SOIL CHARACTERIZATION AND EFFECT OF INTEGRATED SOIL FERTILITY MANAGEMENT ON SOIL PROPERTIES AND COMMON BEAN (*Phaseolus vulgaris* L.) YIELD IN DIFFERENT SOIL TYPES OF SOUTHERN ETHIOPIA

PhD DISSERTATION

BY

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HAWASSA UNIVERSITY

COLLEGE OF AGRICULTURE

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PHILOSOPHY IN SOIL SCIENCE

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SCHOOL OF GRADUATE STUDIES HAWASSA UNIVERSITY

ADVISORS' APPROVAL SHEET

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This certifies that the dissertation titled "**Soil Characterization and Effect of Integrated Soil Fertility Management on Soil Properties and Common Bean (*Phaseolus vulgaris* L.) Yield in Different Soil Types of Southern Ethiopia**" has been submitted by **Rameto Wabela Buser** for the degree of Doctor of Philosophy (PhD) in Soil Science at the Graduate Program of the School of Plant and Horticultural Sciences. The student, ID № PhD/SoSc/0004/12, conducted the research under our supervision. We recommend that the student has fulfilled all requirements and can submit the dissertation to the school.

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As members of the Board of Examiners for the final PhD degree defense, we have thoroughly read and evaluated the dissertation titled "**Soil Characterization and Effect of Integrated Soil Fertility Management on Soil Properties and Common Bean (*Phaseolus vulgaris* L.) Yield in Different Soil Types of Southern Ethiopia**" by **Rameto Wabela Buser**. We recommend that it be accepted as meeting the dissertation criteria for the Doctor of Philosophy degree in **Soil Science.**

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DEDICATION

This dissertation is dedicated to the loving memory of my father, Wabela Buser Betkero. I owe my current position to the strong foundation he laid for me and the unwavering support he provided. Baba, I wish you could see the achievements I have made!

STATEMENT BY THE AUTHOR

I declare that this PhD dissertation is my original work and that I have duly acknowledged all sources of materials used in its preparation. This dissertation is being submitted in partial fulfillment of the requirements for a PhD degree at Hawassa University and will be available at the university library for borrowing in accordance with library regulations. It has not been submitted to any other institution for the purpose of obtaining an academic degree, diploma, or certificate. Brief quotations from this dissertation are permitted without special permission, as long as proper acknowledgment of the source is provided. Requests for permission to use extensive quotations or reproduce the manuscript in whole or in part can be considered by the head of the major department or the Dean of the School of Graduate Studies if it is deemed beneficial for scholarly purposes. Otherwise, permission must be directly from the author.

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Date of Submission: January, 2026

BIOGRAPHICAL SKETCH

The author, Rameto Wabela Buser, was born on 05 September 1988 in Werabe Ketema Administration of the Central Ethiopia Region to his parents Wabela Buser and Shfite Oumer. He attained his primary and secondary education in Hawassa Hikdar, Tabor and Addis Ketema before enrolling at Hawassa Tabor Preparatory School in 2004. He obtained his first degree in AREM from Hawassa University College of Agriculture in 2008. Starting his professional career at Hulbarage Wereda's Finance and Economic Development Office, he held developmental planner, then become head of land and administration, head of youth and sport, head of rural politics, and head of agriculture and rural development and deputy manager, respectively. Pursuing his MSc in soil science at Hawassa University's School of Plant and Horticultural Science, he graduated in 2016 and then served as Wereda administrator in Hulbarage Wereda in 2016 and 2017. Subsequently, he led the Siltie Zone enterprise and industry office before starting on his PhD studies and joining Werabe University. Joining Werabe University as a lecturer in 2019, he later returned to the School of Plant and Horticultural Science at Hawassa University College of Agriculture to pursue his PhD in soil science in 2019.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAS	Atomic absorption spectrophotometer
ANOVA	Analysis of variance
Avail. P	Available soil phosphorus
BD	Bulk Density
Cmol/c	Centimole per charge
CRD	Completely Randomized Design
CSA	Central Statistics Agency
DTPA	Diethylenetriaminepentaacetic acid
EC	Electrical Conductivity
EPR	External Phosphorus Requirement
ESP	Exchangeable Sodium Percentage
Ha	Hectare
HNMSA	Hawassa National Meteorological Service Agency
HU	Hawassa University
IUSS	International Union of Soil Sciences
Logkf	Intercept of Freundlich equation
LSD	Fisher's least significance difference
m.a.s.l	Meter Above Sea Level
Max	Maximum
MPBC	Maximum phosphorus buffering capacity
Min	Minimum
NH_4Oac	Ammonium acetate
SOC	Soil organic Carbon
OM	Organic Matter
PBS	Percent Base Saturation
ppm	Parts per million
RCBD	Randomized Complete Block Design
RF	Rainfall
RSG	Reference Soil Group

