Moreover, the concentrations of soluble Fe and Mn could be significantly increased under fine-textured and/or waterlogged soils that exhibit reduced O_2 and redox potential, especially in lower pH conditions. Havlin *et al*. (2017) also pointed out that Cu concentration is usually low, at which most of the soluble Cu^{+2} in surface soils is organically complexed and is strongly bound to OM than any other micronutrient. For soils with similar clay and OM contents, the role of OM in complexing Cu is the highest with 1:1 versus 2:1 clays. The adsorption mechanism with oxides is unlike the electrostatic attraction of Cu^{+2} on the CEC of clay particles, and involves the formation of Cu-O-Fe/Al surface bonds (Havlin *et al*., 2017). A significant fraction of soil Cu is also occluded in various mineral structures, such as clay minerals and Fe, Al, and Mn oxides.

Similar to Cu^{+2}, soil solution Zn^{+2} is low as more than half of it creates stable complexes with high molecular weight organic compounds (lignin, humic acid, and fulvic acid) that exist as soluble or insoluble forms. Typically, thirty-fold declines in solution Zn^{+2} due to complexation with OM have been observed for every unit pH increase between 5 and 7 (Havlin *et al*., 2017). Zink is also strongly adsorbed by magnesite ($MgCO_3$) and dolomite [$CaMg(CO_3)_2$] via getting into the crystal surface at sites normally occupied by Mg atoms (Havlin *et al*., 2017). Although the soils of the study area are not deficient in Fe and Mn, the low levels of available Zn and Cu indicate the potential deficiencies of the elements. This finding is in line with Abayneh (2005) who reported Fe and Mn were at adequate levels across Ethiopian soils. Previous findings also indicated Zn and Cu deficiencies in Ethiopian soils as a widespread problem (Ali *et al*., 2024; Karltun *et al*., 2013; Abayneh, 2005). All the micro-nutrients were positively correlated with OC, while they acquired negative correlations with soil pH. However, they were negatively related to clay particles and CEC, except for the available Zn (Appendix Table 3).

Table 2. 5. Values of selected soil chemical properties around excavated pedons

		Properties								
		pH	OC	TN	Av. P	Ex. K	Ex. Na	Ex. Ca	Ex. Mg	CEC
Pedons	Values	(H_2O)	(%)	(%)	(ppm)			($cmol_c$ kg^{-1})		
Summit	Mean	5.60	1.85	0.20	18.63	0.91	0.16	29.23	6.12	41.18
	SD	0.04	0.04	0.04	0.05	0.03	0.03	0.04	0.03	0.04
	CV (%)	0.71	2.16	20.00	0.27	3.30	18.75	0.14	0.49	0.10
Shoulder	Mean	6.22	1.67	0.14	15.82	0.68	0.14	22.67	11.13	39.46
	SD	0.05	0.06	0.05	0.13	0.07	0.03	0.10	0.12	0.11
	CV (%)	0.80	3.59	35.00	0.82	10.29	21.43	0.44	1.08	0.28
Back slope	Mean	5.94	1.71	0.13	22.79	0.44	0.18	14.35	23.18	40.91
	SD	0.06	0.08	0.04	0.15	0.03	0.04	0.10	0.12	0.12
	CV (%)	1.01	4.68	30.77	0.66	6.82	22.22	0.70	0.52	0.29
Foot slope	Mean	5.63	1.81	0.18	11.50	0.43	0.15	19.76	18.51	42.49
	SD	0.05	0.05	0.06	0.10	0.03	0.04	0.08	0.09	0.10
	CV (%)	0.89	2.76	33.33	0.87	6.98	26.67	0.40	0.49	0.24
Toe slope	Mean	6.20	2.01	0.16	23.98	0.75	0.19	20.97	8.04	31.41
	SD	0.04	0.04	0.03	0.04	0.03	0.03	0.02	0.03	0.03
	CV (%)	0.65	1.99	18.75	0.17	4.00	15.79	0.10	0.37	0.10
Depression	Mean	5.60	1.98	0.18	8.42	0.55	0.13	13.49	22.98	42.97
	SD	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03	0.03
	CV (%)	0.54	1.52	16.67	0.36	5.45	15.39	0.22	0.13	0.07

SD: standard deviation, CV: Coefficient of variation

There was low SD between the results in chemical properties of the surface soils of the horizons and their surrounding surface soils, although a high SD value was obtained at the back-slope position (Table 2.5). Apart from the intermediate variability (15% < CV ≤ 35%) in TN and Ex. Na contents for surface horizons of the pedons and the corresponding surface soils around the pedons, the other chemical properties showed similarities (CV < 15%) among themselves at a particular topographic position (Wilding and Drees, 1978). Thus, soils at the surface horizons of the profile at a given topographic position represent the soils of their surrounding area.

2.3.2. Classification and mapping of the soils

Generally, the morphological and physicochemical properties of all the surface horizons were found within or very near the range of their concerned adjacent surface soil samples at a typical position of the toposequence (Tables 2.2-2.5). Akin to the pedons excavated and their surrounding surface soils, those soil mapping units (SMU) having uniform or nearly identical results of common morphological (color, structure, consistence, and texture-feel) and selected physico-chemical properties (texture, pH, OC, basic cations, and CEC) were considered and mapped as a similar soil group (Figure 2.2).

The soils of SMU 06 (the summit pedon), 09, 13, 18, and 29 were heavy-textured blackish soils having a high proportion of alternatively shrink-swell clays which form wide and deep cracks inward to ≥ 50 cm from the surface upon drying. The surface soils (≤ 30 cm) were evidenced by a dusty appearance, having a moist Munsell color value of ≤ 3 and chroma of ≤ 2. Besides, they had wedge-shaped aggregates with signs of frequent internal turnover (churning) of the soil materials after the upper 20 cm. Specifically, the summit pedon had thick (≥ 25 cm) subsurface horizons having more than 30% clay and 80% effective base saturation in 20-100 cm from the soil surface. About 80% volume of the subsurface horizon between 25-70 cm depth was occupied by periodically broken wedge-shaped structural elements having an average horizontal length of < 10 cm. These properties qualify the soils for a vertic diagnostic horizon (IUSS, 2022). Also, there was a brownish subsurface horizon beyond the depth of 100 cm that has a clayey (≥ 30%) texture with very firm and extremely hard consistence when moist and dry, respectively, and produces effervescence when adding 1M HCl due to its cementation by the microcrystalline form of $CaCO_3$. Thus, such soils are classified as Pellic Bathypetroduric Vertisols (Hypereutric, Amphifractic), abbreviated as VR-pe-pdd-je-fcm (IUSS, 2022).

Similarly, the soils of SMU 05 (the shoulder pedon), 02, 04, 07, 08, 11, 12, 19, 26, and 28 exhibited wedge-shaped aggregates with a high proportion of alternatively shrink-swell clays that broke when dried, hence were verified for the vertic property (IUSS, 2022). However, the soils were at incipient stages of horizon differentiation, which is evident from the changes in soil structure and color (mostly brownish discoloration) in their subsurface. According to IUSS (2022), these soils were qualified for a Cambic diagnostic horizon like that of the SMU 01, 03, 10, 14, 15, 16, 20, 21, 23, 24, 27, 30, 31, and 32. The soils were also characterized by slightly to moderately weathered medium and fine-textured materials, and the absence of considerable amounts of illuviated clay, OM, or Fe/Mn compounds within 100 cm from the soil surface. The soils of the shoulder pedon (SMU 05) exhibited ≥ 1% OC in the fine earth fraction of the upper two horizons to a weighted average depth of 65 cm. There were some noticeable soil structure and color changes from 30 to 65 cm because of a moderate pedogenetic alteration and wedge-shaped structural elements between a depth of 65 and 100 cm. Moreover, the soils had ≥ 30% clay and 80% effective base saturation in all horizons; hence, they are classified as Hypereutric Vertic Cambisols (Pantoclayic, Humic), abbreviated as CM-vr.je-cle-hu (IUSS, 2022).

The soils of SMU 16 (the back-slope pedon), 01, 03, 10, 15, 20, 23, 24, and 27 were situated in human-made terraces, whereby ≥ 40% of their soil surface was covered by fragments of stones and boulders with ≥ 6 cm dimension. Also, their subsoils starting ≤ 100 cm from the soil surface had a very to extremely hard and broken layer of indurated yellowish-brown materials which were cemented by Fe/Mn (hydr-) oxides with an insignificant amount of OM. Particularly, over 40% of interconnected yellowish-brown concretions and/or nodules of Fe/Mn (hydr-) oxides were found in the back-slope pedon. The concretions and/or nodules were arranged in reticulate patterns at which roots only traversed through vertical fractures of sheets having about 10 cm horizontal length at 40 to 60 cm depth. An illuvial accumulation of OM in the subsurface horizon was evident with an iron-caused nearly continuous cementation between the depths of 60-110 cm. Besides, there was an illuvial accumulation of silicate clays with fragipan characteristics that developed a brittle structure between 110 and 125 cm depth. All of the horizons throughout the pedon had clay content ≥ 30%; with an effective base saturation (1 M NH_4OAc, pH 7) of ≥ 80%; soil organic carbon of ≥ 1% in the fine earth fraction to a depth of 50 cm from the mineral soil surface; and an exchangeable Ca to Mg ratio of below 1 in the major part within 100 cm of the soil surface. Therefore, all the diagnostic criteria qualified the soils for Hypereutric Akroskeletic Plinthofractic Cambisols (Pantoclayic, Escalic, Humic, Magnesic) abbreviated as CM-px.kk.je-cle.ec.hu.mg (IUSS, 2022).

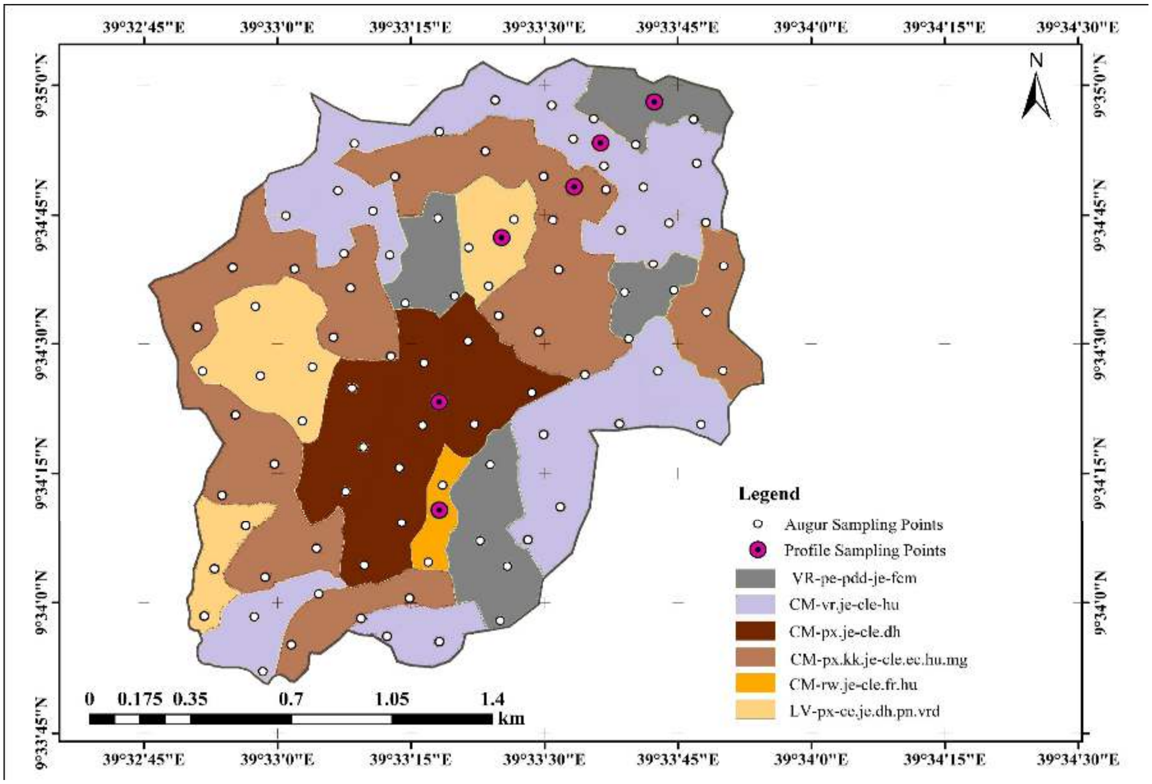

Figure 2. 2. Soil map of the study area

The soils of SMU 17 (Foot-slope pedon), 22, and 25 had parent materials from colluvial deposition of different unconsolidated materials, whereby higher clay content was noticed in the subsurface horizon that directly overly coarser textured subsoil as a result of pedogenetic processes (especially clay migration) within the upper 100 cm. This satisfied the criterion for the Argic diagnostic horizon of the Luvisols (IUSS, 2022). Principally, the foot-slope pedon was characterized by a pedogenetic clay differentiation with a lower clay content in the topsoil than the subsoil without marked leaching of basic cations or advanced weathering of high-activity clays. The Argic subsurface horizon existed directly below a coarser-textured horizon, not separated by a lithic discontinuity between 70 and 95 cm deep, at which its clay content did not decrease by ≥ 20% (relative) from its maximum within 150 cm of the soil surface. The ratio of clay in the argic horizon to that of the coarser textured horizon was 1.47. Besides, more than 40% of the subsurface soil volume was occupied by strongly cemented to indurated reddish and blackish pea-like concretions of Fe/Mn (hydr-) oxides with a diameter of ≥ 2 mm. The amount of organic carbon in the fine earth fraction as a weighted average to a depth of 100 cm from the mineral soil surface was ≥ 1.4% with an effective base saturation (1M NH_4OAc, pH 7) of ≥ 80% in layers between 20 and 100 cm from the mineral soil surface. The pedon had a texture class of clay, in a layer ≥ 30 cm thick within 100 cm of the mineral soil surface, while the depth beyond a meter was attained by shiny-faced (slickensides) structures. Consequently, these soils are grouped as Pisoplinthic Luvisols (Clayic, Hypereutric, Profundihumic, Profondic, Bathyvertic) abbreviated as LV-px-ce.je.dh.pn.vrd (IUSS, 2022).

Although there was no evidence of advanced pedogenesis, appreciable signs of incipient weathering of primary minerals upon free internal and external drainages indicated that the soils of SMU 32 (the toe-slope pedon), 14, 21, and 31 were at an early stage of soil formation. According to Havlin *et al.* (2017), hydrolysis of iron-containing minerals (biotite, olivine, pyroxenes, and amphiboles) in a weakly acidic environment produces ferrous iron that is oxidized to ferric oxides and hydroxides (goethite and hematite). This ‘free iron’ coated sand and silt particles and cemented clay, silt, and sand into aggregates of yellowish-brown to reddish. There was some evidence of leaching of basic cations, but no clear migration of Fe, OM, or clay was noted. The oxidative weathering process was not limited to the cambic horizon; rather, it also occurred in the surface A-horizon as the accumulated soil OM obscures its appearance. Explicitly, all horizons of the toe-slope pedon to a depth of 100 cm contained a pea-like yellowish, reddish, and/or blackish concretions or nodules of ≥ 2 mm diameter that were strongly cemented to indurated with Fe/Mn (hydr-) oxides in their ≥ 40% volume. Moreover, all horizons of the pedon had clay contents higher than 30% with an effective base saturation (1 M NH_4OAc, pH 7) of ≥ 80% and soil OC of ≥ 1.4% in the fine earth fraction to a depth of 100 cm from the mineral soil surface. Thus, the soils are grouped as Hypereutric Pisoplinthic Cambisols (Pantoclayic, Profundihumic), abbreviated as CM-px.je-cle.dh (IUSS, 2022).

The soils in the bottom depression pedon (SMU 30) had a layer ≥ 25 cm thick starting ≤ 75 cm from the soil surface characterized by stagnic properties in which the area of reductimorphic colors plus the area of oximorphic colors is ≥ 25% of the total layer area, and no reducing conditions. The segregation of ≥ 5% reddish to blackish Fe and Mn oxides with a diameter of ≥ 2 mm in the subsurface horizon at a depth of 65 to 110 cm has taken place to such an extent that large mottles or discrete concretions or nodules were formed, and the matrix between mottles, concretions, or nodules was largely depleted of Fe and Mn. They did not have enhanced Fe and Mn contents, but Fe and Mn were concentrated in mottles, concretions or nodules. Such segregation led to the poor aggregation of the soil particles in Fe- and Mn-depleted zones and compaction of the horizon. All horizons throughout the pedon had clay contents higher than 30% with an effective base saturation (1M NH_4OAc, pH 7) of ≥ 80%, and soil organic carbon of ≥ 1% in the fine earth fraction to a depth of 50 cm from the mineral soil surface. According to IUSS (2022), these soils are considered as Hypereutric Relictistagnic Cambisols (Pantoclayic, Ferric, Humic), abbreviated as CM-rw.je-cle.fr.hu.

2.4. Conclusion

This study investigated the properties (morphological, physical, and chemical) and distribution of soils along the toposequence of the Qenberenaweti sub-watershed, which were influenced by the variations in a topographic position and key slope features (steepness, aspect, and form). These factors have direct effects on erosion-deposition and eluviation-illuviation processes of the soil materials through the action of water moving laterally over the surface and percolating vertically deep into the subsoils, respectively. They can also influence the extent of soil formation, development, and distribution in the area. Therefore, this study emphasized that recognizing the impact of topography on overall soil properties is crucial for effective soil management and agricultural planning. It provides clear insights into how different soil types can be utilized based on their specific characteristics. Besides, the findings revealed that detailed soil surveys and mapping at watershed levels enhance our understanding of soil resources and their distribution, thereby optimizing agricultural productivity via addressing the most important problems of soil fertility.

In conclusion, soil sampling and analysis revealed significant differences in soil characteristics across diverse topographic positions. The study identified 32 soil mapping units (SMUs) with varying depths, textures, and chemical compositions, reflecting the dynamic interplay between topography and soil formation processes. Hence, six different soil types are coined as the Pellic Bathypetroduric Vertisols (Hypereutric, Amphifractic), Hypereutric Vertic Cambisols (Pantoclayic, Humic), Hypereutric Akroskeletic Plinthofractic Cambisols (Pantoclayic, Escalic, Humic, Magnesic), Pisoplinthic Luvisols (Clayic, Hypereutric, Profundihumic, Profondic, Bathyvertic), Hypereutric Pisoplinthic Cambisols (Pantoclayic, Profundihumic), and Hypereutric Relictistagnic Cambisols (Pantoclayic, Ferric, Humic). The results showed that the upper slopes generally exhibited thinner, coarser-textured soils, while lower slopes and depressions had thicker and clay-rich profiles due to erosion and deposition processes. The study also highlighted the role of soil OM, pH, and nutrient availability, which varied significantly across the topographic positions. For instance, OC content was higher in surface soils but declined with depth, reflecting the effects of topographic features along the toposequence. Further research is recommended to explore the impacts of topography on the geo-spatial variability of soil properties and fertility implications for enhancing crop production in the study area.

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3. POTASSIUM FORMS AND RELATIONS WITH SELECTED PHYSICOCHEMICAL PROPERTIES IN SOILS OF QENBERENAWETI SUB-WATERSHED, CENTRAL HIGHLANDS OF ETHIOPIA

Haymanot Awgchew[1,2], Sheleme Beyene[1], Alemayehu Kifilu[1], Asmare Melese[2]

[1]School of Plant and Horticultural Science, Hawassa University, Ethiopia

[2]Department of Plant Science, Debre Berhan University, Ethiopia

ABSTRACT

The site-specific status and distribution of all K forms (water-soluble, exchangeable, non-exchangeable, and mineral) in the upper soil layer are distinctly determined by soil properties. Thus, this research aimed to analyze fractions of the K forms and their interactions with selected physicochemical properties (texture, pH, organic carbon, CEC, exchangeable cations) in soils of the Qenberenaweti Sub-watershed, Central highlands of Ethiopia. Three composite surface (0-20 cm) soil samples were collected from farmland in the most representative soil mapping units of six preidentified soil types (Vertic Cambisols, Pisoplinthic Cambisols, Akroskeletic Cambisols, Relictistagnic Cambisols, Pellic Vertisols, and Pisoplinthic Luvisols). All soils were clayey, among which Vertic Cambisols, Relictistagnic Cambisols, and Pisoplinthic Luvisols exhibited the highest pH (6.11), CEC (40.03 cmol$_c$ *kg*$^{-1}$*), and OC (2.19%), respectively. The Relictistagnic Cambisols showed the lowest amounts of all K forms. Pellic Vertisols contained the highest water-soluble and exchangeable K, while Pisoplinthic and Vertic Cambisols were richest in non-exchangeable and mineral K forms, respectively. The K forms had significant correlation ($p < 0.01$) among themselves and specifically with exchangeable Na in Plinthofractic Cambisols. The exchangeable K was positively associated with clay and CEC, when the non-exchangeable K did with clay and pH, and mineral K with silt and clay fractions. Principal Component Analysis identified soil texture, pH, and CEC as primary drivers of K dynamics, explaining 80.9% of variability. The study emphasized the analysis of all K forms alongside soil properties for effective K management at a site-specific level. Besides, it revealed widespread Mg-induced K deficiency due to imbalanced cation ratios (K:Ca < 0.05 and K:Mg < 0.08) and the limitations of NH*$_4$*OAc extraction in soil K assessment. Eventually, a soil test-based application of ash amendments might enhance the bioavailability of K in the experimental soils. However, future research on clay mineralogy should be conducted to draw sound conclusions.*

Keywords: potassium supply, labile K, non-labile K, K fractions, soil properties.

3.1. Introduction

Potassium (K) is the 7th most abundant element, comprising about 2.5% of the Earth's crust (Havlin *et al*., 2017), with a total amount of 3,000 to 100,000 kg ha^{-1} in the upper 20 cm soil profile (Iskandar *et al*., 2022; Mouhamad *et al*., 2016). About 95-98% of the total soil K reserve is structurally bound in mineral fraction, while 1-3 and 0.02-2% exist as non-exchangeable and exchangeable forms, respectively (Havlin *et al*., 2017). Since their fractions are in a dynamic equilibrium reaction (Lalitha and Dhakshinamoorthy, 2014), all the K forms are potential sources of K without distinct boundaries (Havlin *et al*., 2017). However, each form contributes to plant nutrition at different rates (Zörb *et al*., 2014) due to the widely variable K pools that are mobilized by weathering extents of K-bearing minerals (Simonsson *et al*., 2009; Murashkina *et al*., 2007).

Since the bioavailability of K depends on its form and distribution in the soil profile (Butt *et al*., 2017), proper analysis of concentrations and equilibrium fractions between the K forms is key to understanding the K-supplying capacity of different soil types (Timsina *et al*., 2013). According to Blanchet *et al*. (2017), the distribution and dynamic K statuses in the upper 20 cm soil layer are notably influenced by agro-environmental factors. The major ones are practices of fertilization and cropping (Singh *et al*., 2018; Chatterjee *et al*., 2015), features of topography (Xu *et al*., 2019; Blanchet *et al*., 2017), abundance of soil erosion (Martínez-Hernández *et al*., 2017), as well as physicochemical and mineralogical properties (texture, clay amount and type, aeration, moisture, OM, pH, CEC, and nutrient balance) of soils (Bilias and Barbayiannis, 2019; Havlin *et al*., 2017).

The concentration of K in the soil determines its use efficiency and yield of crops (White *et al*., 2021; Rawat *et al*., 2016). Hence, a test on soil K status provides useful information for possible improvement of soil fertility and proper fertilization (Bell *et al*., 2021; Dotaniya *et al*., 2016). There are many standard K extraction methods with different effectiveness in estimating the plant availability of soil K (Cheng *et al*., 2023; Demiss *et al*., 2020). Fortunately, appropriate K management for a given soil type relies on the preference of diverse methods to assess its availability for crop uptake and production (Sarkar and Patra, 2017). For instance, due to the immediate availability of the labile (exchangeable and water-soluble forms) K fraction (Das *et al*., 2018), most K management and recommendation practices are made using the conventional NH_4OAc extraction method (Islam *et al*., 2017). However, a substantial role of the non-labile (non-exchangeable and structural) K fraction is evidenced in plant nutrition (Kishore *et al*., 2020; Das *et al*., 2019). That means, K availability cannot be explained by the labile K contents alone (Rao and Srinivas, 2017; Lalitha and Dhakshinamoorthy, 2014). In this regard, the NH_4OAc

method becomes a poor indicator of the K supply and uptake during the plant growing season (Charbonnier, 2022; Islam *et al*., 2017). Consequently, the appropriate K management strategy should consider the distribution of all K forms and the dynamic equilibrium among them (Aswad *et al*., 2020; Blanchet *et al*., 2017; Chatterjee *et al*., 2015) for enhancing sustainable crop production (Butt *et al*., 2017).

The fractions of soil K forms may vary with landscape positions (Uzoho *et al*., 2022), especially in soils along a toposequence (Ibrahim *et al*., 2020; Samndi and Tijjani., 2014). As the study area is characterized by the presence of different soil types owing to the effects of topographic features, acquiring proper soil variability data that is concerned with the determinant physicochemical properties of the K availability within a watershed leads to better farm management decisions (Akbas *et al*., 2017). According to Goulding *et al*. (2021), better understanding of all K forms and their dynamic distribution in soils of a watershed is a key issue for proper agronomic management. Besides, a detailed explanation of the relationship among each K form as well as with physico-chemical properties of diverse soils at the site-specific level is a criterion for predicting K supply capacity (Auge *et al*., 2017; Habib *et al*., 2014) and make effective management (Amoakwah and Frempong, 2013). However, analysis of the labile K form by the NH_4OAc extraction is still commonly used to determine the potential K-supplying power of the soils in Ethiopia. Therefore, this research was initiated to analyze some selected soil physicochemical properties and overall fractions of K forms with their relationship in soils of the Qenberenaweti Sub-watershed, Central Highlands of Ethiopia.

3.2. Materials and Methods

3.2.1. Soil sampling and analysis

Twelve sub-samples of surface soil (0-20 cm) were collected in a zig-zag fashion from a typical farmland under three randomly selected soil mapping units (SMU) for each of the six pre-identified soil types in the Experiment 1 (Chapter 2). The soils were Pellic Vertisols, Pisoplinthic Luvisols, Vertic Cambisols, Pisoplinthic Cambisols, Plinthofractic Cambisols, and Relictistagnic Cambisols. After mixing the 12 sub-samples thoroughly into one based on their SMU, three composites were made accordingly per a soil type for the analysis of some selected physico-chemical properties and all K forms. Soil particle size distribution, pH, OC content, exchangeable bases (Ca, Mg, K, and Na), and cation exchange capacity (CEC) were determined following the standard procedures described under Section 2.2.2 of the Experiment 1.

The water-soluble K was extracted by shaking 2.50 g of soil in 12.50 ml of deionized water for 30 minutes (Wang *et al.*, 2010). The exchangeable K was extracted using 50 ml of 1M neutral NH_4OAc solution in 2.50 g of soil for 30 minutes (Knudsen *et al.*, 1982). Since it denotes the labile fraction, the amount of the exchangeable K on the colloidal surface was taken as the difference between water-soluble and ammonium acetate extractable K (Lu, 1999). The non-exchangeable K was determined by 1M HNO_3 boiling extraction at a soil-to-solution ratio of 1:20 with an extraction time of 30 minutes (Martin and Sparks, 1983). The suspension of HNO_3 extraction represents the exchangeable plus non-exchangeable K; hence, the non-exchangeable K was obtained by deducing the NH_4OAc extractable K from the HNO_3 extractable K (Lu, 1999). The total K was estimated using hotplate digestion of 0.50 g soil in 12 ml of Aqua Regia (3:1 mixture of concentrated HCl and HNO_3) solution by following the procedure outlined by Nieuwenhuize *et al.* (1991). The difference between total K and HNO_3 extractable K was considered as the mineral K content. All the extracts were filtered through Whatman filter paper No. 42 to measure quantities of the K fractions using a flame photometer.

3.2.2. Statistical analysis

The analytical data on the selected physicochemical properties and fractions of the K forms in the experimental soils were interpreted with descriptive statistics: mean. standard deviation (SD), and coefficient of variation (CV). According to Wilding and Drees (1978), the extent of variability in each parameter was assessed based on CV values as least (0-15%), moderate (16-35%), and high ($\geq$ 36%). Pearson's simple correlation was determined using the R software to identify the relationships between the selected properties and K-forms under each soil type.

Since there was a significant correlation among the K forms due to the positive or negative effects of the selected soil properties, principal component analysis (PCA) was performed to evaluate and group the variables that caused the variabilities observed between soil properties and K form covariates. The PCA allows similar variables to be grouped into principal components (PCs) without differentiating independent and dependent variables (Jolliffe and Cadima, 2016). The PCA also identifies those variables accounting for maximum variance in the dataset via the dimensional reduction technique (Van Der Maaten *et al.*, 2009). Only statistical dimensions with eigenvalues greater than one were considered as PCs contributing more to the variability in the soil properties (Maskey *et al.*, 2018). Then, the component scores were plotted in a pictorial form to describe behavior, trends, and the spread of identified factors (Shrestha, 2021). The use of component scores enables the whole complex of variables to be incorporated into a pattern, and this permits a better assessment (DiStefano *et al*., 2009).

3.3. Results and Discussion

3.3.1. Physical and chemical properties of the experimental soils

Apart from the clay loam textural class of the Plinthofractic Cambisols that contained the highest percent of silt (38.0±2.0) particles, the other soils had clayey texture with the lowest fractions of sand (18.0±1.0) in the Pellic Vertisols and the highest clay (56.67±0.58) in the Vertic Cambisols (Table 3.1). All the soils were rated as low in their sand contents, except for the moderate content in the Plinthofractic Cambisols and Pisoplinthic Luvisols (Hazelton and Murphy, 2016). Hence, only the Vertic Cambisols were characterized by a low silt fraction, as the others were moderate. Though the Plinthofractic Cambisols had a moderate proportion of clay particles, there were very high fractions of clays in the Vertic Cambisols and Pellic Vertisols, while the rest of the soils had high clay contents (Hazelton and Murphy, 2016). The experimental soils showed the least variability within the distribution of each particle (Wilding and Drees, 1978). This implies a given soil type has received comparable management practices and partakes of identical parent material and topographic features. Because particle size distribution in surface soil is modified by the pedologic processes that are shaped by the nature of parent material, topographic conditions, and anthropogenic management practices (Weil and Brady, 2017; Vanwalleghem *et al*., 2013).

The differences in the distribution of primary particles among the soil types might be due to erosion and washing by runoff and/or percolating water, and soil manipulation during tillage and farm management operations at the specific topographic position where the soil type is located. Generally, the relative proportions of the three soil separates are affected by topography (Ofori *et al*., 2013), which in turn determines the rate of runoff that selectively removes finer particles (Coulthard *et al*., 2012). Besides, fine-sized particles (clay and silt) are washed from the surface by percolating water under a long-term cultivation practice (Chemeda *et al*., 2017; Gebrelibanos and Assen, 2013). However, the relative presence of more clay particles in the soils of a vertic nature could be related to the natural profile intermixing than the others (Jadhao *et al*., 2018).

The Relictistagnic Cambisols and Vertic Cambisols had minimum (5.60±0.15) and maximum (6.11±0.23) mean pH-H_2O values, respectively (Table 3.1). According to Wogi *et al*. (2021), all the study soils were moderately acidic (5.6-6.0) except for a slightly acidic (6.1-6.5) reaction in the Vertic Cambisols. The lower pH variability across the experimental soils (Wilding and Drees,

1978) could be due to inherent properties linked with abundant buffering substances in the soils with self-regulating ability (Husson, 2023; Sparks *et al*., 2022) and similarity within soil-forming materials (Yescas-Coronado *et al*., 2022).

Since soil acidity is a sum of natural and anthropogenic conditions that lower the soil pH (Weil and Brady, 2017), the difference in acidity could be attributed to the prevailing topographic position as well as the crop production and soil management practices. The level of soil reaction is determined by the topographic position (Ofori *et al*., 2013; Chimdi *et al*., 2012) via the effect on erosion-deposition of soil materials and leaching of basic cations (Tesfahunegn and Gebru, 2020), especially under high rainfall conditions. Soils also become acidic upon oxidation of OM (Nega and Heluf, 2013), use of ammonium-based fertilizers (Wang *et al*., 2020), continuous tillage (Mengiste *et al*., 2015), and undue mining of basic cations through total removal of crop residues with sub-optimal/poor fertilization practices (Cherie and Abeje, 2022).

The Pisoplinthic Luvisols had the highest OC (2.19 ± 0.51%) contents, while the Vertic Cambisols had the lowest (1.73 ± 0.58%) amounts (Table 3.1). However, all the soils were rated as medium in their OC (1.5-3.0%) contents (Wogi *et al*., 2021). Apart from the lower variability for the Relictistagnic Cambisols and Pellic Vertisols, the other soils had moderate variability of OC (Wilding and Drees, 1978). The lower to moderate variabilities in OC imply a relatively stable and consistent OM input and decomposition process within the soils (Angst *et al*., 2019).

The low OC in the Vertic Cambisols might be attributed to continuous tillage and poor soil management practices, specifically to their distribution in the shoulder physiographic position of the study area. Rapid mineralization of OM is anticipated following frequent tillage operations at the shoulder part (Abebe *et al*., 2020), which enhances soil aeration and microbial activity (Raiesi and Kabiri, 2017; Valboa *et al*., 2015); thereby reducing the OC content in agricultural soils at the shoulder position (Jandl *et al*., 2019). In addition to a faster rate of SOM decomposition (Abegaz *et al*., 2016) and/or complete removal of crop residues (Cherie and Abeje, 2022; Jakšić *et al*., 2021), the intense topsoil erosion at this topographic position results in low OC content (Juřicová *et al., 2022;* Jandl *et al*., 2019; Zhang *et al*., 2015).

Table 3. 1. Mean values of selected physicochemical properties in the soils of the sub-watershed

Soil types	Value	Soil testing parameters										
		Sand	Silt	Clay	Textural class	pH-H_2O (1:2.5)	OC (%)	Ex. Ca	Ex. Mg	Ex. K	Ex. Na	CEC
			(%)							(cmol$_c$ kg^{-1})		
Plinthofractic Cambisols	Mean	29.67	38.00	32.33	Clay loam	5.63	2.15	15.03	9.56	0.73	0.05	30.10
	SD	1.15	2.00	2.31		0.26	0.45	2.83	0.98	0.20	0.02	3.93
	CV (%)	3.89	5.26	7.14		4.62	21.00	18.84	10.29	26.91	33.33	13.05
Pisoplinthic Cambisols	Mean	23.67	34.66	41.67	Clay	5.73	1.97	17.11	9.74	0.65	0.10	33.14
	SD	1.15	1.15	1.15		0.35	0.39	1.79	3.14	0.16	0.03	2.85
	CV (%)	4.88	3.33	2.77		6.11	19.71	10.46	32.27	24.18	26.46	8.59
Relictistagnic Cambisols	Mean	24.33	28.67	47.00	Clay	5.60	1.97	19.08	12.39	0.61	0.08	40.03
	SD	0.58	1.15	1.00		0.15	0.24	3.40	1.23	0.07	0.02	2.88
	CV (%)	2.37	4.03	2.13		2.68	12.18	17.80	9.93	10.72	19.92	7.19
Pisoplinthic Luvisols	Mean	27.67	32.00	40.33	Clay	5.73	2.19	21.24	10.57	0.75	0.06	37.26
	SD	1.15	1.73	0.58		0.29	0.51	3.33	2.42	0.18	0.02	5.84
	CV (%)	4.17	5.41	1.43		5.06	23.20	15.67	22.86	23.70	25.30	15.68
Vertic Cambisols	Mean	19.67	23.33	56.67	Clay	6.11	1.73	19.82	10.21	0.79	0.04	37.94
	SD	1.53	1.15	0.58		0.23	0.58	2.96	1.78	0.26	0.01	5.25
	CV (%)	7.76	4.95	1.02		3.77	33.36	14.93	17.44	32.91	29.30	13.85
Pellic Vertisols	Mean	18.00	32.00	50.33	Clay	5.81	2.13	20.21	10.79	0.72	0.06	37.07
	SD	1.00	1.00	1.53		0.32	0.27	4.12	1.47	0.25	0.02	4.32
	CV (%)	5.56	3.13	3.03		5.51	12.70	20.37	13.62	34.72	24.12	11.66

Maximum mean values of exchangeable Ca, Mg, K, and Na (21.24, 12.39, 0.79, and 0.10 cmol_c kg^{-1}) were found in the Pisoplinthic Luvisols, Relictistagnic Cambisols, Vertic Cambisols, and Pisoplinthic Cambisols, respectively (Table 3.1). The Plinthofractic Cambisols had the minimum contents of Ca and Mg (15.03 and 9.56 cmol_c kg^{-1}, respectively), while Relictistagnic Cambisols and Vertic Cambisols exhibited the lowest K and Na (0.61 and 0.04 cmol_c kg^{-1}, respectively). All the soils had very low Na (< 0.10 cmol_c kg^{-1}), high K (0.6-1.2 cmol_c kg^{-1}), very high Mg (> 8.0 cmol_c kg^{-1}), and high Ca (10-20 cmol_c kg^{-1}) on their exchange sites, except for very high Ca in Pellic Vertisols and Pisoplinthic Luvisols (Wogi *et al*., 2021). All cations showed low to moderate variability, except for the moderate Na across the study soils (Wilding and Drees, 1978). The moderate variability could be related to heterogeneity in pedogenic and/or hydrologic processes that are verified by topographic features at sampling units (Mwendwa, 2021; Santos *et al*., 2017).

The maximum (40.03±2.88 cmol_c kg^{-1}) and minimum (30.10±3.93 cmol_c kg^{-1}) CEC values were recorded from the Relictistagnic Cambisols and Plinthofractic Cambisols, respectively (Table 3.1). All the study soils were rated as high (25-40 cmol_c kg^{-1}) in their CEC (Wogi *et al*., 2021). Apart from the moderate variability of CEC under the Pisoplinthic Luvisols, all soils had low variability in CEC (Wilding and Drees, 1978). Lower to moderate variabilities in soil CEC infer a relatively consistent ability of the soil to retain and exchange cations (Obalum *et al*., 2013).

The existing quantities of basic cations could be attributed to the factors that determine their distribution and dynamics in the agricultural soil system. The best-known ones are the intensity of farming practices (cultivation, use of acidifying inorganic fertilizers, application of organic amendments, and residue management) and weathering rate of the parent materials (Anindita *et al*., 2022; Chimdi *et al*., 2012). In addition to the sub-optimal use of acid-forming fertilizers, the presence of substantial exchangeable bases owing to the intermediate soil OM and high clay contents in the upper layer of cultivated soils could result in the high CEC (Horneck *et al*. 2011).

The exchange sites of all the experimental soils were dominated by Ca, Mg, K, and Na in decreasing order. The high amounts of Ca and Mg compared to K and Na in the soils (Table 3.1) might be due to the nature of the cations in a given soil parent material. According to Hailu *et al*. (2015), the presence of high exchangeable Ca and Mg is attributed to the release of divalent cations from soil parent material and colloidal particles. Although the absolute values of K in the soils were above the optimum threshold, their imbalance with Ca and/or Mg might reduce K availability and potentially result in K deficiency (Laekemariam *et al*., 2016; Hailu *et al*., 2015).

The ratios of K:Ca, K:Mg, and Ca:Mg in the soils ranged from 0.03 to 0.05, 0.05 to 0.08, and 1.53 to 2.03, respectively. Havlin *et al*. (2017) pointed out that maximum yields of crops can only be achieved by keeping the ideal ratios of K:Ca (1:13) and/or K:Mg (1:2). According to these authors, a Ca:Mg ratio lower than 3:1 results in Ca deficiency with the possibility of P inhibition. The values of K:Ca, K:Mg, and Ca:Mg ratios indicate the need for balancing the relative saturation of these cations for optimum field crop production (Firmano *et al*., 2020; Fageria and Nascente, 2014). Moreover, the optimum K:Mg ratio in soils is 0.7:1, and values below 0.5:1 may affect K uptake (Loide, 2004). Consequently, all the soils were characterized by Mg-induced K deficiency.

3.3.2. Fractions of potassium and their relations with selected soil properties

The Relictistagnic Cambisols had a low (34±0.3 mg kg^{-1}) amount of water-soluble K, while the Pellic Vertisols had a high (59±0.8 mg kg^{-1}) water-soluble K in the soil solution phase (Table 3.2). According to Akrawi (2018), the contents of water-extractable K in all experimental soils were above the critical value (19.5 mg kg^{-1}). Apart from the Pellic Vertisols and Vertic Cambisols, the quantity of this K fraction was found within the common range of 20-50 mg K kg^{-1} in agricultural soils of humid regions (Mouhamad *et al*., 2016). The amount of water-soluble K varies narrowly with soil types, which could be attributed to the K status, fertilization practices, and clay and OM compositions of soils (Blanchet *et al*., 2017; Lalitha and Dhakshinamoorthy, 2014).

The readily available K form in the solution of the studied soils accounted for 0.44 to 0.70% of the total K fraction; hence, it could be considered as very small to support plant growth via initiating immediate release from the exchange sites and/or resisting leaching loss. Because the release of exchangeable K into the soil solution is fairly slow (Das *et al*., 2018; Ghiri *et al*., 2012), its availability is a bottleneck for fast-growing crops (Bhaskarachary, 2011). Since this K form is unbound by cation exchange forces and often subjected to leaching losses (Kianira, 2021; Lalitha and Dhakshinamoorthy, 2014), it could be inadequate to meet the instant K requirement of short-duration crops (Wakeel and Ishfaq, 2022; Malhotra, 2016).

The maximum K amount in the solution phase of heavy-textured soils compared to the others could be due to the presence of substantial fine-sized minerals in the Vertisols and soils of Vertic subgroups (Ghiri *et al*., 2011). In addition to the equilibrium reaction among the K forms, the differences in solution K concentration are determined by soil moisture content, soil pH, CEC, clay type and amount, OM content, and quantity of cations on the exchange site (Aurangzeib *et al*., 2021; Kaur, 2019; Blanchet *et al*., 2017; Jalali and Khanlari, 2014). In line with these results, Aurangzeib *et al*. (2021) found more water-soluble K in heavy-textured soils than in the others owing to the limited rate of water percolation.

Pearson's outputs (Appendix Table 4) showed a negative correlation between the solution K and Ex. Mg on all the study soils, except for the Vertic Cambisols, as well as with Ex. Na and CEC on the soils apart from the Relictistagnic and Vertic Cambisols. Hence, it confirmed that the decline of water-soluble K was due to the primary competition of the cations for adsorption sites that could displace and cause its leaching from the soil solution. According to Ding *et al*. (2019), the larger charge densities of Mg and Na ions on and around the colloidal surface, respectively, can reduce the amount of K in the soil solution via facilitating its substitution and removal. Despite the pH, silt, and clay of the Pellic Vertisols and Vertic Cambisols, the water-soluble K followed an opposite mode of interaction with OC, exchangeable cations, CEC, and sand. The higher value in the Pellic Vertisols might be due to the positive role of OM in enhancing the aggregation of silt and sand particles compared to the Vertic Cambisols. Generally, OM binds soil particles into aggregates that slow down water movement (Murphy, 2015), improving K retention in the soil.

As shown in Table 3.2, the negatively charged colloidal surfaces of the Pellic Vertisols (226±4.0 mg kg^{-1}) and Vertic Cambisols (222±6.2 mg kg^{-1}) were more swarmed with exchangeable K than the Relictistagnic Cambisols (133±1.9 mg kg^{-1}). Although 40 to 400 mg K kg^{-1} soil is common for arable soils (Mengel, 2016), the concentration of ammonium acetate extractable K (soil to NH_4OAc solution ratio of 1:20) in the study soils falls under the optimum (190-600 mg kg^{-1}) range, except for the low (90-190 mg kg^{-1}) contents in the Plinthofractic and Relictistagnic Cambisols (Karltun *et al*., 2013).

Considering the nature of the parent material (Portela *et al*., 2019), variation in exchangeable K of the soils is determined by pH, CEC, bivalent cations, OM, and quantity plus type of clay particles (Akbas *et al*., 2017; Jalali and Khanlari, 2014). The maximum exchangeable K in the heavy textured soils compared to the others could be attributed to the presence of high clay particles (Jalali and Khanlari, 2014). Because the mineral structure of smectite (Habib *et al*., 2014), illite (Taleb *et al*., 2010), and/or mica (Patil *et al*., 2011) clays provides huge charged surface areas for the attachment of more K ions (Elbaalawy *et al*., 2016). The increment of such K fraction is probably caused by equivalent competition of the dominant exchangeable Ca for the surface fixing sites and/or replacement of the reserved K in lattices of silt (mica) and clay (illite) sized particles (Bell *et al*., 2021; Kome *et al*., 2019; Simonsson *et al*., 2016). The higher Mg might also prevent the adsorption of the released K to the organic colloidal surface and/or isomorphically substitute K from the exchange sites of the inorganic colloids (Burcher-Jones, 2018; Robin *et al*., 2015). In support of the present findings, Aurangzeib *et al*. (2021) reported high ammonium acetate extractable K from heavy-textured soils because of K-bearing smectite clay, whereas Souza *et al*. (2018) found lower levels of exchangeable K in the Cambisols owing to limited K mobility from illite and kaolinite clay structures.

The exchangeable K form of the Relictistagnic Cambisols and Pellic Vertisols was in a weakly negative association with soil pH, OC, and sand particles, while forming a positive association with the Ex. K, Ex. Na, CEC, and clay contents (Appendix Table 4). The prevailing negative correlation between OC on the Relictistagnic Cambisols, Vertic Cambisols, and Pellic Vertisols could indicate that the better release of this K fraction from the clay and/or silt particles due to isomorphic substitution under permanent (pH-independent) charge systems (Auge *et al*., 2017; Van Ranst, 2006). Besides, its negative interaction with the Ex. K on the Plinthofractic and Pisoplintic Cambisols might reveal the retention of exchangeable K form and possible condition of balanced K supply. In spite of the significantly positive interaction among all the K forms, except for the Pellic Vertisols, there was a significantly negative correlation between the NH_4OAc extractable K and Ex. Na as well as with the non-exchangeable K form in the Plinthofractic Cambisols and Pisoplintic Luvisols, respectively.

The non-exchangeable K fraction varied from 177±1.5 to 322±5.4 mg kg^{-1} in the experimental soils (Table 3.2). As per the critical level suggested by Srinivasarao *et al*. (2007) for the HNO_3 extractable K, the study soils were considered as low (< 300 mg kg^{-1}) in their non-exchangeable K contents, except for the medium (300 to 600 mg kg^{-1}) range in the Pisoplinthic Cambisols and Pellic Vertisols. According to Kaur (2019), the relative amount of this K form in the soils is determined by the type and quantity of clay minerals, particle-size distribution, and its exclusion from mineral interphase in response to soil properties and composition. Therefore, these could be some of the prime reasons for the variation in non-exchangeable K contents of the soils.

Compared to the other soils, the lower non-exchangeable K in the Relictistagnic Cambisols could be related to the acidic reaction and limited accessibility of the lattice for the bivalent cations. Jalali (2008) revealed the release of more K from the internal colloidal sites of soils with higher pH values due to the occurrence of greater Ca and Mg ions. The relatively higher result of non-exchangeable K in Pisoplinthic Cambisols than Pellic Vertisols might be attributed to the pH, ex. Ca, as well as the type and amount of clay mineralogy. Regardless of the excessive K desorption from the expanding smectitic clays (Aurangzeib *et al*., 2021), the illite clays typically have a K-selective narrow lattice (Srinivasarao *et al*., 2007) that results in low K release (Bell *et al*., 2021; Bergaya *et al*., 2011). However, the dominant Ca opens the interlayer space of the illitic structure and promotes the desorption of the lattice K (Shakeri and Abtahi, 2019; Dzene *et al*., 2016).

Table 3. 2. Mean values of potassium forms in soils of the sub-watershed

Soil types	Forms of potassium in the soil (mg kg^{-1})				
	Water soluble	Exchangeable	Non-exchangeable	Mineral	Total
Plinthofractic Cambisols	37 ± 0.9	184 ± 4.0	271 ± 3.8	7068 ± 81.4	7560 ± 78.8
Pisoplinthic Cambisols	38 ± 0.4	213 ± 0.6	322 ± 5.4	8047 ± 81.2	8620 ± 41.1
Relictistagnic Cambisols	34 ± 0.3	133 ± 1.9	177 ± 1.5	5996 ± 29.3	6340 ± 51.1
Pisoplinthic Luvisols	36 ± 0.7	207 ± 4.8	211 ± 4.0	6316 ± 16.6	6740 ± 64.0
Vertic Cambisols	52 ± 0.9	222 ± 6.2	298 ± 4.9	8068 ± 78.5	8640 ± 138.2
Pellic Vertisols	59 ± 0.8	226 ± 4.0	303 ± 5.0	7872 ± 143.5	8460 ± 223.4

The nitric acid extractable K in all the experimental soils showed a direct interaction with the percent clay and/or silt particles (Appendix Table 4). Because soils hold an excessive amount of non-exchangeable K form in their clay and/or silt fractions (Sarkar *et al*., 2013; Ghiri *et al*., 2012). Nilawonk *et al*. (2008) also reported that about 96% of the whole release of non-exchangeable K comes from such soil particles. On the other hand, there was an indirect association with OC contents in the experimental soils, except for the Pisoplinthic Cambisols and Pellic Vertisols. According to Auge *et al*. (2017) and Ranathunga (2015), the negative correlation with the OC indicates that the non-exchangeable K is dependent on the exchange capacity of mineral colloids. Moreover, the negative relationship between Ca and/or Mg ions could verify their easy access into the lattice of mineral colloids (Kumari and Mohan, 2021; Jalali, 2008).

Concentrations of 5996±29.3 to 8068±78.5 mg K kg^{-1} were incorporated as structural components of the mineral particles in the Relictistagnic and Vertic Cambisols, respectively (Table 3.2). Most of the soil K existed as structural K, which accounted for 93.05 to 94.57% of the total K in the soils. Similarly, the mineral K predominates over the other K forms and constitutes about 86% (Shilpa Babar *et al*., 2015) to 98% (Elbaalawy *et al*., 2016) of the entire soil K.

The difference in the quantity of mineral K in the diversified soil types might be caused by the nature of their parent material and physiographic set-up, which notably influenced the extent of weathering as well as the type and amount of K-bearing primary and secondary minerals. The relative K content in soil particle sizes is determined by the nature of the parent material (Dhakad *et al*., 2017), topographic setting (Samndi and Tijjani, 2014), and mineralogical composition

(Najafi-Ghiri and Abtahi, 2013). The quantity of mineral K form in the diversified soil types is determined by the type and amount of K-bearing primary and secondary minerals (Ambrosini *et al*., 2022; Li *et al*., 2021; Han *et al*., 2015). Mouhamad *et al*. (2016) conveyed that K-bearing minerals vary among fractions of clay (illite), silt (micas, orthoclase, microcline), and sand (biotite, muscovite, microcline, orthoclase) particles. Alike the agronomic practice of the study area, continuous cropping experience without K nutrient application could also result in mica weathering, particularly biotite into vermiculite and smectite, and the decomposition of feldspar structure over a longer period (Shirale *et al*., 2019; Kumar *et al*., 2018).

Mineral K had positive relationships with clay and silt particles (Appendix Table 4). Since substantial quantities of K-bearing minerals are present in silt and clay particles of the soils under investigation, the content of mineral K form depends on the proportion of these soil particles (Aurangzeib *et al*., 2021). The mineral K formed highly significant and positive correlations with all the K forms, except for the negative correlation with the non-exchangeable of the Pisoplinthic Luvisols and the exchangeable of the Pellic Vertisols. In addition to the importance of soil properties (texture, mineralogy, pH, and OM) in the dynamics of K forms, the prevailing negative correlation implies the specific context of the study soils. According to Derakhshan-Babaei *et al*. (2020), a negative correlation could indicate the presence of intense weathering processes that break down primary minerals and release their K to the ion exchange site through successive transformation to non-exchangeable and exchangeable forms. A negative correlation could indicate a predominance of clay minerals with a high capacity to hold K in the non-exchangeable form (Shakeri and Abtahi, 2018). Hence, a negative correlation might suggest that mineral K is acting as a significant source for the non-exchangeable pool. However, a negative correlation proposes that the release of exchangeable K from minerals might not be as significant as the other factors in determining exchangeable potassium levels (Azadi and Shakeri, 2020). For example, a negative correlation could reveal that the studied soils have low OM and pH, leading to more potassium being fixed in the mineral form (Liu *et al*., 2020; Shakeri and Abtahi, 2018).

The lowest (6340 ± 51.1 mg kg^{-1}) and the highest (8640 ± 138.2 mg kg^{-1}) total K were obtained from the Relictistagnic and Vertic Cambisols, respectively (Table 3.2). These results are in line with Sparks (2001), who exhibited 0.4 to 30 g kg^{-1} of total K contents in different agricultural soils. Total K is influenced by soil types, whereby those with moderately differentiated profiles (Cambisols) have higher content than poorly evolved soils with a thin organic-mineral horizon (Blanchet *et al*., 2017). In addition to the proportion of mineral K form (Dhakad *et al*., 2017), significant differences in total K of given soils are known mainly due to their texture and mineralogy (Kome *et al*., 2019; Ghiri *et al*., 2011). The amount of total K along diverse physiographic units is affected by disparities in the geomorphological settings and pedogenetic processes (Blanchet *et al*., 2017; Samndi and Tijjani, 2014).

3.3.3. Extraction of dominant factors in the relations of K forms and soil properties

The K forms showed significant correlations ($p < 0.01$) among themselves and specifically with Ex. Na in the Plinthofractic Cambisols due to the overall effects of the physicochemical properties existed under each experimental soil (Appendix Tables 4). Generally, the principal component analysis (PCA) summarized the K forms and selected properties of the study soils into two distinct groups (Figure 3.1). The first group accounted for 35.7% of the variability that was explained negatively by its sand component, while the pH, clay, and all the K forms did so positively. The second group described 25.3% of the soil variability with the negative contribution of silt content and positive contribution from the CEC and divalent exchangeable cations.

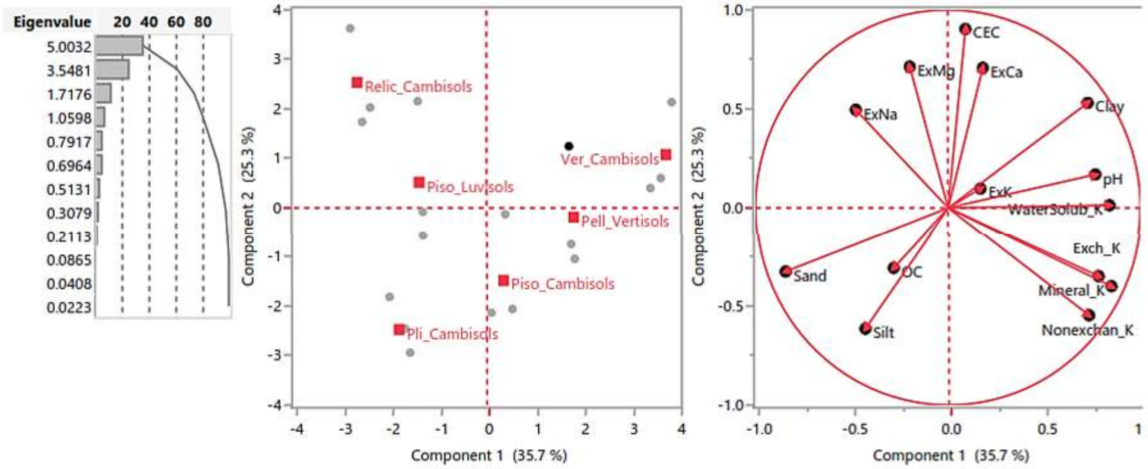

Figure 3. 1. Correlation summary of principal components

Compared to the variables in the second component, the variables of the first factor explained a larger proportion of variability and contributed the most (Jolliffe and Cadima, 2016). These groups also showed the relative importance of principal components (PCs) in elucidating the overall variability of soil characteristics within a given studied soil type (Figure 3.1). Hence, silt and OC contents better described the Plinthofractic Cambisols, whereas clay content, pH, and water-soluble K did for the Vertic Cambisols and Pellic Vertisols. The Pisoplinthic Cambisols were mainly defined by the exchangeable, mineral, and non-exchangeable K forms, while the Pisoplinthic Luvisols and Relictistagnic Cambisols were defined by Ex. Na and Ex. Mg contents.

The PCA outlined the variables into four PCs having eigenvalues greater than one to make a major contribution to the total cumulative loading (Table 3.3). These components explained 80.9% of the total variability, with PC1 depicting the highest role (35.7%), followed by PC2, 3, and 4 with values of 25.3, 12.3, and 7.6 percent of the total variance, respectively.

Table 3. 3. Loadings and explained variance of the soil variables

Soil variables	Factor 1	Factor 2	Factor 3	Factor 4
pH	0.34303	0.08994	-0.12778	-0.16165
OC	-0.12789	-0.16274	0.38968	-0.57785
Ex. K	0.07603	0.05224	0.54491	-0.44232
Ex. Na	-0.21409	0.26340	0.08935	0.08828
Ex. Ca	0.08144	0.37555	0.31442	0.24182
Ex. Mg	-0.08843	0.37890	0.26917	0.16843
CEC	0.04098	0.48000	0.19899	0.20851
Sand	-0.37901	-0.17246	0.00657	0.10457
Silt	-0.19363	-0.32583	0.39810	0.34134
Clay	0.32512	0.28162	-0.22762	-0.25161
Water-soluble K	0.37601	0.00734	0.15739	0.04217
Exchangeable K	0.34797	-0.18472	0.24009	0.10724
Non-exchangeable K	0.32581	-0.28994	0.13068	0.25926
Mineral K	0.37785	-0.21179	0.07857	0.18691
Eigenvalue	5.0032	3.5481	1.7176	1.0598
Proportion explained (%)	35.7	25.3	12.3	7.6
Cumulative proportion (%)	35.7	61.0	73.3	80.9

Key: the bold font implies the most important factors

As shown in Table 3.3, the first dimension related positively to mineral K (0.38), water-soluble K (0.38), exchangeable K (0.35), pH (0.34), non-exchangeable K (0.33), and clay (0.33), while it was negatively attributed to sand (-0.38) and Ex. Na (-0.21). Based on their direction from the center and proximity of the variables to the unit circle in Figure 3.1, the first component denoted soil factors (pH, Ca, Mg, and OM) that related to the concentration and mobility of cations in the soil solution and colloidal surfaces. Soil nutrient concentrations were impacted by variables linked to soil reactions, which make the soils exhibit significant variations (Xu *et al*., 2015; Phoenix *et al*., 2012). According to Romanens *et al*. (2019), the negative correlation of sand particles and sodium ions to the first component could imply that sand and Na^+ had little effect on the variability of soil properties. The main reason for the soil texture is most probably connected to pedogenetic parameters (Schulz *et al*., 2023), whereas that of the Na^+ has been related to its leaching and/or weaker adsorption from the colloidal surface (Liu *et al*., 2022).

In addition to the intersection angle of the vector lines (Figure 3.1), the outcomes of PCA (Table 3.3) proved the second dimension was positively correlated with CEC (0.48), Ex. Mg (0.38), Ex. Ca (0.38), clay (0.28), and Ex. Na (0.26), while negatively attributed to silt (-0.33), non-exchangeable K (-0.29), and mineral K (-0.21). This component shows the characteristics of soils that are linked to the extent of the soil adsorption complex. The second PC's increased clay loading besides of CEC, which could imply the role of clay in the CEC of the soils (Droge and Goss, 2013). Analogous to the findings of this research, higher PC loading values and commonality reflecting CEC were reported by Tiruneh *et al*. (2021).

The third component highlighted the importance of K, silt, OC, and Ca (Table 3.3). The dimension had a positive correlation with Ex. K (0.54), silt (0.40), OC (0.39), Ex. Ca (0.31), Ex. Mg (0.27), and exchangeable K form (0.24), but a negative relationship with clay (-0.23) and pH (-0.13). Hence, this component demonstrated the maximum contribution of OM, silt particles, and exchangeable cations than the clay particles in the ability of soils to retain exchangeable and soluble cations. In addition to the better role of OM and fine-sized silt particles, such a scenario could result in the presence of low-activity clay particles, and possible conditions of soil pH and colloids for the adsorption of essential nutrients (Samson *et al*., 2020; Obi and Udoh, 2011). Similarly, Liu *et al*. (2020) and Almajmaie *et al*. (2017) reported the better role of OM and fine-sized silt fractions in the electrochemical properties of soil colloidal surfaces.

High loadings were found for OC, K, and silt in the fourth dimension (Table 3.3). The dimension was positively related to silt (0.34), non-exchangeable K (0.26), Ca (0.24), and CEC (0.21) but ascribed negatively to OC (-0.58), K (-0.44), and clay (-0.25). The interplay with the mineralogy of silt, non-labile K, and divalent cations has clarified their vital role to this component. Because the existing features of minerals in the soil are modified by the pedogenesis process of the parent material (Han *et al*., 2015). The pedogenesis process of the parent materials can enhance the adsorption and expose it to the surrounding solution while promoting the release of interlayer K and Ca ions (Georgiadis *et al*., 2020; Donatus *et al*., 2018; Ryan *et al*., 2016).

3.4. Conclusion

The differences in physicochemical properties of the experimental soils arose due to the prevailing topographic features and agricultural management practices. Furthermore, the results of this study confirmed that the dynamics status of K forms and distribution in the surface (0-20 cm) soils of the Qenberenaweti Sub-watershed are influenced by the overall properties of the soils. The Pellic

Verisols had the highest labile K content and were followed by the Vertic Cambisols, Pisoplinthic Cambisols, Pisioplintic Luvisols, Plinthofractic Cambisols, and Relictistagnic Cambisols in decreasing order. The maximum non-labile K content was found in the Pisoplinthic Cambisols, while it accordingly declined in the Vertic Cambisols, Pellic Verisols, Plinthofractic Cambisols, Pisioplintic Luvisols, and Relictistagnic Cambisols. The low to optimum levels of exchangeable K in the experimental soils indicated that bioavailability is determined by the rest of the K forms and diverse soil properties. Though it is fixed in clay lattice and limited to being an immediate source, the maximum non-exchangeable K contents of all soils were believed as the primary to compensate for the uptake of the exchangeable form. The K forms showed significant correlations ($p < 0.01$) among themselves and specifically with ex. Na in the Plinthofractic Cambisols due to the overall effects of the physicochemical properties existed under each study soil. The principal component analysis also summarized the K forms and selected properties of the soils into two distinct groups that accounted for explaining 61.0% of the variability. Such information on K forms and relations with soil properties helps to understand the K-supply power of soils at a site-specific level. Therefore, analyzing all the K forms and their relationships with the physico-chemical properties of soils along a given toposequence should be considered to formulate effective K fertilization and management practices. For instance, improving the soil pH and ex. Ca content through a soil test-based application of lime and/or ash amendments might enhance the bioavailability of potassium. However, research should be done on clay mineralogy to draw sound conclusions by calibrating the potassium reserve pool and the extent of degradation.

3.5. References

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4. POTASSIUM ADSORPTION CAPACITY AND DESORPTION KINETICS IN SOILS OF QENBERENAWETI SUB-WATERSHED, CENTRAL HIGHLANDS OF ETHIOPIA

Haymanot Awgchew[1,2], Sheleme Beyene[1], Alemayehu Kifilu[1]

[1]School of Plant and Horticultural Science, Hawassa University, Ethiopia

[2]Department of Plant Science, Debre Berhan University, Ethiopia

ABSTRACT

The supply of K is a complex phenomenon involving many biogeochemical properties and processes in the soil. However, determining the supply and uptake of K nutrient and the dynamic equilibrium (adsorption-desorption) reactions among the K forms in the soils are not commonly addressed in the highlands of Ethiopia. A study was therefore initiated to determine the adsorption capacity of the exchangeable K and the release kinetics of the non-exchangeable K in the soils of the Qenberenaweti Sub-watershed. Twelve disturbed surface (0-20 cm) soil sub-samples were collected from every farmland, which was representative of each pre-identified soil type (Vertic Cambisols, Pellic Vertisols, Pisoplinthic Luvisols, Relictistagnic Cambisols, Pisoplinthic Cambisols, and Plinthofractic Cambisols). A composite sample was made in duplicate for the determination of K adsorption capacity and desorption kinetics per soil type via extracting with 0.01 M $CaCl_2$ *solution and using different mathematical models. The mean maximum (69.47±4.31%) and minimum (56.16±6.04%) K adsorption rates were obtained from the Plinthofractic Cambisols and Vertic Cambisols, respectively. Among the tested isotherm models, the goodness of the Freundlich model was better fitted for all experimental soils; hence, a modified equation of this model* ($qe = aCe^{b/a}$) *could be used to describe the theoretical doses of K fertilizers required to develop K levels in soil solutions. The highest constant K releases from the Plinthofractic Cambisols (47 mg* kg^{-1}*), Pisiopllintic Cambisols (46 mg* kg^{-1}*), and Pisoplinthic Luvisols (44 mg* kg^{-1}*) were attained at the 9th (120 hours) extraction. Instead, it was noticed at the 7th (72 hours) and 11th (168 hours) extractions of Relictistagnic Cambisols (45 mg* kg^{-1}*) and both Pellic Vertisols (48 mg* kg^{-1}*) and Vertic Cambisols (42 mg* kg^{-1}*), respectively. The equation of the power function was the best to successfully describe the released* K^+ *from all the experimental soils. Eventually, determining the adsorption capacity and release kinetics of K at a site-specific level helps to know the relative potential of each soil type to supply K. Thus, planning an effective K fertilization strategy is better through optimization of internal (crops') and external (soils') K-requirements at a site-specific level.*

Keywords: fixation, release, equilibrium reaction, solution concentration, isotherm model

4.1. Introduction

Potassium is an essential macronutrient in plant, animal, and human nutrition (Simonsson *et al*., 2009; Wakeel *et al*., 2016). It is among the exhaustively extracted elements under intensive cropping systems (Chaudhary *et al*., 2017; Panda *et al*., 2022). The availability of native and applied K nutrients to plants depends on their buffering and adsorption capacities in the soils (Aurangzeib *et al*., 2021). Continual refill of the K-depleted soil solution and exchangeable sites via the release of the non-exchangeable K^+ reserves notably contributes to the optimal K^+ nutrition of crops (Das *et al*., 2021; Ma and Bell, 2020). Without optimum soil K supply, 70 to 90% of plants' K demand comes from the non-exchangeable pool (Habib *et al*., 2014).

The supply of K is a complex phenomenon involving many biogeochemical properties and processes in the soil (Sardans and Peñuelas, 2015; Zörb *et al*., 2014) that determine the equilibrium kinetic reactions between the K forms (Singh *et al*., 2019). Different studies revealed factors such as the degree of weathering (Mouhamad *et al*., 2016; Portela *et al*., 2019), nature of parent materials (Ikiriko *et al*., 2022; Portela *et al*., 2019), and soil taxonomy (Blanchet *et al*., 2017; Jalali and Khanlari, 2014) had great effects on K release and fixation. For example, the action of rainfall and temperature causes excessive leaching of K in highly weathered tropical soils (Havlin *et al*., 2017). According to Ghiri *et al*. (2011) and Srinivasarao *et al*. (2007), Vertisols and Vertic subgroups released more K than Alfisols, Inceptisols, Entisols, and Aridisols. Toposequence also determines the K distribution due to the influence of slope on erosion, transportation, and deposition of soil materials (Uzoho and Okechukwu, 2014).

Under the K depletion condition, the ability of clay minerals to release K normally follows the sequence of tri-octahedral micas > di-octahedral micas > K feldspars (Shakeri and Abtahi, 2018; Galán and Ferrell, 2013). For instance, illite and vermiculite-rich soils have high electro-negativity and K^+ specificity with a much slower rate of K^+ adsorption than smectite and kaolinite types (Shakeri and Abtahi, 2018; Raheb and Heidari, 2012; Ghiri and Abtahi, 2011). Similarly, montmorillonite and kaolinite clay minerals easily release all of their fixed K compared to illite and vermiculite (Kumari and Mohan, 2021; Shakeri and Abtahi, 2019). Stoichiometric dissolution can be an important means for K release from tri-octahedral micas at low pH, but selective loss of interlayer K (part of the vermiculitization process) accounts for most K release from micas and illites (Kumari and Mohan, 2021; Duan *et al*., 2018). This process may consistently modify the K exchange reactions and availability to crops in highly weathered soils of the tropics (Kumar *et al*., 2018; Adeoye *et al*., 2008). Instead, the di-octahedral vermiculite is a principal K-fixing clay mineral in acid soils owing to the marked K^+ affinity from Al^{3+} in the interlayer of 2:1 clays and mixed-layered silicates (Gulati *et al*., 2017; Nakao *et al*., 2017).

The K adsorption-desorption process depends on the level of soil solution K^+, the type of clay minerals, and soil moisture (Havlin *et al*., 2017; Liao *et al*., 2013). However, the fixation of K is faster than the release (Havlin *et al*., 2017; Mouhamad *et al*., 2016) due to the strong binding by the inorganic (clay) and organic (organic matter) colloids (Ghiri and Abtahi, 2012; Zhang *et al*., 2009). Based on the rate and speed of K removal, the initial adsorption equilibrium in the soil solution phase serves as the K release index (Al-Obaidi *et al*., 2015; Khalil, 2013). The appropriate K nutrient management practice for increasing crop production should consider the adsorption-desorption mechanism (Li *et al*., 2014; Simonsson *et al*., 2009). Hence, the concept of quantity-intensity has received attention to make better K fertilizer recommendations because of its key information on K availability (AL-Obaidi *et al*., 2020; Bilias and Barbayiannis, 2019).