R	Correlation Coefficient
Rpm	Revolution per Minute
SAS	Statistical Analysis System
SGC	School Graduate Committee
SPR	Standard Phosphorus requirement
SSA	Sub-Sahara África
ST	USDA soil taxonomy
TN	Total Nitrogen
USDA	United States Department of Agriculture
WRB	World Reference Base for Soil Resources
Xm	Langmuir sorption maximum

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STRUCTURE OF THE DISSERTATION

This dissertation consists of six chapters.

The chapters in the dissertation are:

Chapter I is an overview of the study and description of the study area.

Chapter II of this dissertation focuses on characterizing and classifying various soil types found in southern Ethiopia. The goal of this chapter is to describe the morphological and physicochemical properties that determine the classification of different soil types according to the World Reference Base for Soil Resources (WRB). Three representative profiles from three different sites were studied, along with soil auger samples taken from the surrounding areas. This chapter also assesses the soil fertility status of the area, setting the baseline for the following chapter.

Chapter III of this dissertation focuses on phosphorus sorption characteristics and the effect of integrated soil fertilizers on phosphorus sorption. The objective is to investigate how phosphorus availability varies with soil type and integrated fertilizers, and to identify the most suitable amendment for different soil types at each site.

Chapter IV of this dissertation aimed to investigate the effect of native rhizobia population on rhizobia inoculation, nitrogen application, and the symbiotic effectiveness in different soil types. The native rhizobia population was determined by using the most probable number enumeration technique. The relative symbiotic effectiveness showed the performance of inoculated plants with reference or control treatment. This index evaluates how effective rhizobia is in promoting plant growth through symbiosis (typically nitrogen fixation).

Chapter V of this dissertation was intended to evaluate the combined soil fertility management improving the soil properties and common bean yield and yield component under two consecutive years in the field study. For this study, the samples of compost and biochar were characterized for liming and other properties and applied separately or combined along with inorganic P fertilizer. Finally, the general conclusion drawn from the entire study are provided. Figures and tables are embedded in the text and Appendices have been placed at the end.

Chapter VI of the overview of the study work as summary, conclusion and recommendation

Published Articles and Manuscripts under review:

I. Wabela, R., Abera, G., Lemma, B. and Gobena, A. 2024. Characterization and Classification of Soils for Selected Sites in Southern Ethiopia. Tropical and Subtropical Agroecosystems 27 (2024): Art. No. 148 http://doi.org/10.56369/tsaes.5764 **[*Published*]**

II. Wabela, R., Abera, G., Lemma, B. and Gobena, A., 2025. Effects of Integrated Soil Fertility Management on Soil Properties and Phosphorus Sorption Characteristics at Three Soil Types in Southern Ethiopia. Journal of Plant Nutrition and Soil Science, 2025; 188:507–518 https://doi.org/10.1002/jpln.12005 **[*Published*]**

III. Wabela, R., Abera, G., Lemma, B. and Gobena, A., 2025. Effect of Native Rhizobia Population on Commercial Rhizobium Inoculation and Yield of Common Bean (*Phaseolus vulgaris* L.) in Relation to Symbiotic Effectiveness. [*Under Peer Review (Journal of* Soil Science and Plant Nutrition**].**