In addition to factors determining the supply and uptake of K nutrient, its fixation capacity and release kinetics in the soils are not frequently addressed in Ethiopia, and yet not done particularly in the study area. Since it determines the effectiveness of fertilization strategies (Bangroo *et al*., 2012) by predicting the possible fates of the applied K nutrient (Kenyanya *et al*., 2013), assessment of K dynamics in soils under a given watershed is crucial (Akbas *et al*., 2017; Blanchet *et al*., 2017). Therefore, this research was conducted to determine the adsorption capacity of the exchangeable K and the desorption kinetics of the non-exchangeable K in the soils of the Qenberenaweti sub-watershed.

4.2. Materials and Methods

4.2.1. Soil sampling and laboratory analysis

Twelve disturbed surface (0-20 cm) soil sub-samples were collected in zig-zag mode from a farmland representing each of randomly selected three soil mapping units (SMU) under the six pre-identified soil types in Chapter 2 (Experiment 1). The soils were Pellic Vertisols, Pisoplinthic Luvisols, Vertic Cambisols, Pisoplinthic Cambisols, Plinthofractic Cambisols, and Relictistagnic Cambisols. All the sub-samples of the three SMU per a given soil type were thoroughly mixed and accordingly prepared in duplicates for the analysis of their exchangeable K adsorption capacity and non-exchangeable K desorption kinetics. The K adsorption capacity was determined as per the method used by Kenyanya *et al*. (2013). Composites of 2.50 g air-dried soil samples were equilibrated in 100 ml plastic bottles with 25 ml of 0.01 M $CaCl_2$ solution containing 0, 25, 50, 75, 100, 125, 150, 175, 200, 225, and 250 mg K L^{-1}. The suspensions were shaken for 24 hours at room temperature (25±1 °C) and filtered through Whatman filter paper No. 42. Then, the K contents in the filtrate were measured using a flame photometer. The amount of K adsorbed was calculated as outlined by Rowell (1994):

$$\mathrm{qe} = (\mathrm{Ci} - \mathrm{Ce}) * \frac{V}{M}$$

Where: qe (mg kg^{-1}) is the amount of K absorbed; Ci and Ce (mg L^{-1}) are the initial and equilibrium solution concentrations, respectively; V (ml) is the volume of the solution and M (kg) is the mass of the soil.

The K adsorption rate (ΔK) was obtained using the equation below (Huang and Jin, 1996).

$$\Delta\mathrm{K}\ (\%) = \left(\frac{\mathrm{qe} * 100}{\mathrm{Ci}}\right)$$

Adsorption isotherms were created through a combination of experimental data collection (adsorbent-adsorbate preparation, equilibrium reaches with time, and analytical separation and measurement) and mathematical modeling (data analysis, isotherm plotting, and fitting) (Rowell, 1994). The quantitative K adsorption data were fitted into the linearized equations of the most common adsorption isotherm models such as Langmuir, Freundlich, and Temkin.

The Langmuir model, which generates theoretical monolayer reactions in the soils, was used to fit the data into the equations as given by Pal *et al*. (1999):

$$\frac{Ce}{(qe)} = \frac{1}{\mathrm{kb}} + \left(\frac{Ce}{b}\right)$$

Where: Ce is the equilibrium K concentrations of solutions (mg L^{-1}), qe is the mass of K adsorbed per unit mass of soil (mg kg^{-1}), k is a constant related to the bonding energy of K to the soil, and b is the maximum K adsorption capacity of the soil.

The Freundlich model, which considers an empirical adsorption phenomenon in the soils, was checked if fitted the data as formulated by Pal *et al*. (1999):

$$\log qe = loga + blogCe$$

Where: qe is the mass of adsorbed K per unit mass of soil (mg kg^{-1}), Ce is the equilibrium K concentrations of solutions (mg L^{-1}), a, and b are constants obtained from the intercept and slope, respectively.

The Temkin model, which accounts for uneven distribution of fixed molecules on the surface, was used to fit the adsorption data in to the following theoretical equation (Pal *et al*., 1999):

$$qe = a + blnCe$$

Finally, the release kinetics of non-exchangeable K^+ was carried out as per the method used by Hosseinpur *et al*. (2012). A weight of 2.50 g composite sample from each soil type was transferred into a 100 ml plastic bottle. The samples were repeatedly extracted with 25 ml 0.01M $CaCl_2$ at room temperature (25±1 °C) for 2, 4, 6, 12, 24, 48, 72, 96, 120, 144, 168, 192, 216, 240, 264, and 288 hours (until a nearly constant release rate was attained). The suspensions were shaken for 30 minutes, allowed to equilibrate for a moment, and shaken for another 30 minutes before centrifuged at 1000 revolutions per minute for 10 minutes. Then, each was filtered through Whatman filter paper No. 42 to measure the released amounts of non-exchangeable K^+ using a flame photometer. The release kinetics of non-exchangeable K^+ was studied by plotting the amount of desorption (mg kg^{-1}) on Y-axis against time (h) on X-axis (Rezaei and Naeini, 2009), and fitted to the following equations of mathematical models (Sparks, 2003).

Zero-order reaction ($q = a-bt$)

First-order reaction ($lnq = a-bt$)

Second-order reaction ($1/q = 1/a+bt$)

Parabolic diffusion ($q = a+bt^{0.5}$)

Power function ($lnq = lna+blnt$)

Elovich ($q = a+blnt$)

Where: q = amount of K (mg kg^{-1}) released at some time, t = time (h), a = initial K desorbed (mg kg^{-1}) and intercept, b = rate constant (mg kg^{-1}) of the tested equations, and slope which indicates the desorption rate of non-exchangeable K.

4.2.2. Statistical analysis

The goodness of diverse K adsorption and desorption models to fit both measured and predicted amounts of K was analyzed by looking for the highest coefficient of determination (R^2) and the lowest standard error of estimate (SE) values. The SE was calculated as:

$$SE = [\sum(q - q')^2 / n - 2)]^{0.5}$$

Where: q and q' represent the measured and predicted K^+ released at time t (h), respectively, and n is the number of data points evaluated.

4.3. Results and Discussion

4.3.1. Dynamics of exchangeable potassium adsorption capacity

The equilibrium K concentrations in the solution (Ce) and the amounts of K adsorbed on the colloidal surfaces (qe) were inconsistently increased with increasing added K (Ci) throughout the experimental soils. Generally, all the soils exhibited clear variation in their K adsorption characteristics with oppositely acting Ce and qe values. As shown in Table 4.1, the highest Ce and qe, or the lowest qe and Ce, values were recorded from the Plinthofractic Cambisols and Vertic Cambisols, respectively. Hence, these soils had the mean maximum (69.47 ± 4.31%) and minimum (56.16 ± 6.04%) K adsorption rates (ΔK) that ranged from 62.6 to 78.1% and 49.16 to 68.7%, respectively (Figure 4.1).

The variabilities of Ce, qe, and ΔK could be related to the differences in clay types and amounts, OM and other cations (Ca and Mg) contents, and soil pH and CEC levels. Bangroo *et al*. (2012) and Zhang *et al*. (2009) reported that soils with high clay and CEC have fixed more K than soils low in clay and CEC. The release of anions ($COOH^-$ and OH^-) into the rhizosphere upon OM oxidation may enrich the net negative charge of the soils (Adeleke *et al*., 2017; Kleber *et al*., 2015), which consequently enhances the K^+ adsorption (Meena *et al.,* 2014; Xu *et al*., 2005).

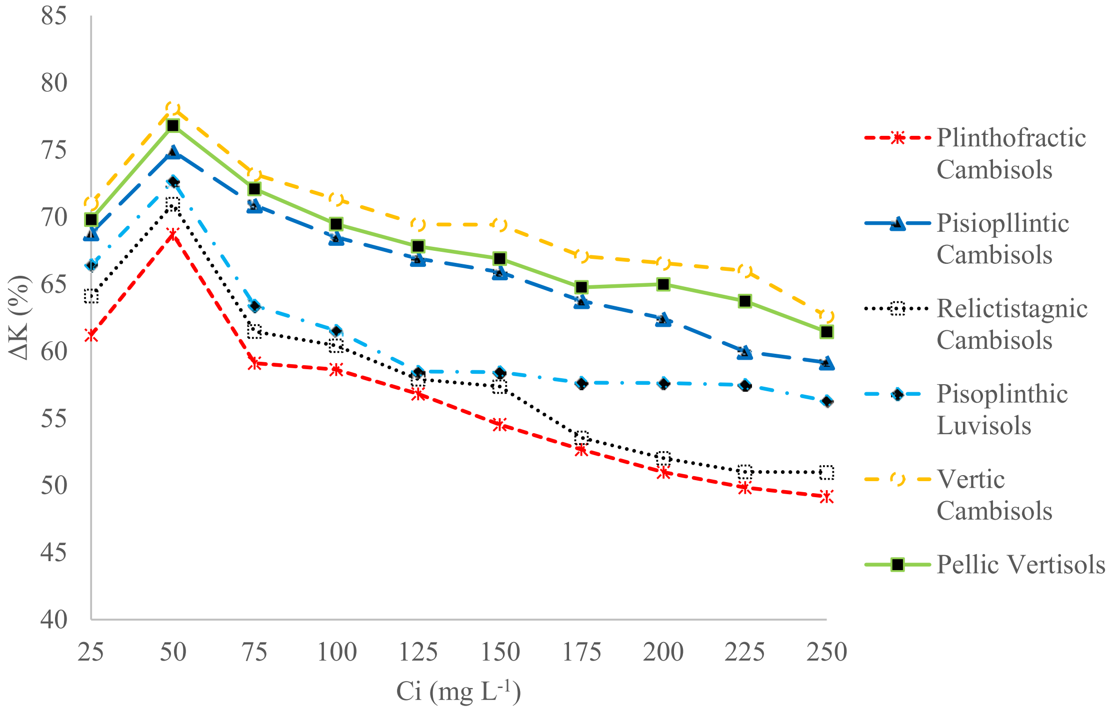

Figure 4. 1. Potassium adsorption rate and initial solution saturation of study soils

Table 4. 1. Mean amount of adsorbed potassium in the soils of the sub-watershed

	Soil types											
	Plinthofractic Cambisols		Pisiopllintic Cambisols		Relictistagnic Cambisols		Pisiopllintic Luvisols		Vertic Cambisols		Pellic Vertisols	
Ci (mg L^{-1})	Ce (mg L^{-1})	qe (mg kg^{-1})	Ce (mg L^{-1})	qe (mg kg^{-1})	Ce (mg L^{-1})	qe (mg kg^{-1})	Ce (mg L^{-1})	qe (mg kg^{-1})	Ce (mg L^{-1})	qe (mg kg^{-1})	Ce (mg L^{-1})	qe (mg kg^{-1})
0	4.35	-43.50	5.25	-52.50	4.55	-45.5	4.70	-47.0	5.60	-56.0	6.30	-63.0
25	9.70	153.0	7.80	172.0	8.98	160.25	8.40	166.0	7.25	177.50	7.55	174.50
50	15.65	343.50	12.55	374.50	14.53	354.75	13.68	363.25	10.95	390.50	11.60	384.0
75	30.68	443.25	21.85	531.50	28.90	461.0	27.45	475.50	20.13	548.75	20.93	540.75
100	41.38	586.25	31.53	684.75	39.60	604.0	38.48	615.25	28.68	713.25	30.53	694.75
125	53.98	710.25	41.38	836.25	52.60	724.0	51.90	731.0	38.18	868.25	40.23	847.75
150	68.20	818.0	51.18	988.25	63.95	860.50	62.35	876.50	45.85	1041.50	49.68	1003.25
175	82.83	921.75	63.45	1115.50	81.30	937.0	74.10	1009.0	57.60	1174.0	61.68	1133.25
200	98.05	1019.50	75.15	1248.50	95.95	1040.50	84.75	1152.50	66.90	1331.0	70.05	1299.50
225	112.88	1121.25	90.10	1349.0	110.23	1147.75	95.65	1293.50	76.53	1484.75	81.63	1433.75
250	127.10	1229.0	102.10	1479.0	122.58	1274.25	109.28	1407.25	93.50	1565.0	96.38	1536.25

Except for the rise between concentration gradients of 25 and 50 mg L^{-1}, all the soils showed a declining mode of ΔK as the Ci was increased to 250 mg L^{-1} (Figure 4.1). This result might be due to the quantity-intensity relationship of the soils, which causes a decrease in the K adsorption rate following the saturation of exchange sites by an increasing addition of initial K concentrations in the soil solution. Such trends of the curve were supported by Bangroo *et al*. (2012) who found a non-linear mass action exchange at sites on external surfaces.

The adsorption data of the experimental soils were fitted to the linearized equation form of the Langmuir adsorption isotherm, which allows the calculation of soil nutrient adsorption maxima and the binding energy for nutrient sorption. However, the data poorly conformed to fit, as plots of Ce/qe vs Ce produced were relatively not straight lines with lower coefficient of determination (R^2) values ranging from 0.7864 to 0.9208 (Table 4.2). This might be due to the presence of a wider range of nutrient concentrations and Langmuir's assumption of an ideal monolayer reaction in the soils. The Langmuir equation correlates the amount of nutrient adsorbed with the equilibrium aqueous nutrient concentrations at a low range (Dabhade *et al*., 2009). That means, it does not yield a straight line when qe is plotted against Ce over a wide range of nutrient concentration (Kamau and Kamau, 2017; Mehdi *et al*., 2007). Besides, the model hypothetically assumes homogeneous surface sites with complete adsorption of solutes on a monolayer adsorbent (Soumya *et al*., 2015; Pal *et al*., 1999). Thus, it does not adequately describe nutrient sorption on exchanging surfaces as heterogeneous as the soil colloids (Gadd, 2009; Mweta *et al*., 2007).

The Temkin adsorption equations were obtained after plotting the adsorbed potassium (qe) against the natural logarithm of the equilibrium solution concentration (Ln Ce). The R^2 values ranged from 0.9096 to 0.9721 for the Pisopllintic Luvisols and Pisopllintic Cambisols (Table 4.2). Thus, the Temkin had a slightly higher R^2 than the Freundlich in the Pisiopllintic Cambisols; but the much lower buffering capacity (slope = 0.0019 L kg^{-1}) made it inferior in fitting the K adsorption data. Equations of the three models followed different assumptions for nutrient sorption affinity, which either decrease linearly (Temkin), decrease logarithmically (Freundlich), or remain constant (Langmuir) with an increase in surface saturation (Genethliou *et al*., 2021; Araújo *et al*., 2018; Pokethitiyook and Poolpak, 2016). Moreover, there is a closer association between the slope (b) of both Temkin and Freundlich equations, and the constant of maximum absorption (b) plus binding energy (k) of the Langmuir equation (Darweesh *et al*., 2022; Ezati *et al*., 2021).

Table 4. 2. Regression equations and R^2 values for the eight soil samples

Soil types	Model form	Linear Equation	R^2
Plinthofractic Cambisols	Langmuir	y = 0.0004x + 0.0523	0.9122
	Temkin	y = 0.0024x + 2.1409	0.9565
	Freundlich	y = 0.7380x + 1.5527	0.9697
Pisiopllintic Cambisols	Langmuir	y = 0.0003x + 0.0355	0.9162
	Temkin	y = 0.0019x + 1.9290	0.9721
	Freundlich	y = 0.7746x + 1.6495	0.9717
Relictistagnic Cambisols	Langmuir	y = 0.0004x + 0.0467	0.9208
	Temkin	y = 0.0024x + 2.0537	0.9534
	Freundlich	y = 0.7158x + 1.6178	0.9694
Pisoplinthic Luvisols	Langmuir	y = 0.0003x + 0.0464	0.7864
	Temkin	y = 0.0020x + 2.1687	0.9096
	Freundlich	y = 0.7639x + 1.5843	0.9757
Vertic Cambisols	Langmuir	y = 0.0003x + 0.0319	0.8485
	Temkin	y = 0.0018x + 1.8906	0.9603
	Freundlich	y = 0.7964x + 1.6729	0.9699
Pellic Vertisols	Langmuir	y = 0.0003x + 0.0343	0.8602
	Temkin	y = 0.0018x + 1.9379	0.9568
	Freundlich	y = 0.7894x + 1.6543	0.9718

Though the slopes of the Temkin equation (b) were higher than the adsorption maximum (b) of the Langmuir, both had lower values than the Freundlich constant (b) for all soils of the study area (Table 4.2). The goodness of the Freundlich model to fit the adsorption data was the best with R^2 values ranging from 0.9694 (Relictistagnic Cambisols) to 0.9757 (Pisoplinthic Luvisols). Besides, Freundlich's plot of log(qe) against log(Ce) gave linear graphs that better described the K fixation characteristics of the soils at medium and high equilibrium concentrations (Figure 4.2). Since the Freundlich isotherm assumes an infinite number of fixation sites in a heterogeneous condition with diverse physicochemical properties, it is the best-fitted model to have inclusive data in soils with multi-layered sorption surfaces and mixed mineralogy (Zhang *et al*., 2021; Al-Ghouti and Da'ana, 2020; Fuentes *et al*., 2014). Independent of the time and temperature, the adsorption data obtained from the Freundlich equations were affected by the concentration of K in the soil solution (Kassa *et al*., 2019; Komy *et al*., 2014). Concurrent to this work, (Kassa *et al*., 2019; Kenyanya *et al*., 2013; Bangroo *et al*., 2012) observed that the Temkin had a better fit than the Langmuir; but its superiority was lesser compared to the Freundlich isotherm model.

The Freundlich isotherm corresponds to a model with more realistic assumptions in which the affinity term decreases exponentially as the number of adsorptions rises (Akrawi *et al*., 2021;

Mehdi *et al*., 2007). Over a limited range of concentration, the simple equation form of the Freundlich ($qe = aCe^{b}$) often describes adsorption well (Saadi *et al*., 2015; Mehdi *et al*., 2007). where 'a' is the amount of K adsorbed (mg kg^{-1}) as the concentration Ce is 1 mg L^{-1} and 'b' is the buffer power (L kg^{-1}) found by the slope of the sorption curve at a point where qe/Ce = 1 L kg^{-1}.

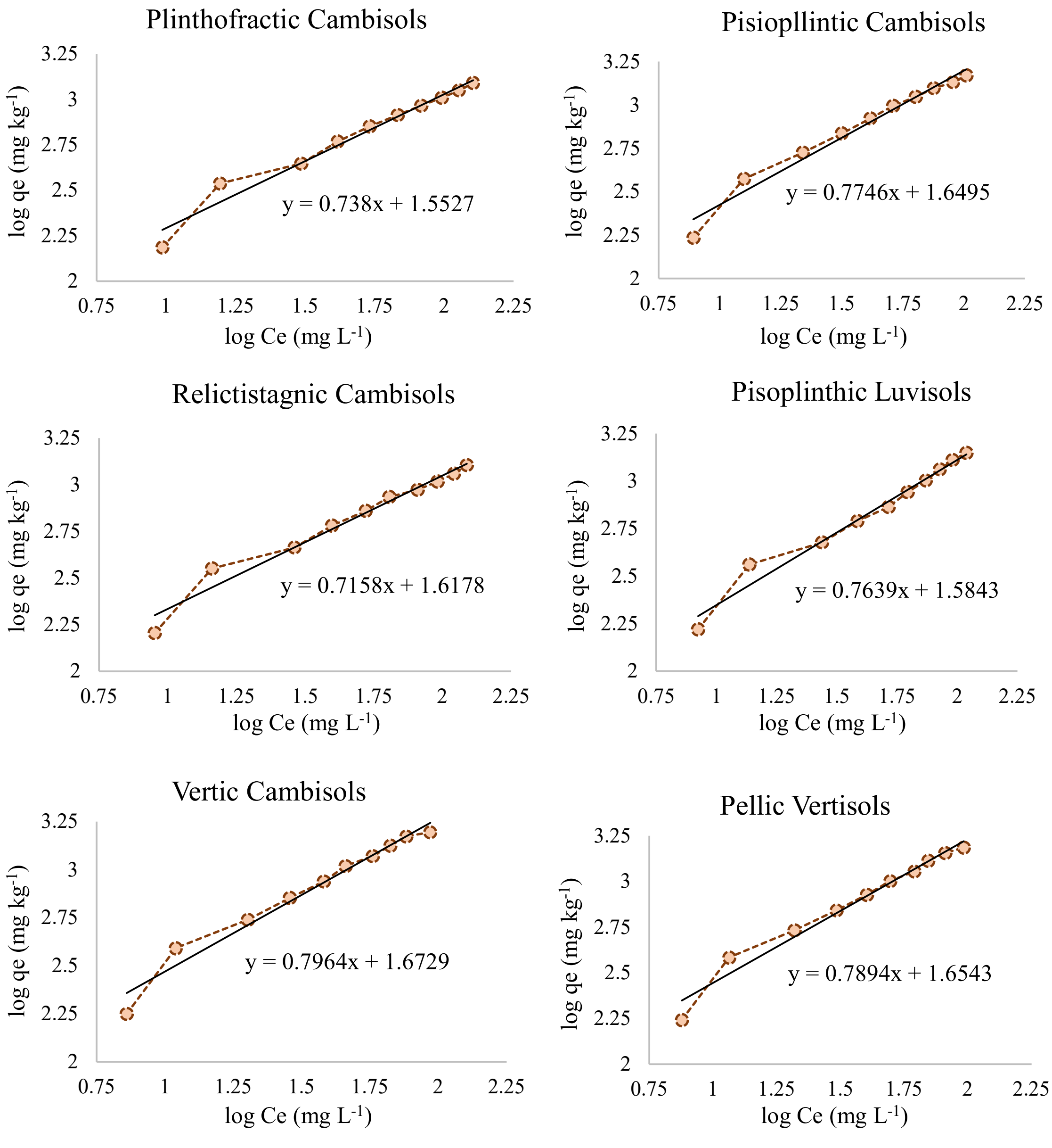

Figure 4. 2. Potassium adsorption data of the study soils fitted to the Freundlich model

Since the point at which the value of qe = Ce occurs varies between different soils, the modified equation of the Freundlich model ($qe = aCe^{b/a}$) was used to describe the soils in this study. For instance, the theoretical doses of K fertilizers required to develop K levels in soil solutions under field conditions were computed from this modified equation of the Freundlich model (Table 4.3).

The main advantage of this equation is that the 'a' and 'b' are found at the same point on the curve where Ce = 1 mg L^{-1}, and this point is the same for all the soils (Jeppu and Clement, 2012). Parameters 'a' and 'b' of the Freundlich equation were estimated by regression of the natural logarithmic form of the data gained from adsorption isotherms (Sarfraz *et al*., 2009). However, the parameters have been considered meaningless because the values of sorption capacity 'a' and buffering energy 'b' were practically zero at equilibrium concentrations for all soils. The exponent 'b/a' values for the Relictistagnic and Vertic Cambisols were 0.7158 and 0.7964 L kg^{-1}, respectively (Table 4.3). All the values were less than one, implying that they are related to properties of the adsorbent (soil colloids). According to Al-Ghouti and Da'ana (2020) and Jawad *et al*. (2018), the values range between zero and one, whereby the soil surfaces become more heterogeneous as the value approaches zero, and below one indicates a chemisorption process.

Table 4. 3. Potassium adsorption characteristics of the study soils in the Freundlich model

Soil types	Model form	Linear form	a (mg kg^{-1})	b (L kg^{-1})
Plinthofractic Cambisols	$qe = 4.7242Ce^{0.7380}$	y = 0.7380x + 1.5527	4.7242	3.4865
Pisiopllintic Cambisols	$qe = 5.2043Ce^{0.7746}$	y = 0.7746x + 1.6495	5.2043	4.0313
Relictistagnic Cambisols	$qe = 5.0420Ce^{0.7158}$	y = 0.7158x + 1.6178	5.0420	3.6091
Pisoplinthic Luvisols	$qe = 4.8759Ce^{0.7639}$	y = 0.7639x + 1.5843	4.8759	3.7247
Vertic Cambisols	$qe = 5.3276Ce^{0.7964}$	y = 0.7964x + 1.6729	5.3276	4.2429
Pellic Vertisols	$qe = 5.2294Ce^{0.7894}$	y = 0.7894x + 1.6543	5.2294	4.1281

Potassium buffering capacity is the soil's ability to withstand sudden changes in K levels of the soil solution at which a high value indicating that adequate K is available for a long time, whereas a low value suggests frequent fertilization (Rani *et al*., 2023; Lalitha and Dhakshinamoorthy, 2014). Therefore, the exponent values represented the amount of K held on unspecific sites and ready to be released for plant uptake during a cropping season. The values of K adsorbed 'a' ranged from 4.7242 to 5.3276 mg kg^{-1} in the study soils (Table 4.3), but they were lower than the amount of available K. This suggests that part of the exchangeable K is held on exchange sites by high bonding energy (Das *et al*., 2019; Kenyanya *et al*., 2013). It was also considered as a capacity factor, implying that soil with a higher 'a' value has greater adsorbing capacity than that having a lower value (Sarfraz *et al*., 2008; Mehdi *et al*., 2007). Additionally, Idris and Ahmed (2012) reported the value of sorption capacity 'a' as a practically useful parameter to describe adsorption properties over a wide range of equilibrium concentrations.

4.3.2. Equilibrium desorption kinetics of non-exchangeable potassium

In general, the release kinetics of non-exchangeable K were characterized by rapid desorption for the first 12 hours; then, declined for the next 72 to 168 hours and remained nearly constant in subsequent extractions until the end of 288 hours (Figure 4.3). The released amount of non-exchangeable K was the highest at the initial extraction from the Vertic Cambisols consequently followed by the Pellic Vertisols, Pisoplinthic Cambisols, Pisoplinthic Luvisols, Plinthofractic Cambisols, and Relictistagnic Cambisols (Figure 4.3; Table 4.4).

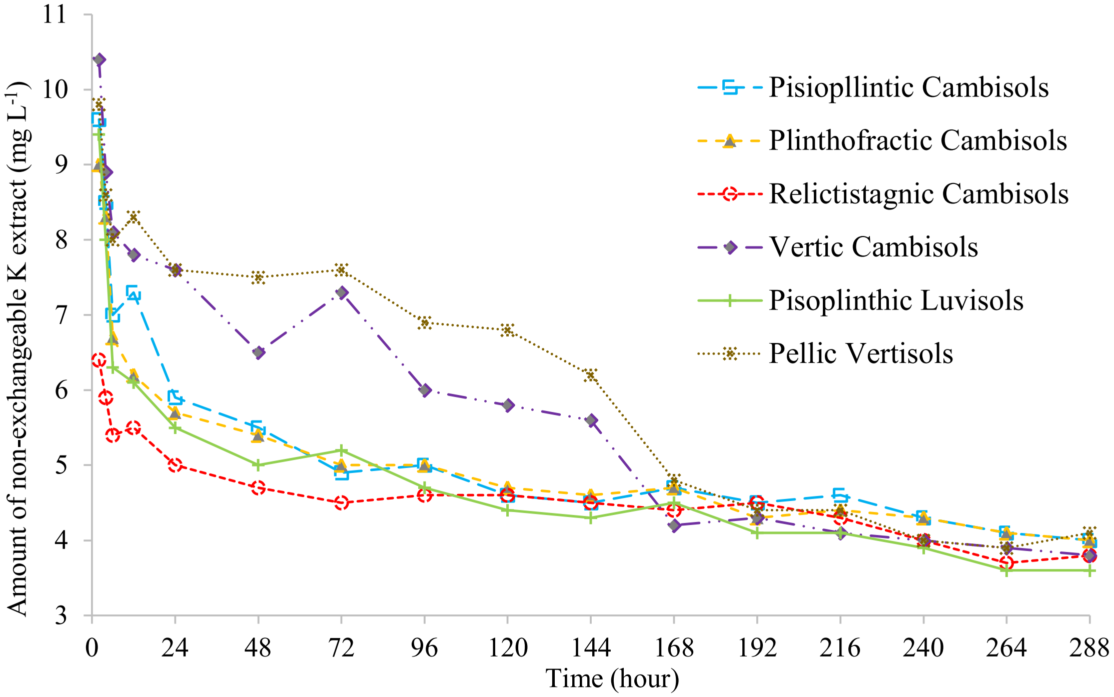

Figure 4. 3. Release kinetics of non-exchangeable K in the experimental soils

The highest constant K releases from the Plinthofractic Cambisols (47 mg kg^{-1}), Pisiopllintic Cambisols (46 mg kg^{-1}), and Pisoplinthic Luvisols (44 mg kg^{-1}) were attained at the 9th extraction (120 hours), while the highest releases were found from Relictistagnic Cambisols (45 mg kg^{-1}) and both Pellic Vertisols (48 mg kg^{-1}) plus Vertic Cambisols (42 mg kg^{-1}) at the 7th (72 hours) and 11th (168 hours) extractions (Table 4.4).

Higher values of K release in the initial period could be attributed to the isomorphic substitution of K^+ by Ca^{2+} at surface exchange sites of different clay minerals such as smectite, vermiculite, mica, and illite (Adeyemo *et al*., 2017; Brouder, 2011). However, further exchange of K^+ by Ca^{2+} would be slower, as the size of hydrated Ca^{2+} (4.3 Å) is larger than hydrated K^+ (3.3 Å) (Wang *et al*., 2020; Loganathan *et al*., 2016). This can also be attributed to non-exchangeable K^+ in the soils being more tightly retained due to the prevalence of micaceous minerals (Dotaniya *et al*., 2016; Mouhamad *et al*., 2016). Mouhamad *et al*. (2016), Al-Obaidi *et al*. (2014), and Simonsson *et al*. (2009) reported the decline of interlayer K of micas and other clay minerals with the constant release of K from sources with no exchangeable K.

Table 4. 4. Amount of desorbed potassium (mg kg^{-1}) in soils of the sub-watershed

Time (hour)	Soil types					
	Plinthofractic Cambisols	Pisiopllintic Cambisols	Relictistagnic Cambisols	Pisoplinthic Luvisols	Vertic Cambisols	Pellic Vertisols
2	90.0	96.0	64.0	94.0	104.0	98.0
4	83.0	85.0	59.0	80.0	89.0	86.0
6	67.0	70.0	54.0	63.0	81.0	80.0
12	62.0	73.0	55.0	61.0	78.0	83.0
24	57.0	59.0	50.0	55.0	76.0	76.0
48	54.0	55.0	47.0	50.0	65.0	75.0
72	50.0	49.0	45.0	52.0	73.0	76.0
96	50.0	50.0	46.0	47.0	60.0	69.0
120	47.0	46.0	46.0	44.0	58.0	68.0
144	46.0	45.0	45.0	43.0	56.0	62.0
168	47.0	47.0	44.0	45.0	42.0	48.0
192	43.0	45.0	45.0	41.0	43.0	44.0
216	44.0	46.0	43.0	41.0	41.0	44.0
240	43.0	43.0	40.0	39.0	40.0	40.0
264	41.0	41.0	37.0	36.0	39.0	39.0
288	40.0	40.0	38.0	36.0	38.0	41.0

The three phases of K^+ release characteristics shown in Figure 4.3 are a diffusion-controlled process (Mengel, 2016; Sanyal, 2015). The first curvilinear part indicated rapid K^+ release from the surface sites; whereas the second and third linear parts represented K^+ release from the edge and internal sites of clay minerals, respectively (Azadi *et al*., 2015; Jalali, 2011). The observed patterns of initial rapid release followed by a slower release in time were also reported in other studies (Hosseinpur *et al*., 2014; Jalali and Khanlari, 2014).

The variation in the rates of K desorption in different soils indicates that the cations retained on the surface sites influenced the rate of K desorption (Zareian *et al*., 2018; Hosseinpur and Motaghian, 2013). The highest K release rate of some soils is most likely due to the transfer of non-exchangeable K to the extractant solution (Najafi-Ghiri *et al*., 2019; Shakeri, 2018). Soils with delayed constant K release are thought to have large K reserves and a greater long-term K supply (Basak *et al*., 2018; Sarkar *et al*., 2013). The releasing power denotes the total availability of nutrients in the soil, which does not correspond to the actual available K in the soil, indicating the K releasing power of the soil (Römheld and Kirkby, 2010; Sarwar *et al*., 2008). As a result, it could be concluded that the experimental soils, except for the Relictistagnic Cambisols, were capable of providing a high amount of K during intensive cropping. Shakeri (2018) and Florence *et al*. (2017) revealed that the virtue of soils to release K is more determined by the amount of smectite clays than the other types of 2:1 mineral. According to Pal and Pal (2017), Vertisols and other soils with a vertic nature had higher K release rates as compared to the other soils due to the dominance of expansible clay minerals.

A plot of cumulative K release vs time displayed discontinuities in slope at time intervals of 2-6, 6-24, and 24-288 hours, whereby the highest (1029 mg kg^{-1}) and the lowest (758 mg kg^{-1}) values were recorded from the Pellic Vertisols and Relictistagnic Cambisols, respectively (Figure 4.4). Such segments on the curves are typically associated with the rate of K release process that varies with the soil types and is controlled by various mechanisms (Hosseinpur and Motaghian, 2013).