IV. Wabela, R., Abera, G., Lemma, B. and Gobena, A., 2024. Effects of integrated fertilizer application on selected soil properties and yield attributes of common bean (*Phaseolus vulgaris* L.) on different soil types, Heliyon, 10(19). https://doi.org/10.1016/j.heliyon.2024.e38163 **[*Published*]**

Soil Characterization and Effect of Integrated Soil Fertility Management on Soil Properties and Common Bean (*Phaseolus vulgaris* L.) Yield in Different Soil Types of Southern Ethiopia

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GENERAL ABSTRACT

Declining soil fertility is a major challenge for crop production in southern Ethiopia. Despite the potential of integrated soil fertility management (ISFM), its effects on soil properties and common beans yield remain inadequately investigated. Therefore, this study was conducted to (1) characterize and classify soils at selected sites, (2) assess P sorption characteristics and the effects of ISFM on P sorption characteristics, (3) quantify native rhizobia populations capable of nodulating common beans, and (4) evaluate the effects of integrated application of inorganic, organic, and biofertilizer on soil properties and yield components of common beans. The research was carried out in three sites of southern Ethiopia: Kokate, Hawassa, and Alage. Three profiles, one from each experimental site, were excavated and characterized. In total, 27 soil samples were collected (9 composite surface samples and 18 from distinct horizons) and analyzed for morphological, physical, and chemical properties. Phosphorus sorption isotherms of study soils were determined by batch equilibrium methods, using the Langmuir and

*Freundlich models. After the incubation experiment, a laboratory analysis was conducted to evaluate the impact of ISFM on the P sorption characteristics of soils collected from each site. For this study, 54 composite soil samples were collected (6 treatments x 3 replications x 3 sites). Native rhizobia abundance was assessed through laboratory and lath house experiments in 2021–2022 using the most probable number (MPN) technique. The pot experiment in the lath house used commercial rhizobia inoculant and inorganic nitrogen fertilizer as treatments, arranged in a completely randomized design (CRD). A total of 27 composite soil samples were collected for the present study (3 composites * 3 sites * 3 replications). Finally, field experiments were conducted for two consecutive cropping seasons (2021 and 2022) at all sites, arranged in RCBD design with three replications. The treatments included three levels of inorganic p fertilizer (0, 8.5, and 17 kg P ha^{-1} for Kokate; 0, 5.8, and 11.6 kg P ha^{-1} for Hawassa; and 0, 7.1, and 14.2 kg P ha^{-1} for Alage) combined with organic amendments (biochar or compost) and biofertilizer. The studied soils showed great heterogeneity in their properties. Based on WRB, the soils were classified as Luvisols (Kokate), Cambisols (Hawassa), and Fluvisols (Alage). This variability highlights the need for site-specific management practices. The analysis of P sorption showed that the Freundlich model better described P sorption characteristic than the Langmuir model. Among the soils, Luvisols had the highest P sorption capacity, while Cambisols had the lowest. Application of ISFM, such as biochar with inorganic P fertilizer in Luvisols and compost with inorganic P fertilizer in Cambisols and Fluvisols, significantly reduced P-sorption capacity. Native rhizobia populations capable of nodulating common beans varied significantly across sites. The lowest counts were found in Kokate, while Hawassa had the highest. Rhizobia abundance was strongly correlated with soil properties, cropping history, and bean yield components. Both inoculation and inorganic N fertilizer increased yield components, and their*