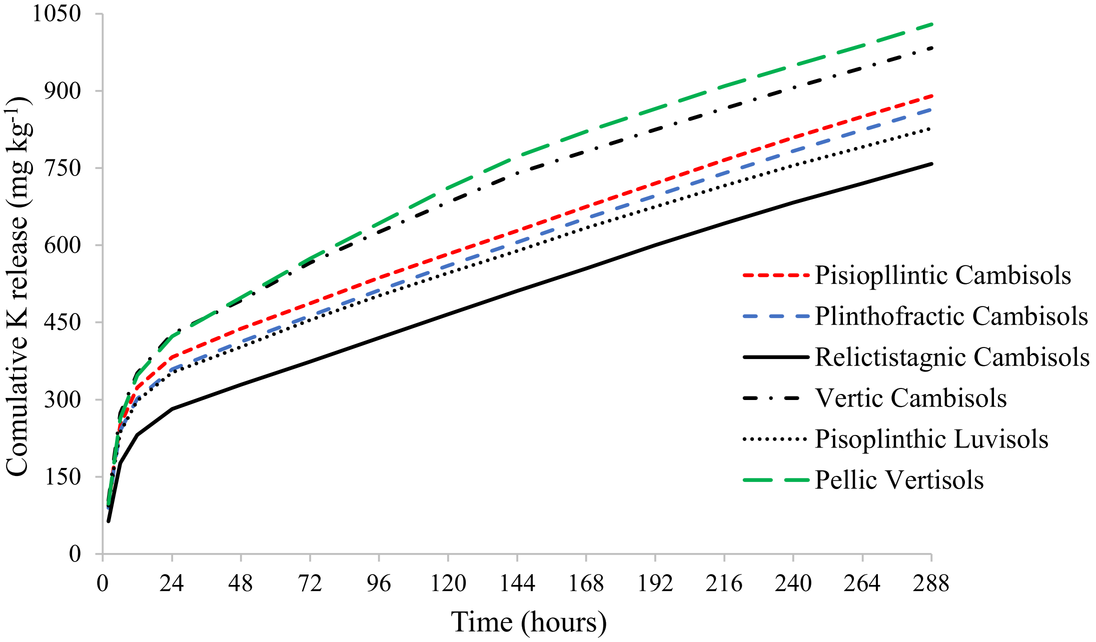

Figure 4. 4. Cumulative desorption amount of non-exchangeable K in the study soils

The initial rapid K release is thought to be caused by mass action exchange from the planar surface of the clay (Kumari and Mohan, 2021; Bharama, 2015). Also, it is mostly attributed to the release of water-soluble and exchangeable K (Bharama, 2015). The second short-term transitional stage of K release represents the rate at which K is desorbed from the edge exchangeable sites and helps refill the liable soil K (Bharama, 2015; Samadi, 2010). The third long-term segment in the cumulative K release represents the rate at which the interlayer K is slowly exchanged by calcium (Das *et al*., 2019; Bharama, 2015). The variation in cumulative K desorption of the study soils indicates that the cations fixed on the surface of clay micelle may influence the rate of desorption in the calcium-potassium system (Bharama, 2015). Soil development and the type of soil minerals had a greater impact on K release (Jalali and Khanlari, 2014). Ghiri *et al*. (2011) found a higher cumulative release of non-exchangeable K from Vertisols and Vertic sub-groups than in Alfisols, Inceptisols, Entisols, and Aridisols.

Table 4. 5. Kinetics of non-exchangeable K release in soils of the sub-watershed

Kinetic models	Values	Soil types					
		Plinthofractic Cambisols	Pisiopllintic Cambisols	Relictistagnic Cambisols	Pisoplinthic Luvisols	Vertic Cambisols	Pellic Vertisols
Zero-order	R^2	0.9408	0.9340	0.9568	0.9370	0.9180	0.9241
	SE	60.2459	64.9822	47.1342	59.0843	82.4905	85.3990
	a	621.48	631.14	578.45	584.89	688.52	740.48
	b	-2.320	-2.3630	-2.1436	-2.2021	-2.6663	-2.8796
First-order	R^2	0.9372	0.9361	0.9343	0.9404	0.9566	0.9625
	SE	0.2206	0.2239	0.2244	0.2198	0.1982	0.1861
	a	6.6067	6.6227	6.5395	6.5516	6.7202	6.7974
	b	-0.0089	-0.0089	-0.0088	-0.0091	-0.0097	-0.0098
Second-order	R^2	0.4204	0.4193	0.4147	0.4368	0.4134	0.4086
	SE	0.0020	0.00187	0.00291	0.00188	0.00177	0.00191
	a	0.0048	0.0045	0.0065	0.0047	0.0041	0.0043
	b	-0.00002	-0.00002	-0.00002	-0.00002	-0.00001	-0.00002
Parabolic diffusion	R^2	0.9847	0.9825	0.9874	0.9852	0.9859	0.9894
	SE	30.602	33.478	25.411	28.661	34.216	31.926
	a	99.619	112.01	50.237	105.59	124.04	105.27
	b	43.803	44.725	40.187	41.669	50.992	54.985
Power function	R^2	0.9604	0.9590	0.9675	0.9637	0.9651	0.9690
	SE	0.1296	0.1299	0.1306	0.1203	0.1236	0.1231
	a	4.5749	4.6439	4.1895	4.6009	4.7114	4.6340
	b	0.3790	0.3730	0.4228	0.3675	0.3856	0.4086
Elovich	R^2	0.9309	0.9363	0.9140	0.9358	0.9564	0.9527
	SE	65.0494	63.8816	66.5226	59.6561	60.0990	67.4197
	a	-53.761	-46.922	-84.960	-41.601	-63.161	-93.881
	b	141.74	145.30	128.67	135.15	167.15	179.56

Among the tested models, the zero-order and parabolic diffusion equations fit the data from the Relictistagnic Cambisols relatively better than the second-order and Elovich models did for the Pisoplinthic Luvisols and Vertic Cambisols, respectively (Table 4.5). However, none of them were adequate for describing the cumulative K-release data. The power function and first-order models were the best in successfully describing the K^+ release from all experimental soils, based on a higher coefficient of determination (R^2) and lower standard error of the estimate (SE) values.

Since the power function had acceptable values of R^2 and SE compared to the first order, it was considered as the most suitable model to describe the rating process. Bharama (2015) chose the first-order equation as the most suitable model to determine the release rate coefficient of K. According to Ghiri *et al*. (2012) and Jalali (2008), the power function model is used to represent the slow diffusion of K^+ from the interlayer sites of mica. Similar findings (Molavi *et al*., 2020; Li *et al*., 2017; Jalali and Khanlari, 2014) were reported on the efficacious appearance of non-exchangeable K^+ release with a power function equation.

The constants 'a' and 'b' of each model represent the intercept and the slope of the linear curves obtained by plotting the released K against time. The constant 'a' represents the initial amount of K released (Molavi *et al*., 2020; Zareian *et al*., 2018) which shows the amount of equilibrium K initially available for plant uptake (Molavi *et al*., 2020; Islam *et al*., 2017). The constant 'b' reflects the release rate of the non-exchangeable K (Molavi *et al*., 2020; Zareian *et al*., 2018). Thus, the 'b' value is known to correlate well with K^+ for plant uptake (Sanyal *et al*., 2019). Negative values of 'b' were obtained in all the soils for first-order, zero-order, and second-order mathematical model equations. Negative 'b' values implied for insufficient K release from non-exchangeable K to meet the K need of the crop (Bharama, 2015). The variation in the equation constants was also observed, which could be due to the soil type, clay mineralogy, pH, $CaCO_3$, adsorption-desorption balance, soil depth, and mathematical models tested (Juhos *et al*., 2019).

The initial amount of K released ranged from 4.1895 to 4.7114 mg kg^{-1} with releasing rates ranging from 0.3675 to 0.4228 mg kg^{-1} min^{-1} (Table 4.5). The values of K release among the studied soils indicated their relative potential to supply plant-available K (Jalali, 2008). For all soils, the slope derived from the power function was less than one, indicating that the K-release rate decreased over time (Molavi *et al*., 2020; Li *et al*., 2017). The variabilities in K release among the soils could be ascribed to the differences in types of clay minerals, contents of clay and silt, and climate conditions (Fatemi, 2017). Li *et al*. (2015) revealed that soil available K is primarily regulated by the rate of K released into forms suitable to be taken up by plants. Vertisols showed higher K release than the other soil orders, mainly due to higher mica and/or smectite clay contents with a relatively lower abundance of illite clay. According to Srinivasarao *et al*. (2006), Vertisols, smectitic Alfisols, and Inceptisols could have superior K-release due to larger wedge zones and expandability of smectites, whereas K in illitic soils is tightly held and exchange of K is slower.

4.4. Conclusion

The results of this study revealed that the nature and distribution of the different soil types of the Qenberenaweti sub-watershed had a great effect on the K release and fixation. Generally, the equilibrium K concentrations of the soil solution (Ce) and amounts of K adsorbed on the colloidal surfaces (qe) were inconsistently increased with the rising of the initially added K (Ci) throughout the experimental soils. The goodness of the Freundlich isotherm model to fit the data was better for describing the K adsorption characteristics of all experimental soils than that of the Langmuir and Temkin models. Thus, the modified equation of the Freundlich model ($qe = aCe^{b/a}$) was used to describe the theoretical doses of K fertilizers required to develop K levels in soil solutions. The release kinetics of non-exchangeable K was characterized by rapid desorption that lasted for the first 12 hours; then, declined during the next 72 to 168 hours, and remained nearly constant in the subsequent extractions to the end of 288 hours. Among the tested models, the power function was the best to successfully describe the cumulative K^+ release data of all experimental soils. After all, assessing the adsorption capacity of the exchangeable K and the release kinetics of the non-exchangeable K at a site-specific level helps know the relative potential of the soils to supply plant-available K and plan for an effective K fertilization strategy.

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5. INTERNAL AND EXTERNAL POTASSIUM REQUIREMENTS OF WHEAT (*Triticum aestivum* L.) ON SOILS OF QENBERENAWETI SUB-WATERSHED, CENTRAL HIGHLANDS OF ETHIOPIA

Haymanot Awgchew[1,2], Sheleme Beyene[1], Alemayehu Kifilu[1], Asmare Melese[2]
[1]School of Plant and Horticultural Science, Hawassa University, Ethiopia
[2]Department of Plant Science, Debre Berhan University, Ethiopia

ABSTRACT

The presence of moderate to high amounts of available K fractions in the soils often meant an opportunity for better crop production, but certain soil types may not be able to sustain continuous cultivation unless additional K fertilization is made through source-sink optimization. Though the study area's soils contained optimum K, 100 kg muriate of potash per hectare has been recommended while ignoring the K demand of the wheat crop and the K supply characteristics of the soils, which are the internal and external K requirements. Therefore, this study was initiated to assess the growth and yield responses of bread wheat to K at critical soil solution K levels, and to determine the optimum external and internal K requirements of the test crop. Five commonly ploughed soils (Pisoplinthic Luvisols, Pellic Vertisols, Plinthofractic Cambisols, Pisoplinthic Cambisols, and Vertic Cambisols) and the most preferred Dend'a variety of bread wheat at the research site were used under greenhouse conditions. Including the control, there were 12 treatments laid in a completely randomized design with three replications. All the smallest agronomic and lab analysis results were recorded from the control effect. The tallest plants (77.06-92.83 cm) and longest spikes (7.82-10.01 cm) were found at treatments 8 to 10 (25-33 mg K L^{-1}). Consequently, these treatments resulted in 15.27-22.32 and 1.15-2.43 cm rises in plant height and spike length over the control, respectively. The maximum numbers of fertile tillers per plant (3.93-4.68) and seeds per spike (39.04-49.52) were obtained from treatments 7 to 10 and 8 to 9 (21-33 mg K L^{-1}), which caused 1.74-2.21 and 13.72-21.84 increments in numbers of fertile tillers and seeds per spike over the control, respectively. The maximum biomass yields (8.06 to 9.06 tons ha^{-1}) were attained at treatment 9 in all soils except for the 10th (33 mg K L^{-1}) of Plinthofractic Cambisols (8.89 tons ha^{-1}). Treatment 8 (25 mg K L^{-1}) caused the highest grain yield (3.83 to 4.31 tons ha^{-1}) in most of the soils, while treatment 9 (29 mg K L^{-1}) had similar effects in the Pellic Vertisols (4.54 tons ha^{-1}) and Plinthofractic Cambisols (4.05 tons ha^{-1}). Hence, there were 0.59 to 0.94 folds and 96.54 to 179.56% increases in biomass and grain yields owing to the effects of these treatments compared to the control. The highest straw (3.53-3.82%) and grain (1.38-1.39%) K contents were obtained from treatment 8, except for treatment 9 on the Pellic Vertisols (3.82-4.19%) and Plinthofractic Cambisols (1.33-1.39%). The quadratic plateau and linear regression models estimated the optimum external and internal K requirements as 24.48 to 30.75 mg K L^{-1} and 1.19 to 1.30%, respectively, and implied for the usage of 113.40 to 149.24 kg K ha^{-1}. However, further research is needed to validate these results and enhance profitable wheat production via formulating balanced fertilization of K and other essential elements, along with some vital agricultural production and management practices under field conditions.

Keywords: Critical concentration, K optimization, crop demand, soil K supply, wheat production.

5.1. Introduction

Potassium (K) is the third, after nitrogen (N) and phosphorus (P), most agriculturally utilized (Olaniyan *et al*., 2022) and the second largest plant-assimilated nutrient next to N (Soumare *et al*., 2023). Crops remove soil K at about three to four times more than P and/or nearly equal to N (Singh *et al*., 2019), whereby the risk of K deficiency has risen as production intensification continues with the omission of K from the fertilizer regime (Laekemariam *et al*., 2018). Therefore, continuous cropping practice with imbalanced fertilization leads to substantial depletion of the soil K reserve (Das *et al*., 2022), which may go unnoticed as per the conventional available-K test (Singh *et al*., 2019; Patra *et al*., 2017). On the other hand, the adsorption isotherm technique is proven as the most accurate method to predict and evaluate the optimum amount of nutrients required for maximum growth and yield of crops (Palanivell *et al*., 2021; Dunne *et al*., 2020). The approach can also determine the ability of soil to supply K and the exchange of K from the available pool by other ions such as Ca^{2+} (Kassa *et al*., 2019; Kenyanya *et al*., 2014).

Since the plant's K uptake is influenced until attaining its critical concentration status (Mengel, 2016; Jatav *et al*., 2012), the K fertilizer optimization for maximum crop production must rely on the soil's available K content and the crop's K demand (Aurangzeib *et al*., 2021). That means an optimized K fertilization calls for the concept of internal and external nutrient requirements, which can be expressed in terms of quantity, intensity, and capacity factors in plant nutrition (Alemayehu, 2019). The internal requirement delineates the minimum uptake of nutrients (quantity) that is related to the near maximum attainable yield of the crop (Bell, 2023). It is also defined as the critical concentration of nutrients in the plant (intensity) tissue at 95% physiological maturity (Riechelman *et al*., 2021). The external requirement of a crop describes the maximum equilibrated concentration of nutrient in soil solution as a critical level below which the specified yield response to applied rate becomes more probable (Briat *et al*., 2020). According to Mbangi *et al*. (2023), the external requirement is considered as the amount of nutrient required to raise the soil test level by 1 mg kg^{-1} (buffer capacity).

Potassium nutrition improves crop productivity as it promotes the growth and development of plants (Sardans and Peñuelas, 2021; Gebreslassie, 2016) under both normal and water stress conditions (Ul-Allah *et al*., 2020; Hasanuzzaman *et al*., 2018). Because K plays a key role in several physiological processes of plants, such as transpiration, photosynthesis, and formation plus translocation of photosynthates and phytohormones (Das *et al*., 2021; Ewais *et al*., 2020). Besides, it activates diverse enzymes that are vital for the synthesis and metabolism of starch and proteins, stimulation of photosynthetic pigments, and efficiency of photo-phosphorylation (Tariq *et al*., 2023; Muhammad *et al*., 2021). Particularly, its addition to wheat production reduces the incidence of pest and disease (Jeer *et al*., 2021; Singh, 2020) and lessens stalk lodging (Zhang *et al*., 2017). Several authors revealed that its optimal application on wheat increases plant height, spike length, number of seeds per spike, number of fertile tillers per plant, grain yield, and total biomass production (Sharma *et al*., 2022; Tesfaye *et al*., 2021).

The presence of moderate to high levels of available K fractions in the soils often implied the capability for better crop production (Srinivasarao *et al*., 2023); but some soils may not support continuous cultivation unless further use of K fertilizers is made (Das *et al*., 2022; Zörb *et al*., 2014). Contempt the fact that crops differ in their responses to the applied K (Haberman *et al*., 2019), labile K fractions are easily exhausted by crop uptake (Das *et al*., 2018; Islam *et al*., 2017) and, hence, need to be replaced continually via the release from non-labile K fractions (Das *et al*., 2021; Dotaniya *et al*., 2016). The amount of K in the interlayer lattice is determined by the content of K with respect to its critical level in the soil (Panda *et al*., 2022; Han *et al*., 2019). However, the optimal K demand of high-yielding crops is not attained due to a very slow release of such K forms (Srinivasarao *et al*., 2023; Das *et al*., 2022; Wakeel and Ishfaq, 2022).

Wheat is a strategic commodity that generates income and improves food security status in sub-Saharan African countries (Anteneh and Asrat, 2020; Amentae *et al*., 2017). In Ethiopia, wheat represents about 15% of the total calorie intake, which puts it second behind maize (19%) but ahead of enset (12%), sorghum (11%), and teff (10%) crops (Alemu *et al*., 2022). Production of wheat has a remarkable contribution to addressing food insecurity and the growing demand of the country (Zegeye *et al*., 2020; Gashaw and Bernard, 2017), especially in the highland areas (Kihara *et al*., 2022). According to CSA (2019), more than 58% of its production in the country is used for household consumption, while about 21, 17, and 4 percent are used for market, seed, and other purposes, respectively. Hence, enhancing its production and productivity is promising to achieve enough food supply in Ethiopia (Anteneh and Asrat, 2020; Zegeye *et al*., 2020).

Though soils of the study area contained an optimum amount of exchangeable K, 100 kg of muriate of potash (KCl) fertilizer has been recommended for a hectare of land (ATA, 2016) without considering the K demand of a particular crop and the K supply characteristics of the soils. However, fertilizer recommendation needs to be customized with explicit soil natures (nutrient reserve and availability) and crop situations on a scientific basis for the targeted maximum growth and yield (Akbas *et al*., 2017). Despite the blanket recommendation along with the sub-optimal and solo uses of P and N nutrients (Woldetsadik *et al*., 2019), there is no adequate information on the custom and benefit of K for wheat and other field crops production in Ethiopia in general (Liben *et al*., 2022) and specifically in the study area (Kassie *et al*., 2019). Besides, the optimum external and internal K requirements for maximum wheat growth and yield have not yet been studied in the study area. All these recall an emerging need for efficient K-fertilization to promote a profitable wheat production while addressing both economic and environmental issues. Therefore, this study was initiated to determine the optimum external and internal K requirements of bread wheat (*Triticum aestivum* L.) through assessing its growth and yield responses at critical solution K levels (fertilizer rates) of the experimental soils.

5.2. Materials and Methods

5.2.1. Determination of fertilizer rates

Generally, the external K requirement is not a single-valued constant that holds the same for all conditions, at which the concentration of K in a dilute salt solution is a useful indicator of the K nutrition of crops (He *et al*., 2023). Thus, it is widely applied in conjunction with K sorption curves to estimate the optimum K fertilization dosage as described below:

- ✓ Plot graph of Ce (mg L^{-1}) vs qe (mg kg^{-1}), and set its linearized line equation (h = tr + e)
- ✓ Compute the value of "h" by using the Ce in place of "r"; then change into its Log value
- ✓ From the graph equation (y = bx + a) of the best-fitted Freundlich adsorption model of each soil sample, calculate the values of "a" in Log, and Ln^{-1} as "k"
- ✓ Solve the results of the desired critical K equilibrium solution concentrations for each experimental soil as Ce = (Logh - Loga)/b
- ✓ Find the mean Ce values of all soils per identified treatment effects, round up to the nearest whole number, and put in progressive cumulative results ($0 \leq Ce \geq 41$ mg L^{-1}).

***<u>Note</u>**: the total number of treatments (12) was fixed from each of the rounded Ce values.*

- ✓ Determine the potassium fertilizer dose (mg kg^{-1}) for experimental soils by using the concerned Freundlich model equation used under Chapter 4 (Experiment 3) as follows:

$$Fertilizer\ dose\ (qe, mg\ kg^{-1}) = kCe^{\frac{b}{a}}$$

Accordingly, the following doses were found for each of the soils:

- ➢ Vertic Cambisols ($qe = 5.3276Ce^{0.7964}$)
- ➢ Pellic Vertisols ($qe = 5.2294Ce^{0.7894}$)
- ➢ Plinthofractic Cambisols ($qe = 4.7242Ce^{0.7380}$)
- ➢ Pisiopllintic Cambisols ($qe = 5.2043Ce^{0.7746}$)
- ➢ Pisoplinthic Luvisols ($qe = 4.8759Ce^{0.7639}$)

✓ Finally, multiply the above doses in mg kg^{-1} by 2 to have a rate on kg ha^{-1} basis.

$$Fertilizer\ dose\ (kg\ ha^{-1}) = qe * 2$$

Where; 'qe' is the amount of K adsorbed per unit mass of soil, 'a' and 'b' were constants obtained from the intercept and slope of the Freundlich model, respectively.

5.2.2. Experimental materials and treatments

The five commonly ploughed soil types (Pisoplinthic Luvisols, Pellic Vertisols, Plinthofractic Cambisols, Pisoplinthic Cambisols, and Vertic Cambisols) of the study area were considered in this research. Twelve sub-samples of surface soil (0-20 cm) were collected in a zig-zag fashion from three typical farmlands under each soil. The air-dried sub-samples were ground by pestle and mortar, sieved with a 5 m mesh, and accordingly composited together into their respective groups. Then, four kg of the composite samples were put in a frustum (shape of a truncated cone) plastic container of 18 cm height and mean diameter (17 cm bottom by 19 cm top) after thoroughly mixing with different treatments per soil type. Including the control (zero kg K ha^{-1}), there were 12 treatments (Table 5.1) adjusted from the critical K equilibrium solution concentrations on adsorption curves of the best-fitted Freundlich model (Chapter 4). They were laid out in a completely randomized design (CRD) with three replications under a greenhouse.

Fifteen seeds of bread wheat (Dend'a variety) were seeded in each pot and thinned to ten plants at 75% crop emergence. Following the fertilizer recommendation for wheat production package set by the North Shewa zone agricultural office, similar rates of P (20 kg ha^{-1}) and N (92 kg ha^{-1}) were used on every treatment. In addition to the determined amounts of K (KCl), full and 1/3 doses of the P (TSP) and N (Urea), respectively, were thoroughly mixed with the soils at the time of sowing; while the remaining 2/3 N was applied at the tillering stage. Then, the amounts of each added fertilizer per pot were prepared in threefold more of the determined rates on a hectare basis (Terman, 1974) to compensate for the actual nutrient demand of the crop (Chien, 2022). Because the roots are restricted to proliferate only in the small soil volume in the pot than what they might do in the field (Yoon *et al*., 2023). The bulk density and nutrient flow depth of the soils were considered as 1,200 kg m^{-3} and 20 cm, respectively (Wogi *et al*., 2021). The soil moisture level was kept at nearly field capacity during the crop growth period.

Table 5. 1. Pre-determined K fertilization doses for wheat crop production

Treatment codes	Ce (mg L^{-1})	K in the soil solution (mg kg^{-1})					K to be applied on the field (kg ha^{-1})				
		PpC	PpL	VrC	PeV	PfC	PpC	PpL	VrC	PeV	PfC
Trt 1	0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Trt 2	3	12.19	11.29	12.78	12.45	10.63	24.38	22.57	25.56	24.90	21.26
Trt 3	6	20.85	19.16	22.19	21.51	17.73	41.70	38.33	44.39	43.03	35.45
Trt 4	9	28.54	26.12	30.65	29.63	23.91	57.09	52.24	61.31	59.26	47.82
Trt 5	13	37.95	34.59	41.08	39.61	31.36	75.90	69.19	82.17	79.22	62.73
Trt 6	17	46.72	42.46	50.87	48.95	38.23	93.43	84.92	101.74	97.90	76.46
Trt 7	21	55.03	49.90	60.19	57.84	44.68	110.05	99.80	120.39	115.68	89.36
Trt 8	25	62.98	57.01	69.16	66.37	50.82	125.96	114.02	138.32	132.74	101.63
Trt 9	29	70.66	63.85	77.84	74.62	56.70	141.31	127.71	155.67	149.24	113.40
Trt 10	33	78.09	70.48	86.27	82.64	62.37	156.19	140.95	172.55	165.27	124.74
Trt 11	37	85.33	76.91	94.50	90.45	67.87	170.66	153.83	189.01	180.89	135.73
Trt 12	41	92.39	83.19	102.55	98.08	73.21	184.78	166.38	205.11	196.16	146.42

Where: PpC = Pisoplinthic Cambisols; PpL = Pisoplinthic Luvisols; VrC = Vertic Cambisols; PeV = Pellic Vertisols; PfC = Plinthofractic Cambisols

5.2.3. Data collection and plant tissue analysis

Starting at 75% heading to 90% physiological maturity, the height and spike length of five randomly selected plants per pot were measured using a ruler from the bottom to the tip of the shoot and from the base of the spike to the apex of the terminal spikelet, respectively, excluding the awns. The mean number of productive tillers per plant was recorded during these growth stages. The entire above-ground tissues from each pot were harvested at 95% physiological maturity and dried in an oven (70 °C for 24 hours) for the determination of biomass (straw and grain dry weight) yield in ton ha^{-1} by adjusting the seed moisture content at 12%. In addition, the number of seeds per spike was counted after hand-threshing.

The oven-dried grain and straw samples were ground by an electrical grinding mill and sieved through a 1 mm mesh-size sieve. Then, the samples were ashed at 500 °C for five hours, dissolved with 0.1M HCl, and digested on a hot plate to analyze the total K concentrations in the suspensions using a flame photometer (Faithfull, 2002). The amount of K in the tissues was expressed as percent content on a dry weight basis. The total K uptake (kg ha^{-1}) was computed from the product of tissue K content and plant dry weight, while the potassium harvest index (KHI) was from the ratio of tissue K utilization as shown in the following formulae.

$$\text{Grain K uptake} = \text{grain yield} * \text{grain K concentration}$$

$$\text{Straw K uptake} = \text{straw yield} * \text{straw K concentration}$$

$$\text{Total K uptake} = \text{grain K uptake} + \text{straw K uptake}$$

$$\text{KHI} = \frac{\text{grain K uptake}}{\text{total K uptake}}$$

Graphs of relative yield (%) were plotted against soil solution K levels and K concentration (%) in wheat grains to determine external and internal K requirements, respectively, by using the Boundary Line Technique with a mathematical regression model (Schnug *et al*., 1995). The yields representing each K solution level were expressed in percentage of the maximum yield as follows:

$$\text{Relative Yield (\%)} = \frac{\text{Actual grain yield} * 100}{\text{Maximum grain yield}}$$

Where: Actual grain yield is a yield at zero K level, Maximum grain yield is a point of maximum yield response at a specific applied K level.

5.2.4. Statistical analysis

Data on plant growth, yield, and tissue analysis were subjected to the Analysis of Variance (ANOVA) using the Generalized Linear Model (GLM) procedure of statistical analysis software package 9.4 (SAS, 2013). Mean comparisons of the parameters were done for each study soil with the Least Significant Difference (LSD) test at 5% probability level ($P \leq 0.05$).

5.3. Results and Discussion

5.3.1. Potassium rates and agronomic traits of wheat

The analysis of variance (ANOVA) revealed that application of different rates of K to all study soils had a very highly significant effect ($P < 0.001$) on plant height and spike length (Table 5.2). Though the effects of treatment 2 were statistically similar in Pellic Vertisols (24.90 kg K ha^{-1}), Vertic Cambisols (25.56 kg K ha^{-1}), and Pisoplinthic Luvisols (22.57 kg K ha^{-1}), the shortest plants and spikes were obtained from the control (0 kg K ha^{-1}) treatment 1. The tallest plants were found at treatments 8 on the Pisoplinthic Cambisols (125.96 kg K ha^{-1}) and Pisoplinthic Luvisols (114.02 kg K ha^{-1}), 9 on the Vertic Cambisols (155.67 kg K ha^{-1}), as well as 10 on the Pellic

Vertisols (165.27 kg K ha^{-1}) and Plinthofractic Cambisols (124.74 kg K ha^{-1}). Additionally, the longest spikes of wheat were from treatments 8 on the Vertic Cambisols (138.32 kg K ha^{-1}), 9 on the Pisoplinthic Cambisols (141.31 kg K ha^{-1}), Pisoplinthic Luvisols (127.71 kg K ha^{-1}), and Plinthofractic Cambisols (113.40 kg K ha^{-1}), and 10 on the Pellic Vertisols. Consequently, these treatments resulted in 15.27 to 22.32 and 1.15 to 2.43 cm rises in plant height and spike length of wheat over the controls, respectively.

Table 5. 2. Plant height and spike length of wheat on soils of the sub-watershed

Treatment	Parameters									
	Plant height (cm)					Spike length (cm)				
	Soil types									
	PeV	VrC	PpC	PfC	PpL	PeV	VrC	PpC	PfC	PpL
1	73.94i	71.17h	60.37i	63.71j	61.79g	7.84g	7.58f	6.76g	6.80i	6.67g
2	75.05hi	72.84gh	65.01h	68.66i	64.48f	8.42f	8.06e	6.89fg	6.94h	6.87f
3	76.93gh	74.11fg	67.07g	70.40h	66.79e	8.39f	8.52d	6.92ef	7.31g	6.88ef
4	77.47gh	75.81ef	68.83fg	72.14g	67.63e	8.45f	8.78cd	6.97def	7.57f	6.91ef
5	80.58ef	78.39d	69.10ef	74.30f	69.47cd	8.55ef	8.76cd	7.08d	7.74e	6.97e
6	79.30fg	77.08de	71.35d	73.29fg	69.93c	8.81de	8.99c	7.05de	7.74e	7.27d
7	82.08def	75.94ef	77.58b	75.67e	68.13de	9.33bc	8.59d	7.37c	7.85de	7.29d
8	83.19cde	84.25b	80.28a	75.81e	77.06a	9.00d	10.01a	7.82b	8.49a	7.43c
9	88.28b	88.25a	77.64b	83.95b	76.92a	9.50b	9.50b	8.08a	8.58a	7.82a
10	92.83a	83.64b	73.65c	86.03a	76.35a	9.87a	9.39b	7.80b	8.33b	7.75ab
11	86.22bc	81.39c	70.83de	81.16c	74.64b	9.05cd	9.49b	7.51c	8.11c	7.69b
12	84.86cd	81.33c	70.67def	77.93d	70.20c	8.64ef	9.33b	7.37c	7.94d	7.46c
CV (%)	2.20	1.66	1.61	1.04	1.29	1.91	1.85	1.19	0.90	0.79
LSD (0.05)	3.03	2.21	1.93	1.31	1.53	0.28	0.28	0.15	0.12	0.10

PeV: Pellic Vertisols, VrC: Vertic Cambisols, PpC: Pisoplinthic Cambisols, PfC: Plinthofractic Cambisols, PpL: Pisoplinthic Luvisols

LSD: Least Significant Difference

Means followed by the same letter(s) within a column are not statistically different at $P \leq 0.05$.

All the wheat crops showed a general declining trend upon applying more K rates after attaining their maximum height and spike growth (Table 5.2), implying that the plant acquires some optimum amount of soil K nutrition. In addition to the synergetic advantage of a balanced N-P-K fertilization (Hasanuzzaman *et al.*, 2018), the increased wheat stalk height and spike length could be ascribed to the vital roles of adequate K on plant cell growth and development (Pandey and Mahiwal, 2020). Vigorous plant growth and development are linked with optimal K consumption (Martineau *et al.*, 2017), which maintains greater osmotic potential and turgor pressure (Rawat *et al.*, 2016) to increase cell expansion and elongation (Da Silva *et al.*, 2021). Potassium is involved in the building up of structural organic compounds (starch and protein) and growth regulatory hormones (auxin) that prompt cell elongation and expansion in young meristematic tissues

(Mesurani and Ram, 2020; Sustr *et al*., 2019; Rawat *et al*., 2016). According to Cosgrove (2024), K makes the ATPase in the plasma membrane generate an acid, which triggers cell wall loosening and hydrolase activation. Whereas, K deficiency causes thin epidermis sclerenchyma and xylem vascular tissues (Attia *et al*., 2022; Irawan and Putra, 2020), thereby reducing the stalk height and spike length of wheat (Waseem *et al*., 2021; Khobra *et al*., 2019).

The ANOVA results showed that the numbers of fertile tillers per plant (NFTP) and seeds per spike (NSPS) were highly significantly ($p < 0.001$) affected by the rates of K fertilization on all experimental soils (Table 5.3). Omission of K (0 kg K ha^{-1}) resulted in the lowest NFTP and NSPS, which was statistical at par with treatment 2 in certain soils. The highest NFTP were obtained from treatment 9 on Pellic Vertisols (149.24 kg K ha^{-1}) and Pisoplinthic Luvisols (127.71 kg K ha^{-1}), 7 on Pisoplinthic Cambisols (110.05 kg K ha^{-1}), 8 on Vertic Cambisols (138.32 kg K ha^{-1}), and 10 on Plinthofractic Cambisols (124.74 kg K ha^{-1}). Despite the statistical similarity among some treatments, the maximum NSPS was obtained from the 8th on Pellic Vertisols, Vertic Cambisols, and Pisoplinthic Luvisols, while the 9th gave maximum NSPS on Pisoplinthic and Plinthofractic Cambisols. Accordingly, the 7th to 10th and 8th to 10th treatments had 1.74 to 2.21 and 13.72 to 21.84 increments in the NFTP and NSPS over the control, respectively.

Table 5. 3. Numbers of fertile tillers and seeds per spike of wheat on soils of the sub-watershed

Treatment	Parameters									
	Number of fertile tillers per plant					Number of seeds per spike				
	Soil types									
	PeV	VrC	PpC	PfC	PpL	PeV	VrC	PpC	PfC	PpL
1	2.61h	2.42i	2.19h	2.14h	1.87j	29.89h	27.68h	24.36h	25.32g	25.05h
2	2.90g	2.68h	2.32gh	2.23gh	2.10i	31.99h	31.38g	26.30g	26.35g	27.31g
3	3.14f	2.79gh	2.54fg	2.36g	2.20hi	34.96g	33.15g	28.89f	30.50f	29.06f
4	3.14f	2.98fg	2.49fg	2.56f	2.30gh	35.49g	35.62f	30.14f	31.61ef	30.19ef
5	3.26ef	3.06f	2.61ef	2.72ef	2.40fg	38.81f	35.65f	31.82e	31.90ef	30.22ef
6	3.41e	3.16ef	2.76de	2.89e	2.48ef	40.14ef	37.95e	33.73d	33.13de	31.12de
7	3.75d	3.77c	3.93a	3.21d	2.62e	45.28bc	38.77de	32.43de	32.86de	32.40d
8	4.16c	4.41a	3.47b	3.67c	3.50b	47.75a	49.52a	39.54ab	34.10cd	39.97a
9	4.68a	4.13b	3.33b	3.92b	4.08a	46.43ab	41.41c	41.03a	39.04a	38.74a
10	4.38b	3.53d	3.28b	4.18a	3.31c	44.40cd	40.62cd	39.15b	38.21a	37.04b
11	4.17c	3.38de	3.02c	3.81bc	3.18c	42.53de	42.31c	37.11c	36.27b	34.59c
12	3.91d	3.50d	2.94cd	3.33d	2.91d	41.41e	46.05b	33.84d	35.05bc	32.01d
CV (%)	3.36	4.14	4.52	4.42	3.68	3.64	3.18	2.74	2.93	2.71
LSD (0.05)	0.21	0.23	0.22	0.18	0.17	2.45	2.06	1.53	1.62	1.48

PeV: Pellic Vertisols, VrC: Vertic Cambisols, PpC: Pisoplinthic Cambisols, PfC: Plinthofractic Cambisols, PpL: Pisoplinthic Luvisols

LSD: Least Significant Difference

Means followed by the same letter(s) within a column are not statistically different at $P \leq 0.05$.