combination gave the highest yield. Relative symbiotic effectiveness ranged from 47% in Kokate to 67% in Hawassa, while absolute symbiotic efficiency varied between 76% and 144%. The commercial Rhizobium was more effective in soils with higher native rhizobia populations (Hawassa and Alage) compared to Kokate, where native rhizobia populations were low. Field experiment results confirmed that ISFM significantly improved soil properties and common bean yields. The integrated application of inorganic P fertilizers, organic inputs (compost or biochar), and biofertilizers increased soil pH, SOC, and avail P. Grain yields increase by 23% in Hawassa and 24% in Alage with the combined use of compost (5 t ha^{-1}) with 11.6 and 14.2 kg ha^{-1} P fertilizer,respectively. In Kokate, combining biochar (5 t ha^{-1}) with 17 kg P ha^{-1} fertilizer increased yield by 18%. Economic analysis revealed that ISFM practices were more profitable than single type of fertilizer use. The most profitable options were 5.8 and 7.1 kg P ha^{-1} + 5 t ha^{-1} compost in Hawassa and Alage and 17 kg P ha^{-1} + 5 t ha^{-1} biochar in Kokate. Overall, the initial fertility status of the soils was characterized by medium SOC and TN but low avail P and micronutrients, indicating generally low soil fertility. The results showed that site-specific ISFM practices can substantially improve soil fertility, crop yields, and profitability of common bean production in southern Ethiopia. This confirms that a "one-size-fits-all" approach is ineffective due to high soil variability, and tailored strategies are needed for sustainable common bean production in southern Ethiopia.

Key words: Abundance, Biochar, Compost, Crop yield, Freundlich P sorption, Profile, Rhizobia, Soil classification

CHAPTER ONE

1. GENERAL INTRODUCTION, SITE DESCRIPTION AND MATERIALS AND METHODS

1.1. Background of the Study

Among the major soil-related constraints, soil acidity is a serious challenge to crop production in Ethiopia's highlands (Kalkhora et al., 2019; Gemada, 2021; Warke, 2024; Regasa et al., 2025). Much of Ethiopia's highlands have acidic soil and low P availability due to high rainfall, which causes basic cation leaching (Melese et al., 2015; Ahmad et al., 2023; Guo et al., 2023; Warke, 2024). Approximately 43% of Ethiopian agricultural land is affected by soil acidity, with 28% of soils naturally acidic (pH 4.1-5.5) (Kassahun, 2015; Agegnehu et al., 2021). Soil acidity is influenced by various factors, including parent materials, leaching of basic cations, and the use of acid-forming mineral fertilizers like urea and diammonium phosphate (Obiri-Nyarko, 2012; Warke, 2024; Sharma et al., 2025). Thus, soil acidity is one of the key constraints to reduced nutrient availability, resulting in low crop yields (Elias and Agegnehu, 2020). Improving acidic soils through different soil amendments is crucial for enhancing soil properties and crop production (Agegnehu et al., 2021; Zhang et al., 2023).

Similarly**,** alkalinity threatens agricultural production, particularly in Ethiopia’s Rift Valley and lowlands. It poses a significant threat to farmers and agricultural production (Devkota et al., 2022; Shaaban et al., 2023). Ethiopia has around 11 million ha of salt-affected soil, primarily found in arid and semi-arid lowlands and Rift Valley areas (Kefyalew and Kibebew, 2016). The common causes of soil alkalinity are geological, hydrological, and pedological processes (Daba and Qureshi, 2021; Demo et al., 2025). The high pH, low permeability, low organic carbon, limited phosphorus availability, and reduced microbial activity of salt properties can hinder plant development and growth by altering soil physical and chemical properties (Daba and Qureshi, 2021; Gong et al., 2021; Shaaban et al., 2023; Xing et al., 2025; Zhao et al., 2025). Therefore, improving salt-affected soils through appropriate soil and agronomic solutions is crucial for enhancing crop production (Huang et al., 2008).

In Ethiopia, the majority of soils are deficient in P, which hinders crop productivity in sub-humid and semi-arid regions due to various factors like weathering, soil composition, and human activities (Melese et al., 2015; Alemayehu et al., 2017; Habte et al., 2022).