The NFTP and NSPS inconsistently rose with increasing application of K but failed upon adding more K beyond the rates of 8th (25 mg K L^{-1}) or 9th (29 mg K L^{-1}) treatment (Table 5.3), which might be considered as a satisfactory amount of K for better results of fertile tillers and seeds. Along with the overall nutrient balance (N and P) of the soils, sufficient K availability could play important roles in the initiation and development of tiller primordia and reproductive structures. Because K promotes cell division, differentiation, and expansion to support the development of new tillers and flowers via controlling the synthesis and distribution of photosynthates and phytohormones (Kumar *et al*., 2020). Potassium interacts with carbohydrates and cytokinin to determine the number of productive tillers and spikes, and ultimately seeds per spike of the wheat crop (Abou Khadrah *et al*., 2020). Adequate K levels promote healthy floral development as well as effective pollen germination, pollen tube growth, and fertilization, which are vital for successful seed setting (Li *et al*., 2018; Higashiyama and Takeuchi, 2015).

The biomass and grain yields of wheat were highly significantly ($p < 0.001$) influenced by the use of different K rates on the experimental soils (Table 5.4). The lowest biomass and grain yields of wheat were obtained from the control in all soils, which were statistically at par with those of treatment 2 in certain soils. The maximum biomass yields were found at treatment 9, except for treatment 10 (124.74 kg K ha^{-1}) on the Plinthofractic Cambisols. The highest grain yields were produced by treatment 9 on the Pellic Vertisols and Plinthofractic Cambisols, though treatment 8 resulted in the highest grain yields in most of the remaining soils (Table 5.4). Hence, there was a 0.59 to 0.94 fold increase in biomass yield due to the effects of these treatments compared to the control under the study soils. Moreover, the treatments enhanced the grain yield by 96.54 to 179.56 percent over the control.

The biomass and grain yields exhibited an overall increasing trend to reach their highest levels, whereby a further K addition resulted in declining yields (Table 5.4). This implies that the plant has its own optimum K dose for attaining better biological yield. According to Godebo *et al*. (2021) and Kubar *et al*. (2019), extra K application beyond a given optimum level affects wheat straw and grain yields. Because the usage of more K than its requirement can lead to diminishing returns in growth and yield responses of wheat (Wakeel and Ishfaq, 2022) via unbalancing the uptake of nutrients (Ca and Mg) and interrupting normal physiological processes of the crop (El-Mageed *et al*., 2023). Adequate K level enhances straw and grain yields of wheat by increasing the number and size of seeds that provide a higher sink capacity for filling photosynthetic assimilates (Munsif *et al*., 2022; Godebo *et al*., 2021). The rise of biological dry mass in response to the increased levels of K could also be attributed to the fact that it is involved in the efficient functioning of chloroplasts via the activation of enzymes in photosynthetic reactions (Rawat *et al*., 2022; Tränkner *et al*., 2018).

Table 5. 4. Biomass and grain yields of wheat on soils of the sub-watershed

Treatment	Parameters									
	Biomass yield (ton ha^{-1})					Grain yield (ton ha^{-1})				
	Soil types									
	PeV	VrC	PpC	PfC	PpL	PeV	VrC	PpC	PfC	PpL
1	5.70h	5.41g	5.06j	4.59i	4.77j	2.31i	2.08i	1.67h	1.97k	1.37i
2	5.76h	5.51g	5.43i	4.77i	5.27i	2.60h	2.26h	1.73h	2.09j	1.53h
3	6.02g	5.83f	5.84h	5.48h	5.59h	2.93g	2.54g	1.95g	2.22i	2.01g
4	6.80f	6.60e	6.31g	6.42g	5.78gh	3.01g	2.62g	2.03g	2.33h	2.14fg
5	6.92f	6.85e	6.47g	6.60fg	5.97fg	3.24f	2.82f	2.30f	2.45g	2.20ef
6	7.24e	7.24d	6.71f	6.76ef	6.66e	3.59e	3.01e	2.64e	2.82f	2.34e
7	7.42de	7.25d	6.99e	6.87e	6.77de	3.83d	3.79c	3.52d	3.46e	3.08d
8	7.85c	8.78a	7.70b	7.95cd	7.53b	4.20bc	4.32a	4.19a	3.71c	3.83a
9	9.06a	8.93a	8.06a	8.57b	8.46a	4.54a	3.96b	4.06b	4.05a	3.61b
10	8.39b	8.22b	7.56bc	8.89a	7.24c	4.31b	3.82c	4.01b	3.90b	3.47bc
11	8.20b	8.20b	7.35cd	8.16c	6.91d	4.15bc	3.76c	3.76c	3.73c	3.41c
12	7.52d	7.62c	7.15de	7.78d	6.04f	4.09c	3.65d	3.67c	3.61d	3.32c
CV (%)	1.94	2.14	1.86	2.02	2.15	3.19	1.76	2.61	1.87	3.42
LSD (0.05)	0.24	0.26	0.21	0.24	0.23	0.19	0.10	0.13	0.10	0.16

PeV: Pellic Vertisols, VrC: Vertic Cambisols, PpC: Pisoplinthic Cambisols, PfC: Plinthofractic Cambisols, PpL: Pisoplinthic Luvisols

LSD: Least Significant Difference

Means followed by the same letter(s) within a column are not statistically different at $P \leq 0.05$.

The results of this experiment revealed that soils of a vertic nature resulted in vigorous growth and yield of wheat than the other soils (Table 5.4), which might be due to the amount and type of fine-sized soil particles. According to Bell *et al*. (2021), soils of a vertic nature are known for their better water- and K-holding capacities owing to the presence of 2:1 clay mineralogy. Brhane *et al*. (2017) and Hagos *et al*. (2017) also reported in conformity to this research, indicating that Vertisols gave greater results of wheat growth and yields than shallow depth soils of Enderta district in South-eastern Tigray, Ethiopia, upon combined use of 100 kg ha^{-1} blended NPKSZn fertilizer (8% K_2O) with increasing KCl levels (0, 30, 60, and 90 kg K_2O ha^{-1}). Additionally, Alemayehu (2019) has recorded significant effects on wheat growth and yields due to the addition of K on Vertisols (148 kg K ha^{-1}) and Cambisols (122 kg K ha^{-1}) of Godnamamas and Cheki localities found near this study area.

5.3.2. Potassium content and harvest index of wheat

The concentrations of K in the wheat tissues were significantly ($P < 0.001$) affected by the different K doses under all the soils (Table 5.5). Although the K concentrations were statistically at par among the K-treated pots, the lowest grain (0.95-1.16%) and straw (1.56-2.98%) K contents were obtained from the control. Treatment 8 caused the highest K quantities in the grain and straw on all the soils, while 9 caused the highest K on the Pellic Vertisols and Plinthofractic Cambisols.

The concentrations of K in the wheat grain and straw parts were progressively increased and then slightly decreased with increasing rates of applied K, possibly due to sufficient K buildup in the soil solution and its active uptake. Such a critical turning point in the wheat tissues' K contents is considered as a luxury consumption (Karthika *et al*., 2018; Dotaniya *et al*., 2016). The greater uptake of K by wheat from soil is achieved through better water uptake and translocation of photosynthates (Singh, 2020). Generally, higher K content was found in the straw than in the grains. This might be because more K is taken up by the above-ground tissues during the flowering stage (Jankowski *et al*., 2016) and translocate photo-assimilates to storage organs based on the concentration gradient (El-Mageed *et al*., 2023; Wang *et al*., 2020). This result was in agreement with the findings of Brhane *et al*. (2017) and Hagos *et al*. (2017), in which the use of K significantly proved superior to control with respect to K uptake by wheat grain and straw, and the maximum value of K uptake was recorded with the highest K level among the treatments.

The potassium harvest index (KHI) of wheat tissues was significantly influenced by the addition of different rates of K to all the experimental soils (Table 5.5). The statistical minimum and maximum KHI values were found in ranges of 0.18-0.29 (Pellic Vertisols), 0.24-0.35 (Vertic Cambisols), 0.21-0.34 (Pisoplinthic Cambisols), 0.16-0.23 (Plinthofractic Cambisols), and 0.15-0.32 (Pisoplinthic Luvisols). There was statistical similarity in KHI values, with the lowest KHI being under all the soils, except for the Pisoplinthic Cambisols. Furthermore, the highest KHI on the Pellic Vertisols and Pisoplinthic Cambisols had statistical similarity with a few treatments.

The maximum KHI results could be due to the initial high level of exchangeable K and mineralization of the medium OM contents in the study soils (Singh *et al*., 2019; Hagos *et al*., 2017). Thus, it becomes available to the wheat requirements, and increasing K fertilizer beyond the critical level may be used as a luxury consumption (Singh *et al*., 2021; Li *et al*., 2020). Optimum fertilizer dosage controls the harvest index of wheat via normalizing the K contents in the straw and grain tissues (El-Egami *et al*., 2024; Li *et al*., 2022). Similarly, Hagos *et al*. (2017) and Brhane *et al*. (2017) revealed the positive effect of optimum fertilization on KHI of wheat.

Table 5. 5. Potassium concentration and harvest index of wheat tissues on soils of the sub-watershed

Treatments	Parameters														
	Grain K concentration (%)					Straw K concentration (%)					Harvest index				
	Soil types														
	PeV	VrC	PpC	PfC	PpL	PeV	VrC	PpC	PfC	PpL	PeV	VrC	PpC	PfC	PpL
1	0.95f	1.06h	1.15f	1.04g	1.16e	2.98f	1.83i	1.56i	2.55h	2.61f	0.18g	0.27bc	0.27cd	0.23b	0.15e
2	1.01ef	1.08gh	1.16f	1.05g	1.18de	2.96f	2.10h	1.64hi	2.87fg	2.65f	0.22f	0.26bc	0.25d	0.22bcd	0.16e
3	1.07de	1.14efg	1.20def	1.10fg	1.24cd	3.26e	2.26gh	1.76h	2.80g	3.02e	0.24c-f	0.28b	0.26d	0.20de	0.19d
4	1.02def	1.10fgh	1.18ef	1.15ef	1.25cd	3.60cd	2.33fg	2.18f	3.04de	3.01e	0.18g	0.24d	0.21e	0.16g	0.20d
5	1.10d	1.17ef	1.18ef	1.17e	1.20de	3.45de	2.44ef	1.98g	2.92efg	3.06de	0.22ef	0.25cd	0.25d	0.17fg	0.19d
6	1.19bc	1.19de	1.21c-f	1.19de	1.24cd	3.52cd	2.52de	2.20f	3.01def	3.08de	0.25cd	0.25cd	0.26d	0.18fg	0.18d
7	1.18c	1.25cd	1.24c-f	1.22cd	1.28bc	3.70c	2.63d	2.50e	3.30c	3.16de	0.26bcd	0.35a	0.34a	0.26a	0.25c
8	1.20bc	1.38a	1.35a	1.23bcd	1.38a	4.02b	3.66a	3.53a	3.10d	4.09a	0.24cde	0.26bc	0.32ab	0.21cd	0.25c
9	1.39a	1.35ab	1.34ab	1.33a	1.38a	4.19a	3.46b	3.30b	3.82a	4.04a	0.27abc	0.24d	0.31ab	0.18ef	0.26bc
10	1.35a	1.31abc	1.30abc	1.32a	1.36a	4.18a	3.08c	3.07c	3.56b	3.43bc	0.28ab	0.27bc	0.33a	0.19ef	0.32a
11	1.26b	1.31abc	1.28a-d	1.29ab	1.35ab	3.68cd	3.08c	2.86d	3.40bc	3.52b	0.29a	0.28b	0.32ab	0.22bc	0.29b
12	1.23bc	1.28bc	1.26b-e	1.27bc	1.32ab	3.71c	3.01c	2.70d	3.30c	3.26cd	0.23def	0.27bc	0.29bc	0.21cd	0.19d
CV (%)	3.95	3.87	4.48	2.95	3.38	4.01	3.70	4.11	3.11	3.64	6.61	4.98	6.01	5.91	6.99
LSD (0.05)	0.08	0.08	0.09	0.06	0.07	0.25	0.17	0.17	0.17	0.20	0.03	0.02	0.03	0.02	0.03

PeV: Pellic Vertisols, VrC: Vertic Cambisols, PpC: Pisoplinthic Cambisols, PfC: Plinthofractic Cambisols, PpL: Pisoplinthic Luvisols

LSD: Least Significant Difference

Means followed by the same letter(s) within a column are not statistically different at $P \leq 0.05$.

The maximum KHI results could be due to the initial high level of exchangeable K and mineralization of the medium OM contents in the study soils (Singh *et al*., 2019; Hagos *et al*., 2017). Thus, it becomes available to the wheat requirements, and increasing K fertilizer beyond the critical level may be used as a luxury consumption (Singh *et al*., 2021; Li *et al*., 2020). Optimum fertilizer dosage controls the harvest index of wheat via normalizing the K contents in the straw and grain tissues (El-Egami *et al*., 2024; Li *et al*., 2022). Similarly, Hagos *et al*. (2017) and Brhane *et al*. (2017) revealed the positive effect of optimum fertilization on KHI of wheat.

5.3.3. Potassium requirements of wheat

The constructed boundary line in plots of relative yield against soil solution or grain K levels (Figure 5.1) showed the general relationship between these variables and estimated the optimal K requirements for better wheat production at the study site by using regression analysis.

The data on external K requirements of the experimental soils were fitted best to the quadratic plateau regression model with higher R^2 results ranging between 0.88 and 0.96 (Figure 5.1/A). Hence, the model estimated the optimum K in soil solution near maximum (95%) yield as 24.48, 25.28, 26.03, 28.88, and 30.75 mg K L^{-1} for the Pisoplinthic Luvisols, Vertic Cambisols, Pisoplinthic Cambisols, Pellic Vertisols, and Plinthofractic Cambisols, respectively. These values implied that 114.02, 138.32, 125.96, 149.24, and 113.40 kg K ha^{-1} were respectively needed to have the maximum wheat grain yields. To determine the amounts of K in the soil solution, Alemayehu (2019) reported that 122 and 148 kg K ha^{-1} were required to develop levels of 2.75 and 1.93 mg K L^{-1}, respectively, for the highest wheat grain yields grown on Cambisols and Vertisols of Cheki and Godnamamas localities in the central highlands of Ethiopia.

The internal K requirement of wheat at the attainable 95% relative yield was well determined with the linear plateau regression model, having the R^2 values of 0.88 to 0.96 (Figure 5.1/B). Therefore, the maximum yields obtained from the Plinthofractic Cambisols, Pisoplinthic Cambisols, Pellic Vertisols, Pisoplinthic Luvisols, and Vertic Cambisols have accumulated 1.19, 1.20, 1.21, 1.25, and 1.30 percent K in the grain, respectively. Alemayehu (2019) estimated 0.77% and 0.86% as the critical internal K requirements of wheat crop produced on Vertisols and Cambisols of Ethiopian central highlands, respectively.

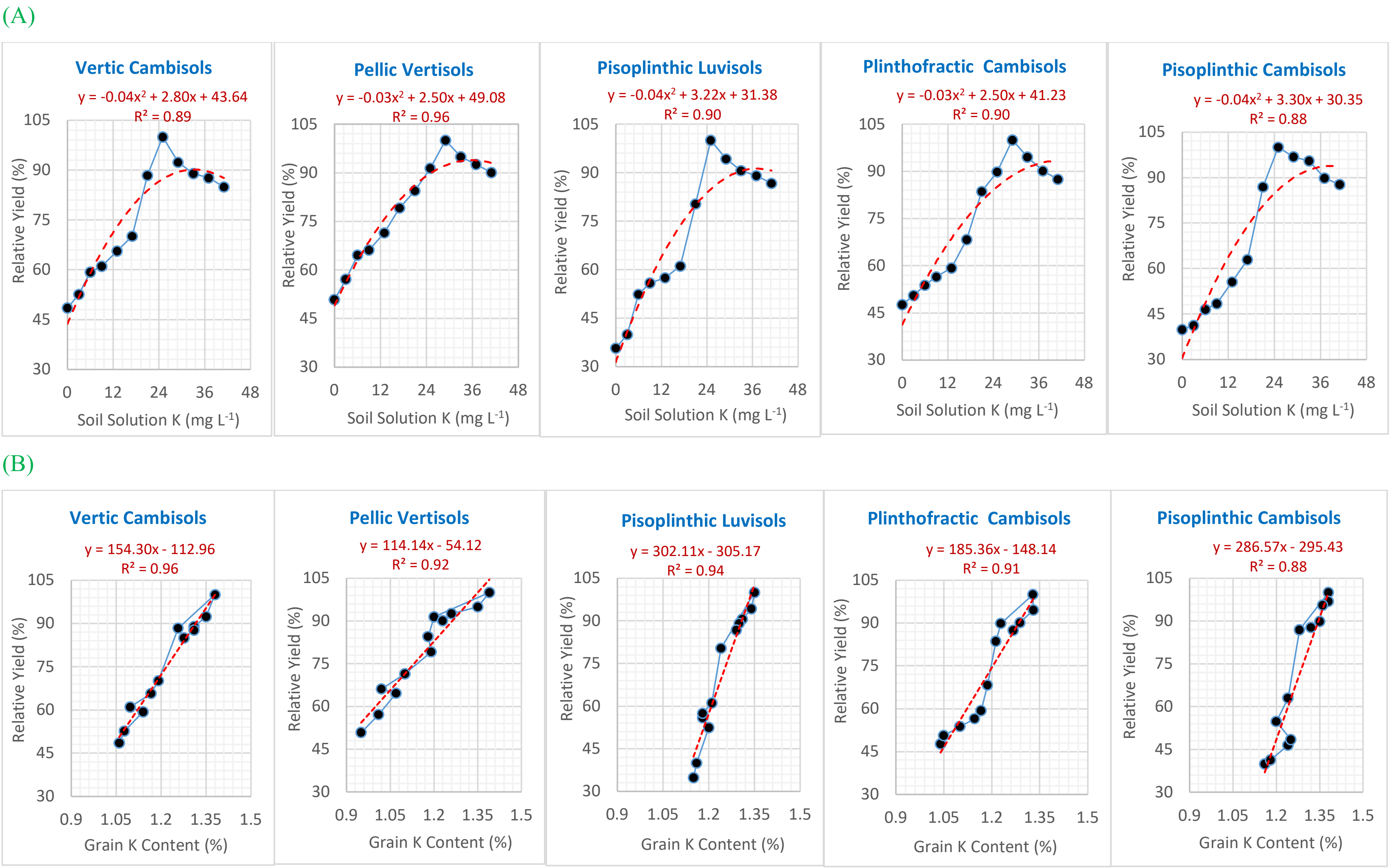

Figure 5. 1. External (A) and internal (B) potassium requirements of wheat

5.4. Conclusion

The soil's available K content and the crop's K demand were considered to optimize K fertilizer for better wheat crop growth and yield at the study area, as plants utilize K in controlled amounts until attaining their critical concentrations. That means an optimized K fertilization of this research recalls the concept of internal and external requirements in the nutrient adsorption isotherm technique. The results of this study revealed that application of the different rates of K to all soils had a very highly significant effect ($P < 0.001$) on plant height, spike length, numbers of fertile tillers per plant and seeds per spike, biomass and grain yields, and tissue K content and harvest index of wheat. Generally, omission of K resulted in lower wheat growth, yield, and K utilization compared to K-treated soils. However, such results exhibited an overall increasing trend to reach their highest levels, whereby a further K addition resulted in declining values. This implies that the wheat plant requires adequate amounts of soil K nutrition for attaining better plant growth, yield, and K concentrations.

Vertisols and soils with a vertic nature showed a better effect on growth, yield, and tissue K contents of wheat than the Cambisols and Luvisols, probably because of the smectitic clays that strongly adsorb and slowly release K for effective crop utilization. The data on external and internal K requirements of the experimental soils were fitted best to the quadratic plateau and linear regression model, respectively. Therefore, the models estimated the optimum K in soil solution (24.48 to 30.75 mg K L^{-1}) and grain (1.19 to 1.30%) for near maximum (95%) yield of wheat at the study area. However, further research is needed to validate the results and enhance profitable wheat production through formulating balanced fertilization of K and other essential elements along with vital agronomic management practices (split K fertilization schedules, water management, and crop rotation) under field conditions.

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6. NATURE AND EFFECTS OF POTASSIUM CONTAINING AMENDMENTS ON SELECTED CHEMICAL PROPERTIES OF SOILS OF QENBERENAWETI SUB-WATERSHED, CENTRAL HIGHLANDS OF ETHIOPIA

Haymanot Awgchew[1,2], Sheleme Beyene[1], Alemayehu Kifilu[1], Asmare Melese[2]
[1]School of Plant and Horticultural Science, Hawassa University, Ethiopia
[2]Department of Plant Science, Debre Berhan University, Ethiopia

ABSTRACT

The availability and overall state of soil chemistry should be considered when applying K-containing fertilizers to sustain the use of soils. This study assessed the effects of potassium (K)-containing inorganic (muriate of potash, MOP) and organic (cattle manure ash, CMA) amendments on the chemical properties and K availability of five different soil types (Vertic Cambisols, Plinthofractic Cambisols, Pisoplinthic Cambisols, Pellic Vertisols, and Pisoplinthic Luvisols). A total of 15 recently produced (not exceeding a week) cattle dung-cake ash sub-samples were collected, thoroughly mixed, and three composite samples were made for the analysis of total elemental composition and chemical characteristics. Besides, a two-month incubation experiment was tested using ten treatments with varying MOP:CMA ratios (0:100 to 100:0) under greenhouse conditions. Results demonstrated that 100% CMA application increased the soil pH values by 0.48–0.57 units due to its alkaline reaction (pH = 9.12) and base cations (Ca, Mg, K, and Na) composition, counteracting the soil acidity. Conversely, 100% MOP slightly raised pH by 0.06–0.13 units but increased salinity by 0.78–0.86 dS m^{-1} above the control because of chloride accumulation. The CMA increased the OC by 0.23–0.38% and CEC by 11.26–13.99 $cmol^{+}$ kg^{-1} better than MOP via providing stable organic matter and mineral inputs. The slow-release K (47,996–48,127 mg kg^{-1}) of CMA and the quick solubility of MOP combined in intermediate CMA:MOP ratios (37.5:62.5–62.5:37.5) yielded the highest K availability (1.75–2.01 $cmol^{+}$ kg^{-1}). Cattle manure ash alone raised P availability (7.67–9.50 mg kg^{-1}) over the control due to alkaline dissolution of phosphate minerals, while MOP's chloride ions at higher doses enhance P fixation (1.24–2.86 mg kg^{-1}). The increased buffering capacity of Vertic Cambisols and the susceptibility of Pisoplinthic soils to acidity were demonstrated by soil-specific responses. These research results justify the use of integrated amendments to enhance long-term soil fertility in a specific agroecosystem, to reduce acidity and optimize K cycling by highlighting CMA's dual role as a liming agent and a source of nutrients. Future studies on the species richness and activity of soil microbial communities, as well as the function of CMA in carbon sequestration and heavy metal mitigation, are necessary to have a comprehensive understanding of sustainable agriculture through CMA application.

Keywords: cattle manure ash, muriate of potash, soil incubation, nutrient management, soil fertility, balanced application.

6.1. Introduction

The nature and rate of fertilizers determine the state of potassium (K) nutrition by influencing the physical and chemical properties of soils (Adekiya *et al*., 2020; Blanchet *et al*., 2017). The amount and type of clays, pH, organic matter (OM), cation exchange capacity (CEC), and other cations in the soil are the important ones (Bilias and Barbayiannis, 2019; Auge *et al*., 2017). Fortunately, none or less amended soils can derive their K demand into a negative balance through the weathering process (Finlay *et al*., 2020; Vadeboncoeur *et al*., 2014). In spite of the bio-uptake and leaching loss, a surplus of K in the soil solution after proper fertilization transfers to its diverse forms via a fixation process (Reimer *et al*., 2020; Yadav and Sidhu, 2016). Hence, it increases the total K content of the soils (Sreelakshmi, 2021) by maintaining the exchangeable pool constant over time with a positive balance (Das *et al*., 2019; Haberman *et al*., 2019).

The overall soil properties, including K status, are affected by the application of K-containing organic and/or inorganic amendments (Shahrokh *et al*., 2019; Abdel-Rahman, 2014). In this regard, muriate of potash (potassium chloride) and ash (leftover of biomass burning process) are the two commonly used types of K-fertilizers (Sreelakshmi, 2021). Besides the soil properties, the K-free fertilizers also affect the important features of K in the soils (Yakovleva *et al*., 2020). The K distribution in soils near monocalcium phosphate placement sites is influenced by interactions with Al/Fe ions (Meyer *et al*., 2020). Mono-ammonium phosphate releases more K than ammonium chloride in several soils due to the dissolution of K-bearing minerals (Huo-Yan *et al*., 2010). A decline in isomorphic substitution of K^+ by NH_4^+ occurs in the order of ammonium bicarbonate, ammonium chloride, and diammonium phosphate (Wang *et al*., 2010).

Muriate of potash (MOP) contains about 52% K by weight, making it the most effective source of K in soil nutrition (Yahaya *et al*., 2023). The MOP (KCl) is a readily water-soluble inorganic fertilizer that enriches soils with a rapid supply of K (Wakeel and Ishfaq, 2022; Yager, 2016). Potassium chloride is a neutral salt ($pH \approx 7$) that does not contribute to the soil acidity or alkalinity (Ganeshamurthy *et al*., 2023). However, its excessive and repetitive applications upsurge the soil pH and salinity levels that disrupt the uptake of Ca and Mg ions as well as the CEC via causing nutrient imbalance and mineral crystals in the soil system (Yu, 2022; Mikkelsen and Roberts, 2021). Generally, excessive KCl use has more indirect impacts on the physical properties of soils (Pahalvi *et al*., 2021). For example, the unique interaction of K^+ with clay particles and OM determines the stability of soil aggregates (Feller *et al*., 2020). However, the resultant salinization deteriorates the soil structure, causing poor permeability and infiltration (Cuevas *et al*., 2019; Mohamed, 2017).

Cattle manure ash (CMA), a byproduct of the burning of animal excreta (dung + urine), is an organic fertilizer (Parihar *et al*., 2019) rich in essential elements such as K, Ca, Mg, P, S, Mn, Cu, Zn, etc (Dhiman *et al*., 2021). Unlike KCl, CMA consists of a blend of nutrients in both soluble and insoluble forms, making it more stable and slow-release of nutrients (Singla *et al*., 2024; Ramos *et al*., 2020). The key benefit of CMA is its long-term capability to improve physicochemical properties with a crucial effect for OM-poor soils (Ayamba *et al*., 2021; Font-Palma, 2019). The cationic contents of CMA directly contribute to the aggregation of soil particles to improve soil structure and porosity, which further optimizes the soil water status (Adekiya *et al*., 2020). Manure ash counteracts soil acidity due to its high Ca, Mg, and/or K compositions that raise the soil pH and promote optimal conditions for plant nutrient availability and uptake (Susianti *et al*., 2022; Meena *et al*., 2019). Moreover, CMA increases the OM content of a soil to enrich it with a diverse and active microbial community (Hanudin *et al*., 2021), which in turn enhances the CEC and K cycling (Taiwo *et al*., 2018). This leads to a temporary K buildup in the upper soil layers, as the OM-bound K is leached only when an equilibrium with the soil is attained (Matisic *et al*., 2024; Blanchet *et al*., 2017). Therefore, the aforementioned chemical properties and nutritional compositions of CMA show its promise as an alternative source of soil fertilizer in countries like Ethiopia (Worku *et al*., 2023).

The natural mineral content, burning conditions, and manure origin are some important factors that affect the chemical composition and characteristics of CMA (Aremanda *et al*., 2023). For instance, a source from free-range cattle manure often has higher silica content than industrial farming, which is richer in calcium (Maj *et al*., 2022). The high silicon and calcium contents are capable of diluting P and K concentrations (Komiyama *et al*., 2013). The reduction rate of solid materials during incineration at diverse environmental conditions directly influences nutrient concentration in the ash (Jiang *et al*., 2020). The combustion process can also lead to the formation of various chemical compounds, including hydroxyapatite, which are relevant for fertilizer applications (Tran *et al*., 2017; Komiyama *et al*., 2013). Variations in P and K amounts are observed due to the type of cattle and their diet (Samoraj *et al*., 2022; Komiyama *et al*., 2013). Thus, consideration of these factors is vital to optimize the utilization of manure ash as a fertilizer source (Yun *et al*., 2023; Guo *et al*., 2021).

The by-products of animal origin tend to have higher levels of nutrients than the plant-based ones (Fazira *et al*., 2024; Khairul *et al*., 2024), suggesting that inputs from animal sources exhibit a better role for sustainable soil fertility and nutrient availability (Neethu and Vardhanan, 2023; Yassin *et al*., 2020). Nowadays, ash derived from livestock manure has been considered as an optional K fertilizer (Tran *et al*., 2018) having a K recovery of 56-95% (Huang *et al*., 2011) and composition of 4-5% (Komiyama *et al*., 2013). In addition, nearly 91% of K in CMA is water-soluble, making it readily available for plant uptake (Tran *et al*., 2018). In general, 1-5 tons per hectare is a common range for applying cattle manure ash as a K fertilizer (Soretire and Olayinka, 2013). Despite the benefits of the MOP and CMA on the overall soil fertility and K availability, there are some gaps besides their unwise utilization on different soils at a site-specific level (Ludwig, 2013). Consequently, there is an emerging need to counter the negative effects of the solo MOP or CMA (Hong *et al*., 2021). Because of the long-term effects of KCl and CMA on most physical properties of soils (Ayamba *et al*., 2021), their influence on K availability and related chemical properties is getting due attention (Shao *et al*., 2024).

Since cattle dung-cake (air-dried manure) is a chief biofuel energy source in the study area, there is an adequate supply of K-containing organic fertilizer (CMA). Unfortunately, the experience of using it as an alternative soil amendment is poor due to the wrong perception of considering ash as a waste material. Moreover, the effects of integrated K fertilization on soil chemical properties, including K availability in different soil types, have not yet been studied in Ethiopia and in the research area. Generally, the availability of nutrients and the overall state of soil chemistry should be considered when applying K-containing fertilizers for sustainable soil usage (Vijayakumar *et al*., 2024; Basak *et al*., 2022). Therefore, this research component was proposed to analyze the effects of K-containing organic and inorganic amendments on selected soil chemical properties and the availability of K in soils of the sub-watershed.

6.2. Materials and Methods

6.2.1. Sampling and analysis of cattle dung-cake ash

A total of 15 recently produced cattle dung-cake ash sub-samples, each with about ten kilograms per homestead level, were collected randomly throughout the study area. The sub-samples were intermixed into a composite on a ceramic-faced floor under dust-free conditions and passed through a 0.5 mm sieve. Then, the composite sample was prepared systematically in triplicate for the analysis of its total elemental concentrations. The total amounts of OC and N were determined by Dumas's combustion method, which ignited the samples in a furnace at 900 °C (Peters *et al.*, 2003). Besides, the total P, Ca, Mg, Na, and K contents were analyzed in suspensions from dry-ashing at 550 °C for 5 hours, digestion with 4 ml diluted HNO_3 (1:1) on a hot plate set at 120 °C, and dissolution by 10 ml diluted HCl (1:1). Hence, the P content was obtained via vanado-molybdate colorometric procedure using spectrophotometer at a 460.0 nm wavelength (Peters *et al.*, 2003). The K and Na concentrations were determined by flame photometer, whilst the Ca and Mg contents were with the atomic absorption spectrometer (AAS) at wavelengths of 589.0, 766.5, 422.7, and 285.2 nm, respectively (Peters *et al.*, 2003). The pH and EC values (sample to water ratio of 1:10) were measured by using pH and EC meters, respectively (Peters *et al.*, 2003).

6.2.2. Soil incubation trial

Twelve sub-samples of surface soil (0-20 cm) were collected in zig-zag fashion from three typical farmlands per each of the five most ploughed soils of the study area. The soil types were Vertic Cambisols, Plinthofractic Cambisols, Pisoplinthic Cambisols, Pellic Vertisols, and Pisoplinthic Luvisols. The air-dried sub-samples were ground using a pestle and mortar, sieved with a 5 mm mesh, mixed thoroughly, and prepared into a composite sample of their respective groups. Then, the composites were accordingly incubated in duplicate by inorganic (muriate of potash) and/or organic (cattle manure ash) K sources for two months under greenhouse conditions.

The treatment effects were taken from the optimum external K requirement of each soil group determined in Chapter 5 (Experiment 4) in accordance with a substitutable percentage proportion of the inorganic-to-organic K sources. The optimum K rates for the Plinthofractic Cambisols, Pisoplinthic Luvisols, Pisoplinthic Cambisols, Vertic Cambisols, and Pellic Vertisols were 113.40, 114.02, 125.96, 138.32, and 149.24 kg ha^{-1}, respectively. Ten treatments made up the control (trt 1 = 0:0) factor and K amendments as the ratio of the inorganic to organic sources (trt 2 = 0:100, trt 3 = 12.5:87.5, trt 4 = 25:75, trt 5 = 37.5:62.5, trt 6 = 50:50, trt 7 = 62.5:37.5, trt 8 = 75:25, trt 9 = 87.5:12.5, and trt 10 = 100:0). Generally, the ideal nutrient flow depth (20 cm) and bulk density (1200 kg m^{-3}) of disturbed soils (Wogi *et al.*, 2021) were considered during the incubation, which made for a one kg dose in a plastic cup and kept to continuous wetting-drying cycles at field capacity.

6.2.3. Soil sample preparation and analysis

After two months of the incubation trial, the treated soil samples were air dried, ground to pass through sieves of 2 and 0.5 mm, and analyzed for selected soil chemical properties (pH, EC, OC, Av. P, TN, Ex. bases, and CEC) as per the standard procedures described in Section 2.2.2.

6.3. Results and Discussion

6.3.1. Chemical characteristics and compositions of cattle manure ash

The mean pH value of the cattle manure ash (CMA) samples was 9.12 ± 0.04 (Table 6.1). Though the pH can vary depending on the extent of temperature during combustion (Smith *et al*., 2020) as well as the farming practices and specific feed composition (Maj *et al*., 2022), CMA exhibits a base reaction nature (Font-Palma, 2019). The alkalinity of CMA primarily occurs due to the presence of oxides/hydroxides and carbonates of basic cations formed during the combustion process (Olowoboko *et al*., 2018b). The subsequent increase in pH with temperature was pointed out by Atienza-Martínez *et al*. (2020) which was related to the release of acidic surface functional groups (Zhang *et al*., 2021) and to the enrichment in alkaline elements such as Ca^{2+}, Mg^{2+}, and K^{+} (Chen *et al*., 2024; Ruiz-Gómez *et al*., 2017). Moreover, CMA is rich in calcite ($CaCO_3$) and fairchildite ($K_2Ca(CO_3)_2$) carbonates (Vamvuka and Raftogianni, 2021). This result is in line with the work of Lee *et al*. (2022), which indicated a pH of 9-12 for manure-derived ashes.

The electrical conductivity (EC) value of the CMA sample ranged from 1.84 to 1.99 dS m^{-1} (Table 6.1). Cattle manure ash often has a salty property (Olowoboko *et al*., 2018b) due to the presence of soluble salts (chloride and/or sulphate of Ca, Mg, K, and Na) formed during combustion (Rao, 2023). The EC of CMA may be altered by the specific characteristics and mineral composition of the manure, as well as the burning process (Atienza-Martínez *et al*., 2020). Variations in EC values can also arise from differences in the nutritional profiles of the manure's source, such as dairy versus beef (Tsai and Liu, 2016). According to Hong *et al*. (2021), the conductivity of ash is influenced by its mineral composition, such as calcium oxide (CaO) and phosphorus pentoxide (P_2O_5). The EC of the ash produced by treating cow dung with the thermophilic aerobic oxidation method often ranges from 3.48 to 4.6 dS m^{-1} (Kim *et al*., 2013). Cattle manure ash exhibits significant salinity, whereby studies indicate EC values that can reach up to 3.91 dS m^{-1} (Hernández *et al*., 2011). Cattle manure ash typically has EC values of 1.0-5.0 dS m^{-1}, based on the specific conditions of combustion and original manure composition (Darapuneni *et al*., 2009).

As shown in Table 6.1, there was no detectable amount of total nitrogen (TN) in the CMA samples, while the average total organic carbon (TOC) content was 0.18 ± 0.03%. The results implied that the raw dung cakes have higher TOC and TN contents than their burned form (Yassin *et al*., 2020). Because significant amounts of these elements are lost through gasification and volatilization in the burning process (Yassin *et al*., 2020; Komiyama *et al*., 2013). Similarly, Olowoboko *et al*. (2018a) reported that CMA typically contains a notable amount of TOC and TN even after the combustion process.

Table 6. 1. Equivalence test of chemical characteristics and composition of cattle manure ash

Parameters		Sample 1	Sample 2	Sample 3	Mean	SD
pH-H_2O (1:10)		9.07	9.13	9.15	9.12	±0.04
EC (dS/m)		1.84	1.90	1.99	1.91	±0.08
Total OC (%)		0.21	0.18	0.16	0.18	±0.03
Total N (%)		ND	ND	ND	ND	ND
Total P	(mg kg^{-1})	23,366.0	23,511.0	23,439.0	23,438.67	±72.51
Total Ca		81,924.0	81,973.0	82,005.0	81,967.33	±40.80
Total Mg		16,983.0	17,132.0	17,040.0	17,051.67	±75.18
Total K		48,127.0	47,996.0	48,089.0	48,070.67	±67.40
Total Na		1,155.0	1,182.0	1,204.0	1,180.33	±24.54

ND: Not detected

The total phosphorus (TP) concentrations in the CMA samples were recorded as 23,366.0-23,511.0 mg kg^{-1} (Table 6.1). Yassin *et al*. (2020) reported that TP is higher in the charred material due to the release of organic P bound in the bulky raw dung cake. Though it is sufficient to supply P, especially in P-deficient soils, the TP content of CMA is widely fluctuating (Li *et al*., 2019), with a range of 4.09 to 23.73% P_2O_5 based on the source (Maj *et al*., 2022). Similarly, CMA contains a high concentration of TP, of which over 90% can be extracted using citric acid (Tran *et al*., 2018). The P concentration can reach levels comparable to phosphate rock when incinerated (Komiyama *et al*., 2013).

The mean compositions of total Ca and Mg were 81,967.33 and 17,051.67 mg kg^{-1}, respectively (Table 6.1). According to Komiyama *et al*. (2013), the concentration of Ca is often higher than the other basic cations in CMA due to the substantial existence of hydroxyapatite ($CaPO_4$). This mineral is essential to the overall nutrient recovery processes and the subsequent separation of P-Ca (Thinh, 2018; Oliveira *et al*., 2016). Contempt its dolomite ($CaMg(CO_3)_2$) mineralogy (Chen *et al*., 2019), CMA exhibits Mg mostly in the form of oxide, sulfates, and chlorides formed during the combustion process (Shi *et al*., 2023).

The accumulations of total potassium (TK) in the CMA were ranging between 47,996.0 and 48,127.0 mg kg^{-1} while the total sodium was in the range of 1,155.0–1,204.0 mg kg^{-1} (Table 6.1). In addition to the lower quantities of Na (Sager, 2007; Shepherd *et al*., 2002), the TK content in the CMA exceeds the total Na due to its higher natural abundance in the cattle feed (Olowoboko *et al*., 2018a) and efficient retention in manure (Aremanda *et al*., 2023). Besides, the chemical characteristics of K make it more stable during the incineration process (Tran *et al*., 2018; Komiyama *et al*., 2013), while over 20% of the Na content in CMA is reduced through the leaching effect (Oshita *et al*., 2016).

Furthermore, the results of the laboratory investigation revealed that the CMA had more K than Mg. This is most likely because of the manure's natural nutrient composition, chemical properties, organic matter selectivity, and burning process. According to Oshita *et al*. (2016), feed, bedding materials, and manure management practices increase the inherent K levels in cattle manure over Mg. Agricultural systems also have greater K retention and excretion compared to Mg (Amachika *et al*., 2016). Though burning of organic matter importantly concentrates more divalent cations (Yi *et al*., 2018), specific monovalent complexes (e.g., K^+ with valinomycin) may enhance K retention (Hakim *et al*., 2021). The less volatility and more solubility of K than Mg during combustion can also increase its relative abundance in the ash (Ma *et al*., 2021; Komiyama *et al*., 2013). The highest Ca in manure reduces Mg availability via competitive retention (Yi *et al*., 2018; Komiyama *et al*., 2013). According to Komiyama *et al*. (2013), the hydroxyapatite specially retains K because of its larger ionic radius (weaker electrostatic interaction) while Mg's higher hydration energy impedes its adsorption.

6.3.2. Effects of potassium amendments on selected soil chemical properties

The pH values of the experimental soils ranged between 5.65 and 6.42 with changes in the CMA and muriate of potash (MOP) mixture (Table 6.2). The results are rated as moderately and slightly acidic conditions (Wogi *et al*., 2021). Generally, the control treatment 1 (0% CMA: 0% MOP) of the whole soils showed the lowest reaction level, which progressively increased by 0.48 to 0.57 units upon rising the CMA proportion to 100% (Treatment 2). The higher pH at treatments 2 and through 6 (50% MOP: 50% CMA) or 7 (62.5% MOP: 37.5% CMA) could imply alkalinizing effect due to the presence of basic compounds (oxides and carbonates of Ca, Mg, and K) in the CMA, indicating its liming role to ameliorate soil acidity (Hanudin *et al*., 2021; Yi *et al*., 2018). Thereby, enhancing microbial activity and nutrient availability statuses of the soils (Holatko *et al*., 2022). Conversely, the pH gradually declined as the percentage of KCl reached to 100 over the CMA (Treatment 10) but still higher by 0.06 to 0.13 units when compared to the control. This pattern reflects how the high chloride ion content of MOP can potentially have an acidifying effect by displacing bicarbonate and calcium and magnesium hydroxides from the colloidal surface while enriching it with exchangeable K. The combination of KCl and CMA (Treatments 3-9) likely led to a transitional effect on pH at which treatments 6 and 7 had a notable convergence in pH of the entire soils, suggesting a point of equilibrium to maintain optimal pH levels for better performance of most plants (Shao *et al*., 2024; Hanudin *et al*., 2021). Although there were some general trends of pH declining across the treatments in each soil, Vertic Cambisols showed highest pH values, while the Pisoplinthic Cambisols and Luvisols had the lowest pH. Thus, it proves the specific treatment effects in relation to the buffering capacity of each soil (Shetty *et al*., 2019).

Table 6. 2. Reaction and salinity levels of the study soils

Treatment	Parameters									
	pH-H_2O (1:2.5)					EC (dS m^{-1})				
	Soil types									
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	5.86	5.91	5.73	5.65	5.70	0.12	0.17	0.10	0.15	0.14
2	6.35	6.42	6.30	6.16	6.18	0.98	1.02	0.89	0.96	0.92
3	6.29	6.39	6.24	6.10	6.11	0.87	0.94	0.78	0.85	0.83
4	6.26	6.33	6.17	6.13	6.07	0.79	0.81	0.68	0.73	0.64
5	6.21	6.27	6.15	6.08	6.03	0.66	0.76	0.59	0.64	0.57
6	6.23	6.19	6.09	6.06	6.04	0.58	0.69	0.61	0.56	0.51
7	6.12	6.20	6.10	6.01	5.96	0.49	0.62	0.52	0.49	0.45
8	5.97	6.14	6.05	6.02	6.00	0.38	0.55	0.44	0.40	0.47
9	6.01	6.07	5.92	5.94	5.98	0.30	0.42	0.32	0.35	0.36
10	5.93	5.99	5.80	5.78	5.76	0.21	0.29	0.18	0.26	0.24

Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols

The lowest (0.10 dS m^{-1}) and the highest (1.02 dS m^{-1}) electrical conductivity (EC) values of the soils were recorded at Treatments 1 (control) and 2 (0% MOP: 100% CMA) on the Pisoplinthic and Vertic Cambisols, respectively (Table 6.2). According to Wogi *et al*. (2021), all the study soils are characterized as non-saline. The laboratory results revealed that increasing the CMA to 100% notably increased the salinity approximately by 5-7 times over the control. This is attributed to the soluble salts and minerals in the CMA that dissolve and concentrate ions in the soil solution (Olowoboko *et al*., 2018b; Oshita *et al*., 2016). The effects of Treatment 10 (100% MOP: 0% CMA) raised the salinity over the control in all soils, but to a smaller extent than the corresponding CMA. The rise in soil EC may be due to the addition of K and Cl ions, as MOP is a salt-based fertilizer (Yang *et al*., 2024; Cancellier *et al*., 2018). However, the lower increments than the CMA could be attributed to the readily soluble nature of KCl, which might increase the dilution of some accumulated salt (Thinh, 2018). Additionally, a general decrease in soil salinity with minor variation was observed across all soil types as the proportion of CMA decreased and KCl increased (Treatments 3 through 9). The salt load from the CMA is probably diluted by the gradual addition of KCl (Mikkelsen and Roberts, 2021; Masís-Meléndez *et al*., 2020). This proves that the type and quantity of amendments have a substantial effect on soil salinity, showing their effects as combined application are not always additive (Oueriemmi *et al*., 2025; Liu *et al*., 2023). Thus, the mixture of these inputs produced a suitable EC range for the potential growth of most crops (Shao *et al*., 2024; Ding *et al*., 2020).

As indicated in Table 6.3, the organic carbon (OC) contents of the study soils varied between 2.03 and 2.51% after treatment, at which the solo CMA treatment had a better contribution (0.23-0.38%) than its counterpart MOP (0.02-0.04%) over the control. Besides, there was a general trend of a slight decrease in OC values with increasing KCl dose to 100% while the CMA was declining (Treatments 3-10). The soil OC (SOC) contents are categorized under the medium range (Wogi *et al*., 2021). The increase in OC most likely arises from the presence of stable and recalcitrant C compounds in CMA (Cantrell *et al*., 2012) that might be beneficial for long-term soil structural aggregation and nutrient retention (Zhang *et al*., 2024). Since incineration of cattle manure ends its ash with a stable C property (Gunamantha *et al*., 2022), the direct addition of CMA significantly enhances the amount of SOC (Olowoboko *et al*., 2018a) by favoring microbial activity and diversity (Bougnom *et al*., 2020).

On the other hand, the decreasing trends due to mixed usage of MOP and CMA could be related to the indirect role of MOP in modifying the microbial function and composition as well as physical characteristics of the soil (structure and moisture). The application of K improves soil structure to boost microbial respiration (Kaewu, 2024), which is vital for better decomposition of OM and stabilization of OC in the soil (Chen *et al*., 2020). Applying KCl fertilizer promotes the growth and diversity of microbial communities (Schwalb *et al*., 2024). Particularly, it boosts the abundance of beneficial bacteria like Bacteroidetes and Mortierellomycota, which are associated with improved metabolic activity and carbon utilization (Song *et al*., 2024).

Table 6. 3. Organic C, total N, and available P concentrations in the study soils

Treatments	Parameters														
	Organic C (%)					Total N (%)					Available P (mg kg^{-1})				
	Soil types														
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	2.15	2.03	2.10	2.17	2.25	0.16	0.15	0.17	0.14	0.16	15.52	14.83	14.16	13.30	13.94
2	2.38	2.41	2.39	2.48	2.51	0.12	0.13	0.15	0.13	0.15	23.19	24.33	22.71	21.33	21.78
3	2.34	2.35	2.36	2.45	2.47	0.14	0.13	0.17	0.14	0.15	25.80	25.07	24.86	23.48	23.37
4	2.30	2.33	2.34	2.46	2.43	0.15	0.15	0.19	0.17	0.17	26.77	27.79	26.29	26.81	24.25
5	2.29	2.31	2.30	2.42	2.44	0.15	0.14	0.18	0.16	0.17	27.98	27.61	30.90	29.47	27.91
6	2.27	2.32	2.31	2.38	2.40	0.17	0.16	0.21	0.18	0.18	35.65	33.29	31.74	28.20	29.04
7	2.28	2.26	2.27	2.35	2.37	0.17	0.18	0.20	0.19	0.18	32.35	36.18	28.94	25.39	26.87
8	2.24	2.25	2.22	2.32	2.34	0.16	0.16	0.19	0.17	0.17	24.37	23.32	20.55	19.56	20.45
9	2.21	2.16	2.19	2.26	2.30	0.16	0.17	0.18	0.15	0.17	20.28	21.44	18.92	17.23	18.57
10	2.18	2.05	2.14	2.20	2.28	0.17	0.18	0.19	0.15	0.16	18.10	17.69	16.05	15.95	15.18

Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols

Several studies reveal that the application of K contributes to SOC dynamics that can lead to a significant increase in easily oxidizable OC (Kaewu, 2024), further enhancing the overall cycling of the SOC pool (Kong *et al*., 2024). Although KCl promotes SOC accumulation, it is essential to consider the potential for imbalanced fertilization, which may lead to decreased soil biological quality in certain contexts, particularly in K-rich soils (Chen *et al*., 2020). The combination of organic and inorganic fertilizers, including KCl, is most effective in enhancing SOC content and stability (Šimon *et al*., 2024). Moreover, studies show that balanced fertilization can improve soil C fractions and stability, leading to increased SOC levels over time (Yang *et al*., 2023; Dutta *et al*., 2022). Hence, the KCl alone has no discernible effect on the SOC (Zhang *et al*., 2023) and might lead to diminishing returns in SOC levels over time (Šimon *et al*., 2024; Yang *et al*., 2023).

The soils treated by 37.5 to 62.5 percent of CMA (Treatment 5 to 7) had the highest total nitrogen (TN) contents (0.17-0.21%), while those with sole CMA and KCl treatments exhibited the lowest (0.12-0.15%) and proportional (0.15-0.19%) compositions when compared to the control, respectively (Table 6.3). Nevertheless, the amounts of TN found in the soils are rated as high (Wogi *et al*., 2021). The increase could be ascribed to the synergistic roles between the nutrients available from the CMA, and the added K might have enhanced N utilization in the soil (Havlin *et al*., 2017). Combined application of CMA and MOP may optimize the soil's C:N ratio (Wang *et al*., 2019), which promotes microbial activity and subsequently N cycling (Xu *et al*., 2017). The reduced carbon input from the lower CMA proportion could minimize the C:N ratio of the soil (Sohail *et al*., 2019), which in turn accelerated the rate of N mineralization (Eckhardt *et al*., 2018). The decline in TN concentrations might be due to CMA's relatively small N reserve and its ability to temporarily immobilize N in the soil (Olowoboko *et al*., 2018a). Moreover, by influencing soil microbial activity, the proportionate amount of TN brought about by the unique application of MOP may indirectly enhance N mineralization (Pereira *et al*., 2019). This could consequently raise the soil's TN levels by increasing the amount of N that is available (Ali *et al*., 2021). The type of organic amendments used and their effects on crop development and soil health can significantly alter the ideal C:N ratio in agricultural soils (Singh *et al*., 2024), which is often taught as 20-30 (Abak and Sakin, 2018). Research indicates that organic amendments with C:N ratios of 10 to 20 are recommended to maximize crop biomass and optimize N availability based on the C:N ratios of soils (van der Sloot *et al*., 2022).

The available phosphorus (Av. P) contents of the experimental soils were low under the control condition (13.30-15.52 mg kg^{-1}) and increased gradually to the peaks (29.04-36.18 mg kg^{-1}) upon the addition of proportional CMA-MOP, with a better effect from the CMA than the MOP (Table 6.3). The experimental soils were categorized as medium (10-17 mg kg^{-1}), high (18-25 mg kg^{-1}), and very high (>25 mg kg^{-1}) in their Av. P quantities (Wogi *et al*., 2021). The highest soil Av. P contents were obtained from the balanced (50:50) use of CMA and KCl (Treatment 6), except for treatments 5 (37.5% MOP: 62.5% CMA) and 7 (62.5% MOP: 37.5% CMA) on the Plinthofractic and Vertic Cambisols, respectively. The balanced usage increased the P availability over the control (15.10–21.35 mg kg^{-1}). This might reveal a synergistic effect among the amendments, as the KCl improves the solubility and release from CMA via altering soil ionic strength, displacing phosphate ions from soil adsorption sites, and shifting the composition of the microbial community (Tran *et al*., 2018; Havlin *et al*., 2017).

Specific microbial communities, such as phosphate-solubilizing bacteria, thrive in the presence of organic amendments, improving P availability for plants (Fan *et al*., 2023). However, the Av. P content declined with the rising share of KCl (Treatments 8-10), indicating that an excessive composition of K ions might interfere with P availability. Besides enhancing the microbial diversity and activity (Bougnom *et al*., 2020), the greater role of CMA in releasing P into the soil solution is concerned with its alkaline nature (Aboltins *et al*., 2020) and the presence of readily soluble P compounds (Tran *et al*., 2018; Tran *et al*., 2017). Thus, it promotes the P availability (Bougnom *et al*., 2020) via increasing the concentrations of both inorganic and organic P fractions in the soils (Mao *et al*., 2023; Tran *et al*., 2017). In spite of its lower pronounced effect than the CMA, the sole application of KCl could marginally raise the Av. P over the control due to its significant influences on ionic strength and P sorption reactions that change the soil pH and cation exchange dynamics (Meyer *et al*., 2020; Tran *et al*., 2017).

The maximum exchangeable calcium (Ex. Ca) amounts (26.85 to 30.60 cmol+ kg^{-1}) were found upon the incorporation of 100% CMA, which caused increases of 7.11 to 9.42 cmol+ kg^{-1} when compared to the control (Table 6.4). As the proportion of MOP in the treatment mixtures increased (Treatments 3-9), the Ex. Ca showed a decreasing mode. The application of 100% KCl resulted in the lowest Ex. Ca, though the values were still higher than those found in the control. This revealed that a high dose of KCl alone is involved poorly in the release of Ca ions existing between the colloidal lattice. Because the intermediate Ca content of the control treatment suggests that some Ex. Ca was already supplied by the initial soil conditions. Apart from the few with a high amount of Ex. Ca at the Plinthofractic Cambisols and Pisoplinthic Luvisols, almost all the study soils had a very high level of Ex. Ca (Wogi *et al*., 2021). The presence of high Ca content in CMA can directly contribute to the increase of Ex. Ca in soils (Komiyama *et al*., 2013), whilst the alkaline nature of the ash can reduce soil acidity to indirectly enhance Ca availability and other base cations saturation in soils (Bougnom *et al*., 2020).

An antagonistic relationship amongst KCl addition and Ca retention in soils is suggested by the reduction in Ex. Ca with increasing MOP additions (Havlin *et al*., 2017). According to Weil and Brady (2017), K^+ and Ca^{2+} ions compete for binding sites on soil colloids, which explains the observed decrease in Ex. Ca with higher MOP application. The preferential adsorption of K^+ in soils might reduce Ca^{2+} in the exchangeable sites by displacing Ca into the soil solution, which is more susceptible to leaching or uptake (Havlin *et al*., 2017). Furthermore, by increasing the soil solution's ionic strength, MOP may affect the solubility and availability of Ca via complexation mechanisms (Najafi-Ghiri *et al*., 2019).

Table 6. 4. Concentrations of exchangeable divalent cations in the study soils

Treatment	Parameters									
	Exchangeable Ca (meq $100g^{-1}$)					Exchangeable Mg (meq $100g^{-1}$)				
	Soil types									
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	21.49	21.95	20.19	18.67	19.25	9.02	9.59	9.61	9.47	9.25
2	30.60	29.58	28.74	26.85	28.67	13.05	13.44	14.07	14.56	14.49
3	28.89	28.45	27.11	25.30	26.49	12.75	12.96	13.69	13.88	14.13
4	27.12	27.36	26.14	24.18	25.33	12.40	12.83	12.91	13.35	13.97
5	26.04	26.29	25.66	23.81	24.81	11.95	12.39	12.10	12.94	13.15
6	25.37	25.14	24.31	23.26	24.00	11.15	11.90	11.57	12.30	12.87
7	24.92	24.65	23.79	22.61	23.42	10.60	11.46	10.95	11.80	11.48
8	24.20	23.60	22.84	21.53	22.78	9.90	10.75	10.20	11.55	10.66
9	23.56	22.80	21.73	20.36	21.39	9.51	10.00	9.93	10.43	9.85
10	22.87	22.18	20.98	19.41	20.64	9.23	9.76	9.79	9.65	9.54

Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols

The smallest (9.02 to 9.61 cmol+ kg^{-1}) and the largest (13.05 to 14.56 cmol+ kg^{-1}) amounts of exchangeable magnesium (Ex. Mg) were recorded from the control and 100% CMA treatments, respectively, with a general declining trend when receiving the Treatments 3 to 10 (Table 6.4). The levels across different treatments reveal a very high composition of Ex. Mg (Wogi *et al*., 2021). The high Mg concentrations could be ascribed to the high Mg content in CMA (Hanudin *et al*., 2021; Tran *et al*., 2018), which is released into the soil solution through decomposition (Tran *et al*., 2017; Komiyama *et al*., 2013). Likewise, the alkaline nature of CMA improved the solubility and availability of Mg by altering the pH of the soil (Havlin *et al*., 2017). Conversely, the decreasing trend of Mg as KCl rates increased might highlight the hypothesis of cationic completion, in which K has replaced Mg on the colloidal adsorption sites (Yang *et al*., 2024).

The amount of exchangeable potassium (Ex. K) initially increased to the highest level (1.75-2.01 cmol+ kg^{-1}) with increasing MOP percentage and then declined to 1.14-1.52 cmol+ kg^{-1}, which is still greater than the control (0.95-1.16 cmol+ kg^{-1}) across all the study soils (Table 6.5). According to Wogi *et al*. (2021), the Ex. K contents are under high and very high ranges. Applications of 100% CMA caused 8.91 to 25.30 percent increments in Ex. K of all the soil over the control, which is likely due to the release of K from the ash matrix upon dissolution. Studies have shown that up to 91% of the potassium in bovine manure ash is water-soluble, indicating that potassium is highly soluble in this material (Tran *et al*., 2018). This confirms that K is readily utilized by plants and justifies CMA as a good source of soil K (Gunamantha *et al*., 2022). However, the magnitudes of increase for this treatment were less (31.04-84.71%) than the 100% KCl (Treatment 10). Although KCl is known to release K rapidly, factors such as soil texture and the potential for K fixation might have contributed to the comparatively modest gains (Portela *et al*., 2019; Yadav and Sidhu, 2016). Havlin *et al*. (2017) suggested that loss through leaching and runoff may also be influenced by the rapid release of K.

Furthermore, the highest Ex. K content was observed equivalent to equal combinations (37.5 to 62.5%) of CMA and KCl. This synergistic effect implies that the combination of organic and inorganic K sources could be more effective than either source alone (Yang *et al*., 2020). The synergy might be due to the slow release of K from CMA, while KCl provides an immediate supply, resulting in better long-term availability (Shao *et al*., 2024; Peng *et al*., 2023). Similar findings indicated that the combined usage can improve K availability and uptake (Rietra *et al*., 2017). The results advocated that a mixture with a higher CMA might be a good option for K fertilization, because it minimizes the need for high KCl input. This approach complies with sustainable agriculture principles via recycling of organic byproducts and optimizing the drawbacks due to excessive use of synthetic fertilizers (Kumar *et al*., 2024; Srivastav *et al*., 2024).

The use of 100% CMA resulted in slight increases (0.06-0.10 cmol+ kg^{-1}) of exchangeable sodium (Ex. Na) contents of the study soils, while the 100% MOP substantially increased Na (0.32-0.41 cmol+ kg^{-1}) as compared to the control (Table 6.5). Moreover, increasing the proportion of KCl in Treatments 3-9 had a pronounced effect of rising Ex. Na levels were over the control treatment in all the soils. The amounts of Ex. Na in most of the experimental soils are rated as very low and low, except for the medium level in some soils at higher KCl proportions (Wogi *et al*., 2021).

Table 6. 5. Amounts of monovalent and overall cations on the exchangeable sites of the study soils

Treatments	Parameters														
	Exchangeable K (meq $100g^{-1}$)					Exchangeable Na (meq $100g^{-1}$)					Cation exchange capacity (meq $100g^{-1}$)				
	Soil types														
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	1.01	0.98	0.83	0.76	0.87	0.07	0.05	0.04	0.05	0.04	33.74	34.30	32.64	31.25	31.44
2	1.10	1.16	1.04	0.95	1.00	0.10	0.09	0.06	0.08	0.07	46.19	45.56	45.41	44.22	45.43
3	1.26	1.23	1.12	1.13	1.06	0.17	0.12	0.09	0.10	0.11	44.54	44.34	43.57	42.28	44.13
4	1.38	1.32	1.60	1.25	1.45	0.16	0.14	0.13	0.15	0.15	42.71	43.19	42.37	40.75	42.43
5	1.93	1.64	1.74	1.69	1.59	0.20	0.18	0.12	0.13	0.19	41.67	42.39	41.20	40.47	41.45
6	1.85	1.89	1.82	1.75	1.79	0.23	0.25	0.17	0.16	0.22	40.36	41.11	39.45	39.15	40.79
7	1.68	2.01	1.52	1.54	1.62	0.25	0.27	0.21	0.24	0.26	39.37	40.22	38.35	37.77	38.62
8	1.72	1.76	1.55	1.50	1.36	0.27	0.31	0.26	0.27	0.25	37.95	37.83	36.64	36.31	36.96
9	1.57	1.49	1.43	1.42	1.21	0.36	0.35	0.30	0.29	0.28	36.80	36.23	35.28	34.29	34.67
10	1.44	1.52	1.34	1.40	1.14	0.39	0.41	0.37	0.34	0.32	35.91	35.98	34.42	33.12	33.55

Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols

The minor increases in Na by using CMA over the control might be attributed to the presence of some soluble sodium in the ash itself. Since CMA lacks the vital organic compounds that facilitate rapid cation exchange (Ayamba *et al*., 2021), there could be a weaker displacement of Na^+ from the slow mineralization process (Meng *et al*., 2019; Wang and Gaston, 2014). The observed increases in Ex. Na with sole KCl application might be due to the stronger and selective adsorption capacity of K than Na to the exchange sites of the clay mineral. The addition of K^+ from KCl can displace Na from the soil exchange complex (Li *et al*., 2021), leading to an increase in the concentration of Na^+ in the soil solution (Ronen, 2016). The trends from the combined usages of the amendments suggested that the CMA at higher proportions hinders the efficiency of MOP to displace Na than the lower rates (Yu *et al*., 2023; Kong, 2021). Such cases are well demonstrated with the concepts of changing the nature of colloidal ion-exchange sites (Weil and Brady, 2017).

The cation exchange capacity (CEC) of the soils varied between 31.25 and 46.19 cmol+ kg^{-1} with higher treatment effects at higher levels of the CMA, whilst the increasing rates of MOP led to successive declines which were still higher than the control (Table 6.5). The overall capacity of the soils to retain cations on the exchangeable sites is found under high and very high ranges (Wogi *et al*., 2021). The maximum effects from higher use of CMA might be attributed to its OM and mineral contents. Some essential compounds found in animal manure ash (Kiran *et al*., 2017; Komiyama *et al*., 2013) can either form clay-organic matter complexes (Garba *et al*., 2018) or surface functional groups that can increase the overall negative charge on soil particles (Fu *et al*., 2022). The observed decrease in CEC with increasing rates of KCl, instead, may be the result of a high K ion concentration competing with other necessary cations for exchange sites in the soil matrix. Such competition offers a chance to displace other cations, hence reducing the capacity of soils to hold nutrients (Khouni *et al*., 2023). Nutrient availability may be impacted by imbalances in the soil solution caused by excessive potassium fertilizer application (Yahaya *et al*., 2023; Havlin *et al*., 2017). Besides, soil microbial activity in the breakdown of OM and the production of negatively charged humic compounds that contribute to CEC might be hampered by high concentrations of Cl^- from KCl (Yang *et al*., 2021; Pereira *et al*., 2019; Zhang *et al*., 2018).

6.4. Conclusion

The study demonstrated that CMA and MOP have different effects on particular soil chemical characteristics. The alkaline minerals in CMA ($CaCO_3$, $K_2Ca(CO_3)_2$) neutralized acidity, whereas the chloride ions in MOP raised the risk of salinity. Additionally, MOP decreased Ca/Mg retention through competitive ion exchange, while CMA increased the soil OC and CEC via organic-mineral complexes. Integrated use of CMA and MOP (37.5–62.5% ratios) has optimized K and P supply by synchronizing immediate and sustained releases. This strategy reduces dependency on synthetic fertilizers and recycles organic waste, which is in line with sustainable agriculture principles, especially in soils that lack OM. The Vertic Cambisols exhibited higher pH buffering ($\Delta pH < 0.3$) with an optimal (50:50) CMA:MOP ratio for balanced nutrient release, whilst Pisoplinthic soils required maximum (≥75%) CMA proportion to mitigate acidity. Hence, prioritizing CMA (75–100%) is needed in acidic, low-OC soils (Pisoplinthic Cambisols) and blended ratios in high-buffer soils (Vertic Cambisols). However, future research works on species richness and activity of soil microbial communities as well as CMA's role in C sequestration and heavy metal mitigation, are recommended to have a comprehensive understanding about sustainable agriculture.

6.5. References

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7. RESPONSES OF WHEAT (*Triticum aestivum* L.) TO INTEGRATED POTASSIUM FERTILIZERS ON SOILS OF QENBERENAWETI SUB-WATERSHED, CENTRAL HIGHLANDS OF ETHIOPIA

Haymanot Awgchew[1,2], Sheleme Beyene[1], Alemayehu Kifilu[1], Asmare Melese[2]
[1]School of Plant and Horticultural Science, Hawassa University, Ethiopia
[2]Department of Plant Science, Debre Berhan University, Ethiopia

ABSTRACT

A fertilization strategy that combines organic and inorganic amendments is becoming more popular in Ethiopia for enhancing site-specific sustainable wheat production. The growth, yield, and nutrient uptake of wheat (Triticum aestivum L.) on five soils of the Qenberenaweti sub-watershed were examined at varying ratios of cattle manure ash (CMA) and muriate of potash (KCl). The soil types were Plinthofractic Cambisols, Vertic Cambisols, Pisoplinthic Cambisols, Pellic Vertisols, and Pisoplinthic Luvisols. Ten treatments, employing CMA:KCl ratios between 0:100 and 100:0, were applied under a greenhouse pot experiment along with the recommended amounts of phosphorus and nitrogen. The results indicated that plant growth and yields were significantly ($P < 0.001$) enhanced by combined applications of CMA-KCl. The control treatment (no K) consistently produced the lowest values, emphasizing the critical role of potassium in wheat productivity. Optimal ratios of CMA:KCl (50:50% or 37.5:62.5%) increased biomass yield by 139.36–169.30%, grain yield by 122.22–144.95%, fertile tillers per plant by 1.90–2.25 folds, seeds per spike by 2.41–2.76 folds, and plant height by 22.89–31.86 cm over the corresponding controls. The ratio of amendments and soil type affected the nutrient harvest indices. The Phosphorus Harvest Index increased under soil-specific combinations, such as the CMA-maximum ratios in Pisoplinthic Luvisols, whereas the Nitrogen Harvest Index peaked with KCl-dominant treatments. The most variable indicator was the Potassium Harvest Index, where KCl performed better than CMA in the majority of soils except for Pellic Vertisols. The synergistic effects between CMA (improving soil structure and micronutrient supply) and KCl (rapid K availability) optimized nutrient uptake and remobilization. The study highlights the necessity of optimized K-fertilization strategies that account for soil-specific properties to minimize the wheat yield gap. However, future research should be conducted under field conditions by including other essential nutrients to have a holistic view of balanced fertilization strategies.

Keywords: Cattle manure ash, muriate of potash, synergistic effects, balanced fertilizer usage, soil-specific fertilization, sustainable agriculture.

7.1. Introduction

Wheat is a known crop for fulfilling nutritional demands worldwide because of its adaptability in several climates and its vital role in a variety of diets (Yanagi, 2024). Bread wheat (*Triticum aestivum* L.) is among the three widely grown crops (teff and maize) in Ethiopia (Nigus *et al*., 2022) comprising about 17% of total cereal production (ESS, 2022). The major wheat-growing areas of the country are situated in the central and southeastern highlands, particularly Arsi, Bale, and parts of Shewa, which are identified as major production zones in East Africa (Zegeye *et al*., 2020). The national wheat production in the year 2022/23 was 5.7-5.8 million tons from nearly 2 million hectares (ha) with yields of 2.85-3.0 tons ha^{-1} (ESS, 2022; USDA, 2022). Ethiopia is the second wheat producer in Africa, next to Egypt (Senbeta and Worku, 2023), but with considerably more potential for yield improvement than Egypt (Zegeye *et al*., 2020; Tadesse *et al*., 2019).