Phosphorus is primarily obtained from the weathering of primary soil minerals like apatite, which is the main natural source of P in crop soils. When P is released from rocks by weathering, it can cycle primarily through sorption-desorption, dissolution-precipitation, and mineralization-immobilization processes (Weil and Brady, 2017). However, more than 80% of P in tropical soils is immobile and unavailable for plant uptake due to processes like sorption, precipitation, and conversion to organic forms (Maluf et al., 2018). Approximately 23–49% of the applied P is adsorbed on Fe and Al oxides and hydroxides through surface complexation at hydroxyl sites in acidic soils (Antonangelo et al., 2020; Asrade et al., 2022; Saentho et al., 2022). In alkaline soils, 40–70% of applied P fertilizers can precipitate and become unavailable to plants over time, further limiting P availability for plant uptake (Hopkins and Ellsworth, 2005).

Soil characteristics such as pH, Fe/Al content, OM, CEC, exchangeable bases, and clay content play crucial roles in P behavior in soils (Antoniadis et al., 2016; Almajmaie et al., 2017; Asrade et al., 2022). The low soil pH promotes P fixation by Fe and Al compounds, while in calcareous soils, phosphate complexes can form, reducing P availability to plants (Rietra et al., 2001). Clay content directly and significantly increases the P sorption capacity of acidic, tropical soils (Getie et al., 2021; Lambano et al., 2022). As the clay percentage increases, soils can fix more P, meaning larger fertilizer input is needed before enough P becomes available for crop uptake. Additionally, soil OM and CEC influence P sorption and desorption processes, with higher CEC soils having more reactive sites for P sorption despite P being an anionic species in soil solution (Antoniadis et al., 2016). Overall, understanding the complex interactions between soil properties and P behavior is essential for optimizing P management in agricultural systems.

Understanding P sorption isotherms is crucial for differentiating soils based on their sorption properties and determining appropriate solutions for P sorption-desorption issues. The Langmuir and Freundlich equations are the most commonly used, typically derived from batch experiments (Taylor et al., 1996). Research on P fixation in Ethiopian soils is limited, with limited data available on sorption characteristics and soil type related factors influencing P sorption.

In Ethiopia, the use of inorganic fertilizers such as urea and di-ammonium phosphate (DAP) is a popular and effective method to enhance soil fertility and crop yield compared to other agricultural practices. Inorganic fertilizers are crucial for achieving high yields in the soils of the humid tropics and can help overcome the limitations of organic fertilizers. However, smallholder farmers often apply low amounts of inorganic fertilizers due to high cost, and a lack of soil and crop-specific recommendations (Binswanger-Mkhize and Savastano, 2017; Sheahan and Barrett, 2017; Tamene et al., 2017; Abay et al., 2019). Furthermore, continuous use of inorganic fertilizers can have a significant adverse effect on soil properties, soil microorganisms, and the environment (Bhatt et al., 2019; Elka and Laekemariam, 2020). Given the economic and soil fertility considerations, there is growing interest in the use of organic fertilizer in developing countries like Ethiopia. Therefore, there is a strong push for fertilization practices that are effective and environmentally sustainable.

Organic fertilizers, including animal manure, farmyard manure, compost, biochar, and other natural sources, are suggested as a way to address soil fertility decline and enhance crop productivity (Katterer et al., 2019; Khan et al., 2020; Wato et al., 2024). Unlike inorganic fertilizers, organic fertilizers help maintain soil quality, increase soil organic matter, and enhance soil physical and chemical properties through decomposition (Kim and Mihara, 2023).

Composting is an effective method to improve SOC, improve P availability, and enhance nutrient levels (Adekiya et al., 2019; Rayne and Aula, 2020). It can directly impact soil P levels by adding P compounds from organic fertilizers or indirectly influence other soil factors like pH and SOC, which can affect P mobility, loss, and transformation. The effects of compost on soil properties, such as P sorption characteristics, may vary depending on the source (Bahl and Toor, 2002; Hafiz et al., 2016; Sharma et al., 2023; Teressa et al., 2024; Ali et al., 2025). Adding compost can increase P availability and reduce P fixation in slightly alkaline soil. Furthermore, organic matter in compost can enhance avail P by increasing negative charges on soil surfaces with varying charges (Tamungang et al., 2016).

Biochar, a carbon-rich material made from biological organic components (Gao et al., 2023; Zhou et al., 2024), is produced by pyrolysis of agricultural waste biomass (Wang and Wang, 2019; Schmidt et al., 2021). Despite biochar being considered a soil conditioner, it can release its own nutrients while retaining nutrients from soil and fertilizers, potentially benefiting crop growth (Major et al., 2010; Alkharabsheh et al., 2021). It can improve soil fertility by promoting OC accumulation (Chagas et al., 2022), enhancing availability of N, P, and K (Gao et al., 2019), and improving soil microbial communities (Zhang et al., 2018; Li et al., 2020). However, its use on salt-affected soils is still controversial (Murtaza et al., 2021). Some studies suggest that applying BC alone may decrease soil fertility and crop yield in alkaline soil (Ding et al., 2010; Graber and Elad, 2013; Yao et al., 2025). Others to mitigate BC alkalinity effects, enhancing BC with organic or inorganic fertilizers (Bekele et al., 2021; Yan et al., 2023; Zhang et al., 2024; Wu et al., 2024) or composting BC with compost (Bai et al., 2022; Zhuang et al., 2024) can be beneficial.

Field studies have shown that biochar can help alleviate salt stress (Lee et al., 2022; Xiao et al., 2022; Yao et al., 2022; Wang et al., 2024). According to Denaxa et al. (2022) and Wang et al. (2024), BC can improve medium-salinity soils and increase crop yield. Researchers have suggested that BC may reduce the levels of P complexing metals (such as Al^{3+} and Fe^{3+}) in acidic soils and potentially mitigate the effects of Ca^{2+} in alkaline calcareous soil. Overall, adding OM to tropical soils, such as Com and BC, can be an effective strategy to enhance P fertilizer efficacy by reducing P sorption and increasing P availability in soils (Guedes et al., 2016). However, the use of organic fertilizer alone is limited due to a lack of sufficient organic inputs, low nutrient content, high application rates, and a high labor requirement for preparation and transportation. Alhrout et al. (2016) suggest that neither inorganic nor organic fertilizers alone can effectively address soil fertility depletion. Therefore, to overcome the limits of both inorganic and organic fertilizers, it is advised that they be used in combination.

Integrating inorganic and organic fertilizers provides a balanced supply of mineral nutrients to the soil and plants, creating a favorable environment for microbial growth–that enhances crop growth and production (Lelago et al., 2022; Habtamu et al., 2024; Sankhyan et al., 2024). The combined application of inorganic and organic fertilizers has shown significant improvements in soil properties and crop yields at a reasonable cost (Yu et al., 2019; Adams et al., 2020; An et al., 2022). This integrated nutrient management method has resulted in a 50% reduction in inorganic fertilizer cost (Wassie, 2012; Lelago et al., 2022; Zhou et al., 2022). Additionally, the combined use of inorganic and organic fertilizers has been found to increase common bean yields (Fouda et al., 2017; He et al., 2017; Fekadu et al., 2018; Elka and Laekemariam, 2020). Zahida et al. (2016) reported that there was a 173.8% grain yield increment in the integrated treatment compared to the control group. The combined application of inorganic and organic amendments to soil can effectively reduce soil acidification and salinization, enhance soil fertility, and limit heavy metal uptake by plants (Lu et al., 2020). Furthermore, the combination of biofertilizer with inorganic and organic fertilizers promotes crop growth and improves the economic and biological output of common beans (Mahato and Kafle, 2018; Yu et al., 2021). Therefore, the integrated use of inorganic and organic fertilizers is crucial for maintaining soil fertility and organic matter levels, ensuring long-term high yields and maximum benefits for smallholder farmers (Roba, 2018; Bitew et al., 2024).