Although a maximum yield of 6-7 tons ha^{-1} was achieved in the country with a 6.1% productivity increment via the wheat research system during the last few years (Alemu, 2024), the yield in the highlands is still unable to conquer 5 tons ha^{-1} (Nigus *et al*., 2022; Zegeye *et al*., 2020). In addition to excessive loss of essential nutrients, depletion of soil fertility and poor fertilizer management practices are the major factors behind the low productivity of wheat (Asmamaw *et al*., 2023; Kihara *et al*., 2022). Since the utilization of wheat is rising at 9% annually, while the production is increasing at 7.8%, the country still struggles to achieve self-sufficiency (Senbeta and Worku, 2023). This necessitates a 37% increase in production to meet the current demand of 6.3 million tons (Mekuriaw, 2023; Zegeye *et al*., 2020). Moreover, wheat production needs to be escalated by about 10 million tons to fill the yield gap with its own production for feeding the future human population in the year 2050 (Senbeta and Worku, 2023; Zegeye *et al*., 2020).

The nationwide fertilizer trials indicated that more than 50 and 25% of Ethiopian soils are highly responsive to the N and P nutrients, respectively (Kahsay, 2019; Woldekiros, 2018; Abdulkadir *et al*., 2017). Hence, less attention has been given to other essential nutrients throughout the country, along with similar management approaches (blanket and/or sub-optimal fertilizer usages) that ignored vital soil characteristics and related plant factors (Erkossa *et al*., 2022; Demiss *et al*., 2020). Such unbalanced nutrient usage can reduce the quantity and quality of crop production due to excessive exhaustion of the essential elements (AbdelRahman and Metwaly, 2023; Getinet, 2021). For instance, the highest K depletion rate with a negative balance of 32 kg ha^{-1} yr^{-1} was reported on Ethiopian soils (Gadisa, 2021), mainly owing to inadequate and sole use of N and P, continuous and intensive cropping, absence of crop rotation and residue management, severe soil erosion, and excessive loss of OM (Gedamu, 2020; Laekemariam *et al*., 2018). Besides, the N-P fertilization strategy has requested more K than necessary (Birhan *et al*., 2017).

The overall fertility and productivity statuses of Ethiopian soils can be improved by applying organic and inorganic amendments in a balanced manner (Wato *et al*., 2024; Abebe *et al*., 2022). Unfortunately, the majority of farmers in the nation are unaware of the benefits that combined fertilization offers for soil physicochemical properties and crop production (Wato *et al*., 2024). Contempt the relative advantages of mineral fertilizer, it is expensive for small-scale farmers and harmful to the soil system (Abebe *et al*., 2022; Reda and Hagos, 2017). Conversely, the organic form optimizes the soil habitat and releases diverse essential nutrients in slow and steady modes to nourish soil organisms (Wato *et al*., 2024; Bhunia *et al*., 2021). For example, cattle manure and its ash increase the efficiency of mineral fertilizers (N, P, and K) by improving the physico-chemical properties of soils (Chali and Genati, 2021; Zewide *et al*., 2019). In general, the efficacy among the amendments varies notably under different soil types as a result of inherent factors like texture, pH, OM content, and nutrient buffering capacity (Shao *et al*., 2024; Ndzeshala *et al*., 2023). Consideration of this soil-specific interaction is imperative for creating sustainable nutrient recommendations for a given area (Meyer *et al*., 2020; Selim, 2020), as their mix ratio determines nutrient availability, uptake, and translocation extents (Gessesew *et al*., 2022; Wajid *et al*., 2020).

The use of K-containing organic and mineral fertilizers is not well practiced for crop production in Ethiopia (Laekemariam *et al*., 2018) merely because of the 1968 Murphy's generalization that stated Ethiopian soils are K-rich (Kassa *et al*., 2021; Birhan *et al*., 2017). However, K content is declining in many parts of the country, whereby a widespread K deficiency has been noticed during recent years (Misskire *et al*., 2019; Laekemariam *et al*., 2018). The deficiency even has been found in soils with optimum exchangeable K due to very high amounts of Ca and/or Mg on the ion exchange complex (Bayle *et al*., 2023; Laekemariam *et al*., 2018). As cases in point, usage of K with optimum doses of N and P has increased growth and yield of wheat on Vertisols (Assefa *et al*., 2021; Ayele *et al*., 2020), Cambisols (Gebreslassie and Berhe, 2023), Nitisols (Tesfaye *et al*., 2021; Ayele *et al*., 2020), and other soil types at different parts of the country (Dargie *et al*., 2022;

Godebo *et al*., 2021). Hereby, the better results are concerned with the role of sufficient K nutrition in regulating the uptakes of water and nutrients (Si *et al*., 2023; Rawal *et al*., 2022), particularly N (Khan *et al*., 2021) and P (Pandey *et al*., 2020).

Effective use of applied nutrients and balanced availability are essential for sustainable wheat production (Pandey *et al*., 2020; Panhwar *et al*., 2019). According to Sharma *et al*. (2023) and Broberg *et al*. (2021), the efficiency of nutrient uptake and remobilization for maximizing wheat grain and biomass yields can be seen in the harvest index (HI), which is the nutrient content ratio of grain to total aboveground biomass (Fageria, 2014). Wheat is among the important field crops grown on different soils of the study area with a yield still lower than the attainable potential due to poor practice of integrated soil fertility management at the site-specific level (Welde, 2023; Gisille, 2020). In Ethiopia, a site-specific fertilization strategy that combines organic and inorganic amendments is becoming more popular as a way to improve sustainable wheat production (Wato *et al*., 2024; Obsa, 2019). Despite the limitation of mineral K fertilizers, the organic types (cattle manure and its dung-cake ash) are widely available but not used as alternative soil amendments in the study area. Moreover, there is less evidence regarding the optimal combination of K-containing fertilizers to enhance sustainable wheat production on the diverse soil types of the area. Therefore, the objective of this study was to assess how different application ratios of cattle manure ash and muriate of potash affect the growth, yield, and nutrient harvest index of wheat (*Triticum aestivum* L.) on the soils of the sub-watershed.

7.2. Materials and Methods

7.2.1. Experimental procedure

The optimum rates of 149.24 (Pellic Vertisols), 138.32 (Vertic Cambisols), 125.96 (Pisoplinthic Cambisols), 114.02 (Pisoplinthic Luvisols), and 113.40 (Plinthofractic Cambisols) kg K ha^{-1} from Chapter 5 (Experiment 4) were set into ten treatments with diverse percentage ratios of inorganic (muriate of potash, MOP) and organic (cattle manure ash, CMA) K sources. The Treatments were:

Treatment 1 = 0% MOP: 0% CMA, a standard check without MOP and CMA
Treatment 2 = 0% MOP: 100% CMA
Treatment 3 = 12.5% MOP: 87.5% CMA
Treatment 4 = 25% MOP: 75% CMA

Treatment 5 = 37.5% MOP: 62.5% CMA
Treatment 6 = 50% MOP: 50% CMA
Treatment 7 = 62.5% MOP: 37.5% CMA
Treatment 8 = 75% MOP: 25% CMA
Treatment 9 = 87.5% MOP: 12.5% CMA
Treatment 10 = 100% MOP: 0% CMA

Every treatment per soil group was mixed accordingly with four kg composite surface soil (0-20 cm) samples and put in a frustum-shaped plastic pot (18 cm height by 17 cm bottom and 19 cm top diameters) under a greenhouse. The pot trial was arranged in a completely randomized design (CRD) with three replications. Fifteen seeds of the test crop, wheat (Dend'a variety), were drilled in every pot a week after incorporating the intended amendments, to allow better decomposition and minimize salt injury. Then, the seedlings were thinned to ten after 75% crop emergence. The North Shewa zone agricultural office's recommended rates of P (100 kg TSP ha^{-1} = 0.17 g pot^{-1}) and N (200 kg Urea ha^{-1} = 0.33 g pot^{-1}) were used throughout the experiment. The determined amounts of K fertilizers were added at the time of sowing with full doses of P and 1/3 of N, while the remaining 2/3 of N was applied at the tillering stage. Hereby, all the fertilizers were set at three times more of the recommended rates on a hectare base (Terman, 1974) to compensate for the actual nutrient demand of the crop (Chien, 2022). Because the roots are restricted to proliferate only the small soil volume in the pot than what they might do in the field (Yoon *et al*., 2023). The bulk density and nutrient flow depth of the soils were taken as 1200 kg m^{-3} and 20 cm, respectively (Wogi *et al*., 2021). The soil moisture level was kept at nearly FC during the growing period.

Starting at 75% heading to physiological maturity, the height and spike length of five randomly selected plants in each pot were measured using a ruler from the bottom to the tip of the shoot and from the base of the spike to the apex of the terminal spikelet by excluding the awns, respectively. Moreover, the number of productive tillers per plant was recorded during these growth stages. At physiological maturity, the plants were harvested, subsequently air dried, and threshed for the determination of grain yield using a sensitive balance while adjusting the seed moisture content to 12%. Biomass yield in each pot was determined by weighing the above-ground plant parts (straw and grain tissues), put in an oven at 70 ℃ for 24 hours (till constant weights were achieved). As stated in section 5.2.3, the dried plant tissues were ground to pass through a 1 mm sieve after separating into grain and straw for the analysis of total N, P, and K contents in suspensions obtained from wet digestion by a 2:1 ratio of nitric (HNO_3) and perchloric ($HClO_4$) acids mixture.

7.2.2. Statistical analysis

Analysis of Variance (ANOVA) was carried out for the growth, yield, and nutrient harvest index of wheat (*Triticum aestivum* L.) in response to the different rates of K-containing amendments by using the statistical analysis software package 9.4 (SAS, 2013). The mean comparisons were performed with Fisher's Least Significant Difference (LSD) test at 95% significance level.

7.3. Results and Discussion

7.3.1. Growth and yield of wheat

7.3.1.1. Plant height and spike length

The results of the ANOVA revealed significant differences ($p < 0.001$) in wheat plant height (PH) and spike length (SL) due to the effects of the treatment on all the study soils (Table 7.1). The control treatment consistently resulted in the lowest PH and SL, indicating the importance of K for wheat growth by using only the recommended rates of N and P nutrients. The tallest plants were obtained from Treatment 7 (37.5% CMA:62.5% KCl) in the soils, except for Treatment 6 (50% CMA:50% KCl) on the Pisoplinthic Cambisols. The longest spikes were found at Treatment 6 in most soils apart from Treatment 7 on the Vertic Cambisols and Pisoplinthic Luvisols.

The growth characteristics followed an overall increasing pattern until the 50:50 and/or 37.5:62.5 percent CMA:MOP ratios before declining with increasing KCl levels, which had better growth than their CMA counterparts. Therefore, the results showed that the combined optimum of the amendments is better than the single source. Other than the pivotal contribution of the easily available K from KCl, the growth improvement (22.89-31.86 and 4.27-5.74 cm increases in PH and SL, respectively) above the respective controls might have been due to the synergistic action of CMA, which is concerned with its extra nutrient content and effect on important soil properties.

Table 7. 1. Effects of CMA and KCl on plant height and spike length of wheat

Treatment	Parameters									
	Plant height (cm)					Spike length (cm)				
	Soil types									
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	72.44^{f}	72.47^{f}	65.78^{e}	66.53^{f}	64.78^{e}	7.53^{h}	7.73^{g}	6.72^{h}	6.43^{g}	6.47^{h}
2	84.67^{d}	87.53^{de}	77.89^{cd}	74.77^{d}	72.11^{d}	8.34^{g}	9.01^{f}	7.31^{g}	7.68^{f}	6.97^{g}
3	84.45^{d}	84.67^{e}	75.56^{d}	72.17^{e}	66.44^{e}	8.91^{f}	9.07^{f}	7.72^{f}	8.01^{e}	7.78^{f}
4	80.89^{e}	88.90^{cd}	81.45^{b}	86.67^{bc}	73.44^{d}	9.01^{f}	9.77^{e}	8.67^{e}	8.83^{d}	8.25^{e}
5	84.89^{d}	89.33^{cd}	80.33^{bc}	85.11^{c}	82.33^{b}	10.51^{c}	10.47^{c}	9.96^{b}	9.93^{b}	10.32^{b}
6	95.44^{b}	97.01^{b}	91.67^{a}	86.78^{bc}	81.89^{b}	13.04^{a}	11.80^{b}	11.04^{a}	11.20^{a}	10.23^{b}
7	100.56^{a}	104.33^{a}	80.22^{bc}	90.86^{a}	87.67^{a}	11.47^{b}	13.47^{a}	9.46^{c}	9.59^{c}	10.74^{a}
8	94.67^{b}	91.13^{c}	78.33^{bcd}	87.22^{b}	77.67^{c}	10.26^{cd}	10.53^{c}	9.10^{d}	9.64^{c}	9.61^{c}
9	95.89^{b}	90.13^{cd}	79.78^{bc}	88.25^{b}	77.89^{c}	10.09^{de}	10.07^{d}	8.95^{d}	9.41^{c}	9.04^{d}
10	90.57^{c}	88.03^{cd}	80.11^{bc}	88.44^{b}	78.56^{bc}	9.88^{e}	9.67^{e}	8.53^{e}	8.87^{d}	8.85^{d}
LSD (0.05)	1.92	3.26	3.20	2.06	3.97	0.30	0.28	0.23	0.26	0.25
CV (%)	1.27	2.14	2.37	1.46	3.06	1.78	1.64	1.55	1.72	1.63

Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols

NB. Means followed by the same letter(s) within a column are statistically different at $P \leq 0.001$.

The CMA contributes to a range of nutrients, OM, stable soil structure (improves water retention and aeration), and normal microbial activity (Bhunia *et al*., 2021), which in turn increases nutrient availability and uptake (Kumar *et al*., 2021). The short plant heights and spike lengths observed in treatments with solo CMA (Treatment 2) could be due to a slower release of K from CMA compared to the readily available K in KCl (Hanudin *et al*., 2021; Tran *et al*., 2018). Studies indicated that the integrated use of CMA and MOP can lead to remarkable improvement in wheat plant height and spike length (Azad *et al*., 2022) because of better nutrient uptake and soil conditions (Mesfin *et al*., 2023). The combination of both organic and inorganic fertilizers enhances the growth of wheat by increasing the availability and uptake of N, P, and K for better biomass production (Amjadian *et al*., 2021).

7.3.1.2. Fertile tillers per plant and seeds per spike

The number of fertile tillers per plant (NFTP) and seeds per spike (NSPS) of wheat had very high statistical variations ($P < 0.001$) as the experimental soils were treated with diverse ratios of CMA:KCl (Table 7.2). The effect of 50% CMA + 50% KCl (Treatment 6) resulted in the highest

NFTP (4.34-4.85) in almost all soils, except for 4.94 on the Pellic Vertisols, which had the highest NFTP at 37.5% CMA + 62.5% KCl (Treatment 7). The highest NSPS (59.76-76.52) was observed at the rate of 37.5% CMA and 62.5% KCl in most soils, whereas the highest NSPS was obtained from the application of 50% of each amendment on both the Pisoplinthic and Plinthofractic Cambisols. The lowest NFTP (2.05-2.62) and NSPS (23.32-29.20) were noted from the control on all the soils and were progressively increased by 1.90-2.25 and 2.41-2.79 folds with increasing balanced ratios (37.5-62.5%) of CMA and MOP. Then, these two yield attributes were decreased upon further rises in the MOP percentage, though they had better results than those of CMA (75:100%) rates, which gave the maximum values.

Table 7. 2. Effects of CMA and KCl on numbers of fertile tillers per plant and seeds per spike.

Treatment	Parameters									
	Number of fertile tillers per plant					Number of seeds per spike				
	Soil types									
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	2.60^{f}	2.48^{g}	2.05^{h}	2.09^{g}	2.11^{j}	27.44^{i}	29.20^{f}	26.17^{h}	25.32^{g}	23.32^{h}
2	3.17^{e}	2.88^{f}	2.78^{g}	2.86^{f}	2.55^{i}	36.43^{h}	40.63^{e}	31.63^{g}	32.44^{f}	29.65^{g}
3	3.19^{e}	2.92^{f}	3.19^{f}	3.24^{e}	3.06^{h}	41.97^{g}	41.20^{e}	36.24^{f}	33.56^{f}	33.08^{f}
4	3.16^{e}	3.53^{e}	3.66^{e}	3.90^{d}	3.32^{g}	46.73^{f}	48.97^{d}	45.43^{de}	40.18^{e}	37.85^{e}
5	3.85^{d}	3.80^{d}	4.02^{b}	4.33^{bc}	4.10^{b}	50.66^{de}	54.17^{c}	54.34^{b}	43.25^{d}	53.13^{b}
6	4.44^{c}	4.85^{a}	4.49^{a}	4.71^{a}	4.34^{a}	61.73^{b}	59.03^{b}	63.14^{a}	61.17^{a}	54.01^{b}
7	4.94^{a}	4.56^{b}	4.00^{bc}	4.41^{b}	3.98^{c}	76.52^{a}	72.03^{a}	50.43^{c}	50.47^{b}	59.76^{a}
8	4.69^{b}	4.32^{c}	3.93^{cd}	4.33^{bc}	3.72^{d}	52.09^{d}	56.20^{bc}	44.48^{de}	47.13^{c}	47.38^{c}
9	4.68^{b}	4.40^{c}	3.91^{d}	4.28^{c}	3.63^{e}	56.56^{c}	53.60^{c}	46.43^{d}	43.56^{d}	43.61^{d}
10	4.66^{b}	4.30^{c}	3.97^{bcd}	4.26^{c}	3.56^{f}	48.76^{ef}	48.73^{d}	44.31^{e}	44.57^{d}	44.05^{d}
LSD (0.05)	0.07	0.10	0.08	0.08	0.05	3.10	3.43	1.99	1.76	2.95
CV (%)	1.09	1.59	1.29	1.23	0.91	3.65	3.99	2.64	2.45	4.06

Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols

NB. Means followed by the same letter(s) within a column are statistically different at $P \leq 0.001$.

The observed best performances in NFTP and NSPS suggest that the balanced ratios (37.5-62.5%) of CMA and MOP are particularly beneficial under the conditions of study soils, which might be due to an optimal interaction between organic and inorganic K sources. The approach of balanced CMA-MOP fertilization leverages their synergistic benefits to improve grains per spike and overall grain weight of wheat via optimizing nutrient availability and uptake (Imran, 2024). The relative advantage of KCl on CMA could be ascribed to its readily available K, which is vital for photosynthesis and plant health, leading to increased tillering and seed formation (Chambers, 2024; Ma *et al*., 2022).

8.3.1.3. Above-ground biomass and grain yields

The above-ground biomass and grain yields of wheat varied considerably ($P < 0.001$) across various treatments and soils (Table 7.3). The lowest biomass (4.45-5.61 tons ha^{-1}) and grain (1.80-2.43 tons ha^{-1}) yields were obtained in the control treatment on experimental soils, which confirmed the importance of K fertilization along with N and P for wheat production. Moreover, Treatment 7 produced the highest biomass yields on the Pellic Vertisols (14.27 tons ha^{-1}) and Vertic Cambisols (13.66 tons ha^{-1}), while it was Treatment 6 on the rest of the soil types (11.48-12.63 tons ha^{-1}). Similarly, Treatment 7 resulted in the highest grain yield (4.21-5.40 tons ha^{-1}) as Treatment 6 did on Pisoplinthic (4.85 tons ha^{-1}) and Plinthofractic Cambisols (4.80 tons ha^{-1}). Accordingly, the outcomes of such treatments reflected an integrated strategy involving the use of KCl and CMA, which is more beneficial than the sole application of either the inorganic or organic form. The combined effect likely arises from the complementary nutrient profiles (Richards *et al*., 2021) at which CMA provides micronutrients and improves soil structure, whereas the KCl delivers readily available K.

The combined usage of CMA and MOP at either effect of Treatment 6 or 7 improved biomass and grain yields by 139.36-169.30% and 122.22-144.95% over the control, respectively (Table 7.3). However, it consistently failed below the treatments with the solo KCl and mixtures of CMA-KCl. This suggests that while CMA provides essential nutrients, it might not supply enough K or in an easily absorbed form to meet the full K demand of crops (Tran *et al*., 2018). The sole KCl treatment (Treatment 10) resulted in improved yields compared to the control, but generally performed worse than the 50/50 and 37.5/62.5 treatments, suggesting that CMA has a positive impact on the overall soil health for plant growth. The combination of readily available K from KCl and the slow-release K from CMA ensures a sustained supply of K throughout the wheat growing season (Jahan and Amiri, 2018). Balanced fertilization strategies optimize N, P, and K nutrients that can lead to maximum increases in biological yields (Jahan and Amiri, 2018). Many studies also pointed out that integrated uses of both cattle manure and KCl improved grain yield via enhancing nutrient concentrations (Wang *et al*., 2025; El-Hamdi *et al*., 2019).

Table 7. 3. Effects of CMA and KCl on above-ground biomass and grain yields

Treatment	Parameters									
	Biomass yield (ton/ha)					Grain yield (ton/ha)				
	Soil types									
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	5.49^{g}	5.61^{f}	5.03^{g}	4.69^{g}	4.45^{h}	2.43^{g}	2.31^{g}	1.98^{i}	2.09^{f}	1.80^{f}
2	6.30^{f}	7.87^{e}	6.94^{f}	6.92^{f}	5.50^{g}	2.76^{f}	3.10^{f}	2.32^{h}	2.72^{e}	2.61^{e}
3	6.42^{f}	7.63^{e}	7.07^{f}	6.96^{f}	5.56^{g}	3.20^{e}	3.21^{f}	2.55^{g}	2.74^{e}	2.75^{d}
4	6.43^{f}	9.05^{d}	8.87^{cd}	8.37^{e}	6.64^{f}	3.33^{e}	3.85^{e}	3.31^{f}	3.35^{d}	3.16^{c}
5	8.22^{e}	9.88^{c}	9.22^{bc}	8.83^{d}	10.35^{b}	3.71^{d}	4.11^{d}	3.97^{de}	3.47^{d}	4.01^{b}
6	11.95^{b}	11.23^{b}	12.04^{a}	12.63^{a}	11.48^{a}	4.65^{b}	4.77^{b}	4.85^{a}	4.80^{a}	4.17^{a}
7	14.27^{a}	13.66^{a}	9.47^{b}	9.34^{c}	9.91^{c}	5.40^{a}	5.22^{a}	4.40^{b}	3.83^{c}	4.21^{a}
8	10.19^{c}	9.81^{c}	8.53^{de}	9.47^{bc}	9.02^{d}	4.39^{c}	4.84^{b}	3.91^{e}	3.86^{c}	3.99^{b}
9	9.51^{d}	9.45^{cd}	8.47^{e}	9.69^{b}	8.79^{de}	4.82^{b}	4.59^{c}	4.19^{c}	4.06^{b}	3.97^{b}
10	9.06^{d}	9.21^{d}	8.21^{e}	8.91^{d}	8.47^{e}	4.30^{c}	4.15^{d}	4.09^{cd}	4.11^{b}	3.96^{b}
LSD (0.05)	0.51	0.54	0.39	0.27	0.34	0.17	0.15	0.15	0.13	0.14
CV (%)	3.42	3.40	2.73	1.85	2.48	2.57	2.15	2.49	2.20	2.32

Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols

NB. Means followed by the same letter(s) within a column are statistically different at $P \leq 0.001$.

7.3.2. Nutrient harvest index of wheat

The Nitrogen Harvest Index (NHI) was significantly varied ($P < 0.0001$) due to effects of the treatment on each soil type (Table 7.4). However, the NHI did not consistently increase or decrease with increasing CMA or KCl proportions, suggesting the optimal mixture was highly dependent on the soil type. Apart from the results on the Pellic Vertisols and Pisoplinthic Luvisols, treatments with higher CMA percentages typically resulted in lower NHI across all soil types, indicating improved N remobilization to the grain. Moreover, at the highest NHI values, which were caused by high KCl levels (Treatment 10) or high KCl percentages in the combinations (Treatment 9), the control effect yielded similar NHI values in the Pellic Vertisols, Plinthofractic Cambisols, and Pisoplinthic Luvisols soils. This implies that the soils either could have unique N partitioning dynamics or sufficient native N availability for the wheat crop (Mălinaş *et al*., 2022).

In spite of the absence of N in CMA, the detected NHI is likely indirect because of its attribution to the physicochemical properties of soils, which could improve nutrient dynamics and microbial activity. As confirmed by Olowoboko *et al.* (2018), the incorporation of manure ash promotes nitrification, that leading to more readily plant available N form (NO_3^-). The presence of manure ash can stimulate microbial populations that are crucial for the mineralization of N (Fischer and Glaser, 2012), thereby improving its release over time. Moreover, CMA's adequate P and K contents improve the plant health and biomass growth by tremendously improving N availability, uptake, and transport (Bhunia *et al*., 2021). The increased NHI following the KCl-dominant treatment on all the soils could be the result of enhanced plant growth due to easily available K or the effect of K on N absorption and translocation processes (Li *et al*., 2023; Godebo *et al*., 2021). The variability in NHI responses, including the good performance from the control of the Pellic Vertisols and Plinthofractic Cambisols, might be related to the native soil N supply and mineralization rates specific to each soil.

The Phosphorus Harvest Index (PHI) was also significantly affected ($P < 0.0001$) by the treatments on the study soils (Table 7.4). Apart from the control on the Pellic Vertisols (0.46), the proportional mixtures (37.5-62.5 %) of the amendments resulted in the lowest PHI (0.37 to 0.47). The highest PHI values were observed in the Pellic Vertisols (0.63) and Pisoplinthic Luvisols (0.59) with maximum CMA levels at Treatments 4 and 2, respectively, while it was with higher KCl percentages in the Vertic Cambisols (0.62), Pisoplinthic Cambisols (0.55), and Plinthofractic Cambisols (0.49) at either Treatment 9 or 10.

Table 7. 4. Effects of CMA and KCl on nutrient harvest index of wheat crop

Treatments	Parameters														
	Nitrogen harvest index					Phosphorus harvest index					Potassium harvest index				
	Soil types														
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	0.75^{a}	0.68^{cd}	0.67^{c}	0.67^{a}	0.75^{ab}	0.46^{e}	0.55^{bc}	0.41^{cd}	0.47^{ab}	0.50^{def}	0.25^{de}	0.34^{a}	0.28^{b}	0.25^{b}	0.25^{cde}
2	0.72^{b}	0.65^{ef}	0.59^{e}	0.61^{bc}	0.75^{ab}	0.52^{d}	0.54^{c}	0.38^{de}	0.44^{bc}	0.59^{a}	0.23^{ef}	0.17^{d}	0.18^{fg}	0.17^{d}	0.29^{a}
3	0.78^{a}	0.69^{bcd}	0.62^{d}	0.60^{c}	0.77^{a}	0.59^{bc}	0.52^{cd}	0.41^{cd}	0.40^{de}	0.52^{bcd}	0.28^{bc}	0.21^{c}	0.17^{g}	0.19^{c}	0.25^{cde}
4	0.77^{a}	0.67^{cde}	0.64^{d}	0.62^{bc}	0.73^{bc}	0.63^{a}	0.52^{cd}	0.42^{c}	0.46^{b}	0.49^{ef}	0.32^{a}	0.25^{b}	0.24^{c}	0.20^{c}	0.26^{bc}
5	0.69^{cd}	0.66^{de}	0.63^{d}	0.56^{d}	0.62^{f}	0.60^{ab}	0.49^{de}	0.42^{c}	0.37^{e}	0.40^{g}	0.30^{ab}	0.24^{bc}	0.26^{b}	0.16^{e}	0.17^{g}
6	0.67^{de}	0.65^{ef}	0.67^{c}	0.60^{c}	0.64^{ef}	0.52^{d}	0.49^{de}	0.37^{e}	0.40^{de}	0.38^{g}	0.26^{cd}	0.25^{b}	0.19^{ef}	0.21^{c}	0.20^{f}
7	0.65^{e}	0.63^{f}	0.72^{b}	0.63^{b}	0.66^{e}	0.49^{de}	0.47^{e}	0.52^{b}	0.43^{cd}	0.47^{f}	0.25^{de}	0.18^{d}	0.23^{cd}	0.19^{c}	0.23^{def}
8	0.70^{bc}	0.70^{bc}	0.72^{b}	061^{bc}	0.70^{d}	0.52^{d}	0.60^{a}	0.51^{b}	0.45^{bc}	0.51^{cde}	0.25^{de}	0.26^{b}	0.21^{de}	0.20^{c}	0.26^{bcd}
9	0.76^{a}	0.73^{a}	0.76^{a}	0.60^{c}	0.71^{cd}	0.56^{c}	0.62^{a}	0.55^{a}	0.45^{bc}	0.53^{bc}	0.27^{bcd}	0.25^{b}	0.28^{b}	0.24^{b}	0.22^{ef}
10	0.75^{a}	0.71^{ab}	0.75^{a}	0.68^{a}	0.76^{a}	0.49^{de}	0.59^{ab}	0.52^{b}	0.49^{a}	0.54^{b}	0.22^{f}	0.24^{bc}	0.31^{a}	0.28^{a}	0.28^{ab}
LSD (0.05)	0.03	0.03	0.03	0.02	0.03	0.04	0.04	0.03	0.03	0.03	0.03	0.03	0.02	0.02	0.03
CV (%)	2.19	2.37	2.19	2.08	2.17	3.95	4.63	3.51	4.25	3.19	6.79	7.29	5.32	4.65	6.63

Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols

NB. Means followed by the same letter(s) within a column are statistically different at $P \leq 0.001$.

The effectiveness of CMA in improving PHI varied significantly based on the soil type and its combination with KCl. The maximum PHI resulted from changing combinations in various soils, sometimes in favor of CMA (Pisoplinthic Luvisols), in favor of KCl (Plinthofractic Cambisols), but often their combinations (Pellic Vertisols, Vertic Cambisols, and Pisoplinthic Cambisols). Since CMA is a known source of P, the PHI responses on the Pellic Vertisols and Pisoplinthic Luvisols highlight that the P supplied by CMA was effectively utilized and moved to the grain in such conditions of soil (Tran *et al*., 2017). The distinct responses likely reflect how P from CMA (often in less soluble forms than mineral P) and native soil P pools interact differently with the mineral fertilizers in each soil matrix (Jindo *et al*., 2023; Yahaya *et al*., 2023). The PHI values at high KCl percentages on Vertic and Pisoplinthic Cambisols were due to synergistic associations between P and K. This means KCl facilitates P uptake and its translocation in wheat via enhanced root growth and nutrient release from the soil (El Mazlouzi *et al*., 2022; Naeem *et al*., 2018).

The Potassium Harvest Index (KHI) ranged from 0.16-0.32 and exhibited pronounced differences ($P < 0.0001$) among treatments under all soil types (Table 7.4). The KHI results emphasized the complexity of K dynamics depending on the soil types. In soils like the Pellic Vertisols and Vertic Cambisols, combinations or even the control performed better than only MOP. Besides, the sole KCl was superior in the Pisoplinthic and Plinthofractic Cambisols, whereas the solo CMA was effective in the Pisoplinthic Luvisols (Table 7.4).

The KHI showed the most variable results, reflecting the distinctive nature of K supplied by CMA versus MOP. Although MOP provides K in a highly soluble and readily available form, CMA provides K primarily bound in ash minerals (Tran *et al*., 2018), which may necessitate dissolution and release (Moe *et al*., 2019). The dominance of KCl-rich treatments (Treatments 10 and 9) in optimizing KHI in most soils except for the Pellic Vertisols is consistent with MOP being a highly effective mineral K fertilizer. However, the superiority of a CMA-rich treatment (Treatment 4) in the Pellic Vertisols might suggest that the K from CMA had a direct relation with its other beneficial effects; for example, soil structure improvement affecting root foraging, and nutrients supplied by CMA. This could be attributed to soil-specific properties such as CEC, K fixation potential, or interactions with other ions, which influence the dynamics of K from different sources (Andrews *et al*., 2021; Das *et al*., 2018).

7.4. Conclusion

The study verified that the combined application of organic (cattle manure ash, CMA) and inorganic (muriate of potash, MOP) K amendments along with recommended rates of N and P nutrients, enhances wheat productivity more effectively than their sole applications. Particularly, the 37.5% CMA and 62.5% KCl proportion (Treatment 7) appeared favorable on the Pellic Vertisols, Vertic Cambisols, and Pisoplinthic Luvisols, whereas the 50:50% rate (Treatment 6) gave the best results on the Pisoplinthic and Plinthofractic Cambisols. This synergy of the amendments addresses both immediate nutrient needs through KCl's rapid availability and long-term soil health via CMA's improvement of the soil structure, water retention, and microbial activity. Implementing such integrated approaches could transform Ethiopia's fertilizer strategies, moving beyond the current N-P-focused approach, which is a paradigm shift towards holistic nutrient management that combats widespread K depletion (32 $kg \cdot ha^{-1} \cdot yr^{-1}$ nationally) while boosting grain yields toward the minimal attainable 5 $tons \cdot ha^{-1}$ threshold.

On the other hand, the pronounced variations in nutrient harvest indices (NHI, PHI, and KHI) are influenced by soil type. Although pure KCl or high KCl combined with organic amendments often favored NHI and KHI in several soils, combinations containing a substantial share of CMA were frequently optimal for PHI. The CMA-dominant combination also maximized KHI only in the Pellic Vertisols. These results necessitate developing localized amendment protocols that account for inherent soil properties (texture, pH, CEC) to maximize nutrient-use efficiency. Rectifying historical negligence of K fertilization offers a direct pathway to close Ethiopia's wheat yield gap via creating awareness for every stakeholder. However, subsequent research needs to be conducted under field conditions employing different crops and micronutrients to develop a comprehensive understanding and draw a sound conclusion on balanced fertilization practices.

7.5. References

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8. SUMMARY AND CONCLUSION

Widespread soil degradation, nutrient depletion, and low agricultural production in the highlands of Ethiopia are caused by a lack of comprehensive soil data at local climatic and topographic variability levels. Alike the nationwide soil degradation and food insecurity scenarios, the unbalanced usage of fertilizers with undue reliance on N-P fertilizers and the historical negligence of K have been identified as key issues, particularly in the study area. On the other hand, K shortage is becoming more common and creating a detrimental effect on sustainable crop production, especially for vital crops like wheat. In general, acquiring site-specific soil data is essential for creating balanced fertilization plans and implementing integrated soil fertility management techniques. To this effect, a set of scientific research, having a total of six distinct but consecutive and interrelated experiments, was initiated to determine the overall characteristics and distribution of diverse soils. Besides, it was to set a precise K management protocol at a sub-watershed level for ensuring sustainable production of wheat through integrated use of mineral (KCl) and locally available organic (CMA) amendments. The brief summaries of the main findings, conclusions, and general recommendations of each experimental component are stated as follows:

This study investigated the critical role of local physiography in creating diverse soil types and thereby influencing proper planning, management, and utilization of the soil resources. It emphasized how topographic positions and slope features (steepness, aspect, and form) govern soil formation, distribution, and overall properties. The research findings revealed that these factors have shaped the extent of soil variability along the toposequence directly by determining the movement of water (surface runoff and deep percolation). The moving water influences processes and material redistribution in soils (erosion-deposition and eluviation-illuviation). Through a detailed characterization and free survaying, six soil types: Pellic Bathypetroduric Vertisols (Hypereutric, Amphifractic), Hypereutric Vertic Cambisols (Pantoclayic, Humic), Hypereutric Akroskeletic Plinthofractic Cambisols (Pantoclayic, Escalic, Humic, Magnesic), Pisoplinthic Luvisols (Clayic, Hypereutric, Profundihumic, Profondic, Bathyvertic), Hypereutric Pisoplinthic Cambisols (Pantoclayic, Profundihumic), and Hypereutric Relictistagnic Cambisols (Pantoclayic, Ferric, Humic) were identified by using the World Reference Base (WRB) classification system.

The study examined potassium (K) forms and their relationships with soil physicochemical properties in six soil types across the sub-watershed, which were influenced by variabilities in topography, agricultural practices, and intrinsic soil characteristics. The labile and non-labile K distribution patterns differed significantly across soil types, which were bioavailability influenced by interactions between K forms and soil properties like pH, clay content, and CEC. Distribution of the labile K form was the highest in Pellic Verisols, followed by Vertic Cambisols > Pisoplinthic Cambisols > Pisioplintic Luvisols > Plinthofractic Cambisols > Relictistagnic Cambisols. On the other hand, the non-labile K form was maximum in the Pisioplintic Cambisols, declining in the order of Vertic Cambisols > Pellic Verisols > Plinthofractic Cambisols > Pisioplintic Luvisols > Relictistagnic Cambisols. All the K forms showed significant correlations ($p < 0.01$) among themselves and specifically with exchangeable Na ions in the Plinthofractic Cambisols due to the roles of selected physicochemical properties in each experimental soil. The principal component analysis (PCA) also categorized the K dynamics and factors behind into two components. The first group accounted for 35.7% of the soil variability that was explained negatively by sand particles, while positively by pH, clay, and all K forms. The second group described 25.3% of the variability with a negative influence of silt separate and a positive influence of CEC and divalent exchangeable cations. Such information on K forms and relations with soil properties helps understand the K-supply power of soils at a site-specific level and formulate effective K fertilization and management practices. For instance, improving the soil pH and contents of exchangeable Ca and Mg through a soil test-based application of lime and/or ash amendments might enhance the bioavailability of K in the experimental soils.

The study investigated potassium (K) adsorption-desorption dynamics in soils of the sub-watershed. It demonstrated that soil type strongly influences K fixation and release patterns, with implications for effective fertilizer management. Generally, the adsorption behavior of entire soils was characterized by non-linear increases of equilibrium K concentration (Ce) and adsorbed K (qe) owing to increases in rising initial K (Ci) levels. The Freundlich isotherm model ($qe = aCe^{b/a}$) outperformed the Langmuir and Temkin models in describing K adsorption, as well as being used to describe the theoretical doses of K fertilizers required to develop K levels in soil solutions. The desorption kinetics also occurred in distinct release phases over time as rapid (within 12 hours), gradual decline (72-168 hours), and stabilization (after 288 hours), while the Power function model best fitted for cumulative K release of each soil type. Thus, mathematical model-based assessment of the K fixation and release statuses of all soil types at a site-specific level enables understanding the soils' K supply potential and planning for an effective K fertilization strategy.

This study has established potassium (K) fertilization thresholds for wheat cultivation in the sub-watershed through adsorption isotherm analysis. It demonstrated how the external (soil's) and internal (plant's) K requirements interact to optimize wheat productivity over the poorest response upon K omission. Accordingly, the K application significantly ($P < 0.001$) improved all growth and yield parameters, whereby the enhanced performance at excessive K doses indicates the need for the crop's optimal threshold. In general, the Vertisols and soils of vertic nature performed better in wheat production than the Cambisols and Luvisols types owing to smectite clays' superior K adsorption-release dynamics. The quadratic plateau and linear regression models estimated the optimum K in soil solution (24.48 to 30.75 mg K L^{-1}) and grain (1.19 to 1.30%) for the critical (95%) yield of wheat at the study area.

This study evaluated how the distinct composition of K-containing organic (cattle manure ash, CMA) and inorganic (muriate of potash, MOP) amendments affects some selected chemical properties of soils in the sub-watershed. The results revealed the importance of their integrated usage to balance immediate nutrient availability with long-term soil health improvements. For example, the CMA has improved soil reaction (pH), OC content, and CEC due to its alkaline nature and organo-mineral complexation, whilst the MOP caused salinization from the Cl^- with reduced Ca^{2+}/Mg^{2+} retention via competitive exchange. The combined application of CMA:MOP at 37.5 to 62.5% ratios achieved immediate K release (MOP) and sustained supply (CMA) with better P availability than their solo uses. The Vertic Cambisols exhibited higher pH buffering ($\Delta pH < 0.3$) at an optimal (50:50) CMA:MOP ratio, whilst Pisoplinthic soils required maximum (≥ 75%) CMA proportion to mitigate acidity. Hence, prioritize CMA in acidic, low OC soils (Pisoplinthic Cambisols) and blended ratios in high-buffer soils (Vertic Cambisols).

The study unveiled the effects of combined organic (cattle manure ash, CMA) and inorganic (muriate of potash, KCl) potassium amendments, along with recommended rates of N and P on wheat growth, yield, and nutrient harvest indices on five soil types in the sub-watershed. In general, the integrated K management strategy at a 37.5% CMA + 62.5 KCl rate maximized yields on the Pellic Vertisols, Vertic Cambisols, and Pisoplinthic Luvisols, while a 50:50 ratio was optimal on

Pisoplinthic and Plinthofractic Cambisols. The responses are attributed to the synergy of KCl supplied in immediate K, and CMA improved long-term soil structure and microbial activity. Moreover, nutrient harvest indices (NHI, PHI, KHI) varied significantly depending on soil type and blending the amendment ratios. High KCl-containing blends favored NHI and KHI in most soils, whereas CMA-dominant blends optimized PHI and KHI (specifically in Pellic Vertisols). Though Ethiopia's annual K deficit (-32 kg·ha^{-1}) impairs wheat yield gaps (≥ 2.5 tons ha^{-1}), the current N-P focused fertilization approach has neglected K. Consequently, it is imperative to develop a balanced N-P-K amendment strategy considering inherent soil properties (texture, pH, CEC) for maximizing nutrient-use efficiency.

The study articulated a need for site-specific agricultural planning in the research area, where soil heterogeneity demands localized solutions to enhance productivity and sustainability. Since the absence of inclusive evidence on the nature and distribution of soils often limits agricultural development in Ethiopia, a detailed soil characterization, classification, and mapping work in other topographically diverse regions to guide sustainable agriculture. Consequently, it is recommended to explore the impacts of topography on the geo-spatial variability of soil properties and their fertility implications for enhancing crop production in the study area. The study also revealed the importance of implementing a phased K application aligned with desorption kinetics, while prioritizing soils with lower K adsorption capacity for fertilization. Hence, future research should investigate clay mineralogy to clarify K reserve dynamics and degradation thresholds, and include subsoil layers for holistic K management frameworks. However, a crop-specific K response study is recommended to observe overall K release patterns and validate the model's predictions under diverse field conditions. Additional research on formulating balanced fertilization of K and other essential elements alongside vital agronomic and soil management practices (split K fertilization schedules, water requirements, and crop rotation strategies) is critical to enhance profitable wheat production in the study area. Ultimately, investigating CMA's carbon sequestration potential, heavy metal mitigation capacity in amended soils, and microbial diversity is needed to draw sound conclusions on the effects of the blended applications. However, further research on other crops, micronutrients, and long-term soil fertility impacts of combined CMA-KCl usage must be done under field conditions to achieve a complete understanding of the balanced and integrated fertilization practices.

9. APPENDICES

Appendix Table 1. On-field topographic, physical, and morphological properties of identified soil map units

SMU Id.	Slope (%)	Soil Depth (cm)	Soil Color (Munsell Code)		Surface Soil Texture (Feel)	Soil Consistency			
			Dry	Moist		Dry	Moist	Plasticity	Stickiness
SMU 01	15-30	50-100	Dark yellowish brown (10YR 3/6)	Very dark brown (7.5 YR 2.5/3)	Clay loam	SHA	VFR	SPL	SST
SMU 02	5-10	100-120	Very dark grayish brown (10YR 3/2)	Very dark gray (7.5 YR 3/1)	Clay	HA	FR	VPL	VST
SMU 03	15-30	50-100	Dark yellowish brown (10YR 3/4)	Very dark brown (7.5 YR 2.5/2)	Clay loam	SHA	VFR	PL	ST
SMU 04	5-10	>120	Dark brown (10YR 3/3)	Very dark brown (7.5 YR 2.5/2)	Clay loam	SHA	FR	PL	ST
SMU 05	10-15	100-120	Dark brown (10YR 3/3)	Very dark brown (7.5 YR 2.5/3)	Clay loam	SHA	VFR	VPL	ST
SMU 06	0-2	>120	Very dark grayish brown (10YR 3/2)	Very dark gray (7.5 YR 3/1)	Clay	VHA	VFR	PL	VST
SMU 07	2-5	>120	Dark yellowish brown (10YR 4/4)	Dark brown (7.5 YR 3/2)	Clay	SHA	VFR	PL	ST
SMU 08	10-15	100-120	Dark brown (10YR 3/3)	Very dark brown (7.5 YR 2.5/2)	Clay	SHA	FR	PL	ST
SMU 09	10-15	100-120	Dark yellowish brown (10YR 3/6)	Dark brown (7.5 YR 3/2)	Clay	HA	FR	VPL	VST
SMU 10	15-30	50-100	Dark yellowish brown (10YR 3/6)	Very dark brown (7.5 YR 2.5/2)	Clay loam	HA	FR	PL	ST
SMU 11	10-15	>120	Dark brown (10YR 3/3)	Very dark gray (7.5 YR 3/1)	Clay	VHA	FI	SPL	SST
SMU 12	15-30	100-120	Very dark grayish brown (10YR 3/2)	Very dark gray (7.5 YR 3/1)	Clay	VHA	FI	VPL	VST
SMU 13	15-30	100-120	Very dark brown (10YR 2/2)	Very dark brown (7.5 YR 2.5/2)	Clay	VHA	FR	VPL	VST
SMU 14	10-15	100-120	Dark yellowish brown (10YR 4/4)	Very dark brown (7.5 YR 2.5/2)	Clay loam	HA	FR	VPL	VST
SMU 15	15-30	50-100	Dark yellowish brown (10YR 3/4)	Very dark brown (7.5 YR 2.5/3)	Clay loam	HA	FR	PL	ST
SMU 16	15-30	100-120	Dark yellowish brown (10YR 3/4)	Very dark brown (7.5 YR 2.5/2)	Clay	SHA	VFR	PL	ST
SMU 17	10-15	100-120	Dark yellowish brown (10YR 4/4)	Dark brown (7.5 YR 3/3)	Clay loam	SHA	VFR	PL	ST
SMU 18	5-10	100-120	Dark yellowish brown (10YR 3/4)	Very dark brown (7.5 YR 2.5/3)	Clay	VHA	FI	VPL	VST
SMU 19	10-15	>120	Dark yellowish brown (10YR 3/4)	Dark brown (7.5 YR 3/2)	Clay	HA	FR	VPL	VST
SMU 20	15-30	50-100	Dark yellowish brown (10YR 3/6)	Very dark brown (7.5 YR 2.5/2)	Clay loam	SHA	VFR	SPL	SST
SMU 21	5-10	>120	Dark brown (10YR 3/3)	Dark brown (7.5 YR 3/2)	Clay loam	SHA	VFR	PL	ST
SMU 22	10-15	100-120	Dark brown (10YR 3/3)	Very dark brown (7.5 YR 2.5/2)	Clay loam	SHA	FR	PL	ST
SMU 23	15-30	50-100	Dark yellowish brown (10YR 4/4)	Dark brown (7.5 YR 3/2)	Clay loam	SHA	FR	PL	ST
SMU 24	15-30	50-100	Dark yellowish brown (10YR 4/4)	Dark brown (7.5 YR 3/2)	Clay loam	SHA	FR	PL	ST
SMU 25	10-15	100-120	Dark brown (10YR 3/3)	Dark brown (7.5 YR 3/3)	Clay loam	SHA	VFR	SPL	SST
SMU 26	5-10	100-120	Very dark grayish brown (10YR 3/2)	Very dark gray (7.5 YR 3/1)	Clay	HA	VFR	VPL	VST
SMU 27	15-30	50-100	Dark yellowish brown (10YR 3/4)	Dark brown (7.5 YR 3/2)	Clay loam	SHA	FR	PL	ST
SMU 28	5-10	>120	Dark yellowish brown (10YR 4/4)	Very dark brown (7.5 YR 2.5/2)	Clay loam	SHA	VFR	SPL	SST
SMU 29	5-10	100-120	Very dark grayish brown (10YR 3/2)	Very dark gray (7.5 YR 3/1)	Clay	VHA	FI	VPL	VST
SMU 30	2-5	>120	Dark yellowish brown (10YR 3/4)	Dark brown (7.5 YR 3/3)	Clay	HA	FR	VPL	ST
SMU 31	5-10	>120	Dark yellowish brown (10YR 4/4)	Very dark brown (7.5 YR 2.5/2)	Clay	SHA	VFR	PL	ST
SMU 32	5-10	>120	Dark yellowish brown (10YR 3/4)	Very dark brown (7.5 YR 2.5/3)	Clay	SHA	VFR	PL	ST

Appendix Table 2. Site characteristics of pedons along the toposequence of the sub-watershed

Basic information	Profiles					
	Summit	Shoulder	Back-slope	Foot-slope	Toe-slope	Depression
Coordinates (Latitude/Longitude)	09°34’58’’N 39°33’42’’E	09°34’53’’N 39°33’36’’E	09°34’48’’N 39°33’33’’E	09°34’42’’N 39°33’25’’E	09°34’23’’N 39°33’18’’E	09°34’11’’N 39°33’18’’E
Altitude (masl)	2957	2946	2927	2894	2859	2845
Major landform	Level land, plain	Sloping land, medium-gradient escarpment	Sloping land, medium-gradient hill	Sloping land, dissected plain	Level land, depression	Level land, depression
Slope gradient (%)	Level (0.5)	Strongly sloping (10)	Moderately steep (17)	Strongly sloping (12)	Sloping (5)	Gently sloping (2)
Slope form and surface flow pathway	Straight-Straight	Straight-Concave	Straight-Concave	Straight-Straight	Straight-Straight	Straight-Straight
Land use	Grazing	Fallowing	Fallowing	Fallowing	Grazing	Grazing
Geologic materials	Basic Igneous rock (Basalt)	Basic Igneous rock (Basalt)	Basic Igneous rock (Basalt)	Basic Igneous rock (Basalt)	Basic Igneous rock (Basalt)	Basic Igneous rock (Basalt)
Parent materials	Weathered products of rocks with a high amount of a 2:1 expanding clay type (smectite)	Saprolite	Saprolite	Variety of fine to medium textured unconsolidated materials from alluvial and colluvial deposits	Fine-textured materials (clay and silt fractions) derived from alluvial deposit	Fine-textured materials (clay and silt fractions) derived from alluvial deposit
Rock outcrops	None	None	None	None	None	None
Surface cover (%) and size dimension (cm) of coarse fragments	None	Many (15-40) stones (6-20)	Common (5-15) boulders (20-60)	Few (2-5) stones (6-20)	None	None
Erosion category, affected area (%), and degree of erosion or material deposition	No evidence	Rill erosion, 10-25, moderate	Rill erosion, 10-25, moderate	Sheet erosion, 5-10, slight	Deposition by water	Deposition by water
Surface sealings	None	None	None	None	None	None
Width (cm), depth (cm) and distance between (m) surface cracks	Very wide (5-10), very deep (>20) and moderately wide spaced (0.5-2)	Wide (2-5), very deep (>20) and widely spaced (2-5)	None	Medium (<1), medium (2-10) and widely spaced (2-5)	None	None
Soil type (WRB)	Vertisol	Cambisol	Leptosol	Luvisol	Cambisol	Cambisol
Local soil name	*Mererie*	*Areda*	*Ajara*	*Bodda*	*Abolsie*	*Abolsie*

Appendix Table 3. Correlation matrix for linear relationships between soil parameters

	Sand	Silt	Clay	pH	EC	OC	TN	Av. P	Ex. Na	Ex. K	Ex. Ca	Ex. Mg	CEC	Av. Fe	Av. Mn	Av. Cu	Av. Zn
Sand	1.00																
Silt	0.31	1.00															
Clay	-0.82***	-0.80***	1.00														
pH	-0.53**	-0.46**	0.61***	1.00													
EC	-0.18	-0.48**	0.40*	0.04	1.00												
OC	0.37*	0.69***	-0.65***	-0.45**	-0.52**	1.00											
TN	0.29	0.66***	-0.59***	-0.42*	-0.62***	0.93***	1.00										
Av. P	0.28	0.55**	-0.51**	-0.42*	-0.29	0.42*	0.50**	1.00									
Ex. Na	-0.55**	-0.42*	0.60***	0.71***	0.49**	-0.66***	-0.70***	-0.46**	1.00								
Ex. K	-0.40*	-0.42*	0.51**	0.39*	0.22	-0.32	-0.22	-0.04	0.34	1.00							
Ex. Ca	-0.48**	-0.15	0.39*	0.39*	-0.06	-0.16	-0.14	-0.25	0.40*	0.28	1.00						
Ex. Mg	0.22	-0.06	-0.10	-0.05	0.22	0.06	-0.05	-0.11	-0.11	-0.33	-0.70***	1.00					
CEC	-0.36*	-0.39*	0.46**	0.48**	0.21	-0.21	-0.30	-0.53**	0.39*	0.04	0.31	0.44*	1.00				
Av. Fe	0.61***	0.65***	-0.78***	-0.69***	-0.34	0.64***	0.67***	0.54**	-0.65***	-0.54**	-0.51**	0.16	-0.52**	1.00			
Av. Mn	0.61***	0.54**	-0.71***	-0.50**	-0.37*	0.65***	0.57***	0.44***	-0.60***	-0.57***	-0.44*	0.24	-0.30	0.70***	1.00		
Av. Cu	0.44*	0.52**	-0.59***	-0.34	-0.28	0.66***	0.64***	0.39	-0.53**	-0.38*	-0.42*	0.24	-0.31	0.71***	0.52**	1.00	
Av. Zn	-0.12	0.05	0.04	-0.08	-0.18	0.08	0.06	-0.20	-0.09	-0.19	0.26	-0.08	0.16	-0.01	0.11	-0.25	1.00

*** Very highly significant ($P \leq 0.001$)

** Highly significant ($P \leq 0.01$)

* Significant ($P \leq 0.05$)

Note: The pair(s) of variables with positive correlation coefficients and P values below 0.05 tend to increase together. For the pairs with negative correlation coefficients and P values below 0.05, one variable tends to decrease while the other increases. For pairs with P values greater than 0.05, there is no significant relationship between the two variables.

Appendix Table 4. Pearson simple correlation matrix between potassium forms and some selected soil properties

		Soil parameters													
Soil types	K-form	pH	OC	Ex. K	Ex. Na	Ex. Ca	Ex. Mg	CEC	Sand	Silt	Clay	WSK	AEK	NEK	MIK
Plinthofractic Cambisols	WSK	-0.868	-0.358	-0.813	-1.000**	0.005	-0.415	-0.070	0.864	-0.503	0.003	1	1.000**	1.000**	1.000**
	AEK	-0.866	-0.356	-0.811	-1.000**	0.008	-0.412	-0.067	0.866	-0.501	0.001	1.000**	1	1.000**	1.000**
	NEK	-0.866	-0.356	-0.811	-1.000**	0.008	-0.412	-0.067	0.866	-0.501	0.001	1.000**	1.000**	1	1.000**
	MIK	-0.866	-0.355	-0.811	-1.000**	0.009	-0.412	-0.066	0.866	-0.500	0.000	1.000**	1.000**	1.000**	1
Pisoplinthic Cambisols	WSK	-0.983	0.910	-0.925	-0.959	0.020	-0.410	-0.622	-0.869	0.863	0.007	1	1.000**	1.000**	1.000**
	AEK	-0.983	0.911	-0.924	-0.960	0.017	-0.408	-0.620	-0.868	0.864	0.004	1.000**	1	1.000**	1.000**
	NEK	-0.982	0.913	-0.923	-0.961	0.013	-0.405	-0.617	-0.866	0.866	0.001	1.000**	1.000**	1	1.000**
	MIK	-0.982	0.913	-0.923	-0.961	0.013	-0.404	-0.616	-0.866	0.866	0.000	1.000**	1.000**	1.000**	1
Relictistagnic Cambisols	WSK	-0.492	-0.611	0.546	0.199	-0.107	-0.071	0.464	-0.871	0.010	0.492	1	1.000**	1.000**	1.000**
	AEK	-0.499	-0.617	0.539	0.190	-0.115	-0.079	0.456	-0.867	0.002	0.499	1.000**	1	1.000**	1.000**
	NEK	-0.498	-0.617	0.540	0.191	-0.114	-0.079	0.457	-0.867	0.002	0.498	1.000**	1.000**	1	1.000**
	MIK	-0.500	-0.619	0.538	0.189	-0.116	-0.081	0.455	-0.866	0.000	0.500	1.000**	1.000**	1.000**	1
Pisoplinthic Luvisols	WSK	0.004	0.892	0.728	-0.651	-0.609	-0.715	-0.609	0.864	-0.864	0.864	1	1.000**	-1.000**	1.000**
	AEK	0.001	0.894	0.731	-0.654	-0.606	-0.712	-0.606	0.866	-0.866	0.866	1.000**	1	-1.000**	1.000**
	NEK	0.001	-0.894	-0.732	0.655	0.605	0.711	0.605	-0.866	0.866	-0.866	-1.000**	-1.000**	1	-1.000**
	MIK	0.000	0.894	0.731	-0.655	-0.606	-0.712	-0.605	0.866	-0.866	0.866	1.000**	1.000**	-1.000**	1
Vertic Cambisols	WSK	0.864	-0.178	0.234	0.330	0.660	0.991	0.735	-0.192	0.868	-0.944	1	1.000**	1.000**	1.000**
	AEK	0.866	-0.181	0.232	0.328	0.662	0.991	0.737	-0.189	0.866	-0.945	1.000**	1	1.000**	1.000**
	NEK	0.866	-0.181	0.232	0.328	0.662	0.991	0.737	-0.190	0.866	-0.945	1.000**	1.000**	1	1.000**
	MIK	0.866	-0.182	0.231	0.327	0.662	0.991	0.738	-0.189	0.866	-0.945	1.000**	1.000**	1.000**	1
Pellic Vertisols	WSK	0.503	0.484	-0.364	-0.983	-0.718	-0.289	-0.613	0.868	0.497	-0.718	1	-1.000**	1.000**	1.000**
	AEK	-0.499	-0.481	0.360	0.982	0.715	0.285	0.610	-0.866	-0.501	0.721	-1.000**	1	-1.000**	-1.000**
	NEK	0.500	0.482	-0.362	-0.982	-0.716	-0.286	-0.611	0.866	0.500	-0.720	1.000**	-1.000**	1	1.000**
	MIK	0.500	0.481	-0.361	-0.982	-0.715	-0.285	-0.611	0.866	0.500	-0.721	1.000**	-1.000**	1.000**	1

*. Correlation is significant at the 0.05 level.

**. Correlation is significant at the 0.01 level.

WSK: water-soluble, AEK: ammonium exchangeable, NEK: non-exchangeable, and MIK: mineral potassium forms

Appendix Table 5. Effects of CMA and MOP on total nutrient concentrations of wheat grain

Treatments	Parameters														
	Grain N concentration (%)					Grain P concentration (%)					Grain K concentration (%)				
	Soil types														
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	2.77^{g}	2.85^{e}	2.76^{g}	2.77^{g}	2.77^{f}	0.51^{f}	0.76^{f}	0.53^{g}	0.61^{e}	0.73^{e}	0.99^{c}	1.18^{f}	1.17^{f}	1.12^{c}	1.19^{e}
2	3.10^{e}	3.07^{a-d}	2.95^{de}	2.94^{f}	2.99^{cde}	0.76^{d}	0.91^{ab}	0.78^{bc}	0.75^{c}	0.99^{a}	1.32^{b}	1.30^{e}	1.40^{abc}	1.29^{ab}	1.54^{a}
3	3.15^{de}	3.05^{cd}	3.01^{c}	3.03^{de}	3.06^{bcd}	0.83^{c}	0.84^{cd}	0.81^{b}	0.73^{c}	0.82^{cd}	1.41^{ab}	1.48^{cd}	1.36^{b-e}	1.33^{ab}	1.32^{bc}
4	3.20^{cd}	3.03^{bcd}	3.08^{b}	3.17^{c}	3.09^{bc}	0.93^{b}	0.88^{bc}	0.92^{a}	0.96^{a}	0.82^{cd}	1.37^{ab}	1.58^{abc}	1.43^{ab}	1.37^{a}	1.32^{bc}
5	3.34^{b}	3.16^{abc}	3.08^{b}	3.27^{b}	3.24^{a}	1.02^{a}	0.82^{d}	0.76^{cd}	0.85^{b}	0.90^{b}	1.44^{a}	1.54^{bc}	1.38^{bcd}	1.34^{ab}	1.25^{cde}
6	3.49^{a}	3.23^{a}	3.14^{a}	3.62^{a}	3.25^{a}	1.04^{a}	0.81^{de}	0.75^{cd}	0.86^{b}	0.91^{b}	1.42^{a}	1.62^{ab}	1.47^{a}	1.37^{a}	1.23^{cde}
7	3.47^{a}	3.20^{ab}	3.02^{c}	3.18^{bc}	3.14^{ab}	1.04^{a}	0.94^{a}	0.73^{de}	0.75^{c}	0.92^{b}	1.39^{ab}	1.68^{a}	1.34^{cde}	1.28^{b}	1.21^{de}
8	3.29^{bc}	3.10^{a-d}	2.98^{bcd}	3.05^{d}	3.03^{bcd}	0.77^{d}	0.86^{c}	0.70^{ef}	0.74^{c}	0.85^{c}	1.40^{ab}	1.52^{bc}	1.29^{e}	1.29^{ab}	1.21^{de}
9	3.17^{de}	3.06^{bcd}	2.93^{e}	2.95^{ef}	2.97^{de}	0.68^{e}	0.80^{def}	0.67^{f}	0.68^{d}	0.80^{d}	1.45^{a}	1.38^{de}	1.31^{de}	1.28^{b}	1.28^{bcd}
10	2.89^{f}	2.95^{de}	2.86^{f}	2.80^{g}	2.90^{e}	0.54^{f}	0.77^{ef}	0.55^{g}	0.65^{de}	0.78^{d}	1.42^{a}	1.32^{e}	1.33^{cde}	1.29^{ab}	1.36^{b}
LSD (0.05)	0.09	0.17	0.05	0.09	0.11	0.04	0.05	0.04	0.05	0.04	0.09	0.11	0.08	0.09	0.09
CV (%)	1.64	3.16	0.87	1.69	2.13	2.73	3.14	2.81	3.74	2.89	3.93	4.54	3.53	3.91	4.24

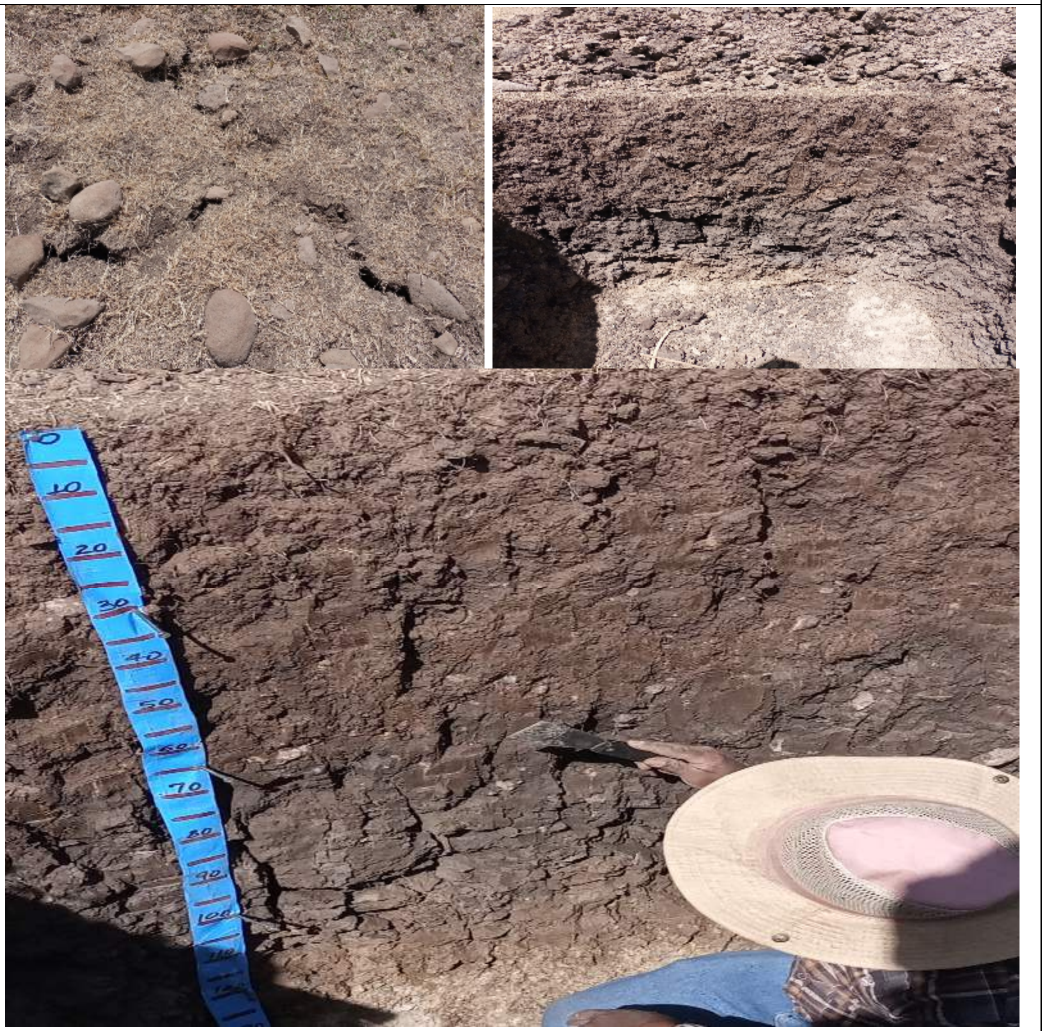
Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols
NB. Means sharing the same letters in a column are statistically alike at ≤ 0.0001% probability level

Appendix Table 6. Effects of CMA and MOP on total nutrient concentrations of wheat straw

Treatments	Parameters														
	Straw N concentration (%)					Straw P concentration (%)					Straw K concentration (%)				
	Soil types														
	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL	PeV	VeC	PpC	PfC	PpL
1	0.72^{g}	0.93^{f}	0.88^{f}	1.01^{g}	0.63^{g}	0.48^{f}	0.43^{h}	0.49^{h}	0.56^{g}	0.50^{f}	2.38^{f}	1.58^{e}	1.98^{g}	2.66^{g}	2.51^{f}
2	0.93^{e}	1.08^{d}	1.01^{bcd}	1.19^{f}	0.88^{e}	0.54^{de}	0.50^{f}	0.64^{e}	0.62^{e}	0.64^{d}	3.64^{c}	4.17^{b}	3.17^{d}	3.96^{b}	3.41^{c}
3	0.90^{ef}	1.03^{e}	1.02^{bc}	1.28^{e}	0.89^{e}	0.56^{cd}	0.57^{d}	0.67^{d}	0.71^{d}	0.74^{c}	3.70^{c}	3.99^{b}	3.84^{b}	3.72^{cd}	4.01^{a}
4	1.04^{d}	1.10^{d}	1.05^{b}	1.29^{de}	1.04^{c}	0.58^{c}	0.60^{c}	0.77^{c}	0.74^{c}	0.77^{b}	3.18^{d}	3.51^{d}	2.76^{f}	3.86^{bc}	3.46^{c}
5	1.25^{a}	1.15^{c}	1.39^{a}	1.62^{a}	1.14^{b}	0.56^{cd}	0.61^{bc}	0.82^{b}	0.92^{a}	0.86^{a}	2.80^{e}	3.47^{d}	2.94^{e}	4.66^{a}	3.90^{a}
6	1.12^{bc}	1.28^{b}	1.04^{bc}	1.44^{b}	1.11^{b}	0.62^{b}	0.63^{b}	0.85^{a}	0.78^{b}	0.85^{a}	2.66^{e}	3.69^{cd}	4.17^{a}	3.34^{e}	2.80^{e}
7	1.14^{b}	1.17^{c}	0.99^{cd}	1.30^{de}	1.20^{a}	0.66^{a}	0.65^{a}	0.58^{f}	0.70^{d}	0.76^{b}	2.62^{e}	4.68^{a}	4.03^{a}	3.80^{bcd}	3.07^{d}
8	1.08^{c}	1.63^{a}	0.97^{de}	1.34^{d}	1.02^{cd}	0.55^{d}	0.55^{e}	0.58^{f}	0.62^{e}	0.65^{d}	3.18^{d}	4.16^{b}	4.12^{a}	3.68^{d}	2.86^{e}
9	1.04^{d}	1.08^{d}	0.95^{e}	1.39^{c}	1.01^{d}	0.55^{d}	0.47^{g}	0.53^{g}	0.60^{ef}	0.58^{e}	4.01^{b}	3.94^{bc}	3.44^{c}	2.82^{fg}	3.67^{b}
10	0.87^{f}	0.99^{e}	0.94^{e}	1.17^{f}	0.80^{f}	0.51^{e}	0.44^{h}	0.50^{h}	0.58f^{g}	0.59^{e}	4.66^{a}	3.44^{d}	3.06^{de}	2.86^{f}	3.14^{d}
LSD (0.05)	0.04	0.05	0.05	0.05	0.03	0.03	0.03	0.02	0.04	0.03	0.19	0.26	0.15	0.16	0.13
CV (%)	2.58	2.50	2.63	2.22	1.61	3.47	2.69	1.88	3.02	2.16	3.89	4.13	2.52	2.67	2.27

Where: PeV= Pellic Vertisols, VeC= Vertic Cambisols, PpC= Pisoplinthic Cambisols, PfC= Plinthofractic Cambisols, PpL= Pisoplinthic Luvisols
NB. Means sharing the same letters in a column are statistically alike at ≤ 0.0001% probability level

Some Additional Pictures

Pedons and Profiles at the Summit Position	**Pedons and Profiles at the Shoulder Position**
	

Pedons and Profiles at the Back-slope Position	**Pedons and Profiles at the Foot-slope Position**
	

Pedons and Profiles at the Toe-slope Position	Pedons and Profiles at the Bottom-depression Position
	

Cattle dung-cake and Cattle manure ash

Sample preparation and lab work partly

Greenhouse works partly