Food legumes, particularly common beans, are crucial in Ethiopia's food diet, providing essential minerals and protein. In addition, its nitrogen-fixing ability enhances soil fertility (Kebede, 2021; Singh et al., 2023). According to four-year CSA data (2018-2021), faba bean (30%), common bean (19%), chickpea (12%), and field pea (14%) are the top four legume crops planted in different regions of the country. The major bean producing regions are central, eastern, and southern Ethiopia, with Oromia and the former SNNPR accounting for 69.05% of total production. Despite its importance, common bean yields in Ethiopia remain low compared to research fields, with an average yield of 1.69 $t \cdot ha^{-1}$, which is significantly lower than the estimated yield of 3.5 $t \cdot ha^{-1}$ (MoANR, 2016; Zerihun, 2017; CSA, 2019; Merkeb et al., 2024).

Low yields are attributed to factors such as inadequate variety selection, farming practices, moisture stress, soil fertility, diseases, and pests.

Inoculating common beans with rhizobia strains can increases nodulation (Argaw and Muleta, 2017; Assefa et al., 2017), but the success of this process depends on factors such as population density, effectiveness, and competitive ability of native rhizobia populations. Soil characteristics, host plant activity, and nutrient deficiencies can also affect rhizobia soil populations (Brutti et al., 1999). Successful inoculation requires the inoculant to be highly effective in nitrogen fixation and competitive against native rhizobia in the soil (Anteneh and Bulti, 2017; Temesgen and Assefa, 2020).

1.1.1. General objective

The general objective of this study is to increase the production of common bean in southern Ethiopia by characterizing soil types under common bean cultivation, determining soil phosphorus sorption capacities, and developing site-specific integrated soil fertility management (ISFM) technologies.

1.1.2. Specific objectives

The specific objectives of the present study are:

I. To characterize and classify the soils of the study areas;

II. To determine the P sorption characteristics of different soil types;

III. To assess the impact of ISFM on soil properties and phosphorus (P) sorption characteristics;

IV. To determine the abundance of native rhizobia populations nodulating common beans;

V. To evaluate the impact of combined inorganic, organic, and biofertilizers on soil properties and yield components of common beans;

1.1.3. Hypothesis of the study

1. The types and properties of soils vary across different agro-ecologies.
2. Phosphorus sorption characteristics of soils vary among different soil types.
3. The soil properties and phosphorus sorption characteristics of soils vary depending on the combinations of ISFM applications.
4. The native rhizobia are sufficiently abundant and competitive to potentially limit the effectiveness of commercial inoculants under specific conditions.
5. The application of rhizobia inoculation and N fertilizer significantly enhances nodulation and increases grain yield in common bean.
6. Phosphorus limitation may impact the growth and yield of common beans at the research sites.
7. Common beans may exhibit varied responses to different fertilizer combinations.

1.2. Materials and Methods

1.2.1. Description of the study area

The study was conducted at three experimental sites in southern Ethiopia: Kokate, Hawassa, and Alage (Figure 1.1). These sites were purposively selected to represent varying soil pH levels and common bean production systems. The selection process was guided by field observations, laboratory analyses, and input from local farmers. Detailed geographic information, including latitude, longitude, altitude, and slope, was recorded for each site using GPS devices, clinometers, and meters. This comprehensive data collection approach allows for a thorough analysis of the relationship between soil properties and common bean cultivation, providing valuable insights into the agricultural of the study area. Climate data from 2012 to 2021 were obtained from the Hawassa Meteorological Station.

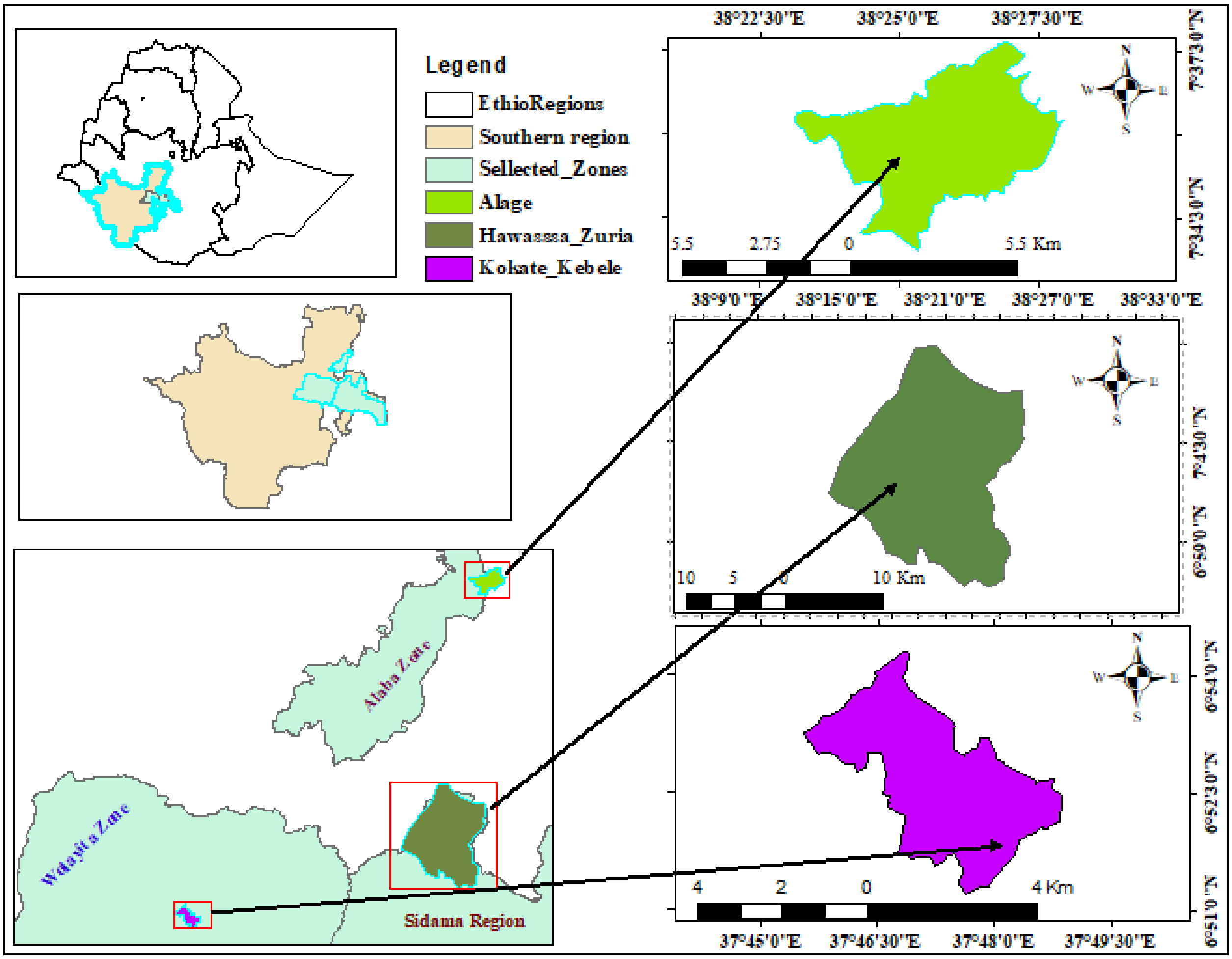

Figure 1.1. Map of the study sites (Hawassa, Kokate and Alage)

Kokate site

The Kokate site is located 390 km south of Addis Ababa and 5-15 km east of Wolaita Sodo in the Wolaita zone of Southern Ethiopia. It lies within the cool sub-humid mid-highlands agroecological zone at coordinates 06°52’42``N and 37°48’30``E, with an altitude of 2,143 meters above sea level (Fig. 1.2). The area receives annual rainfall ranging from 1,200 to 1,300 mm, while daily temperatures fluctuate between 16°C and 29°C (Figure 1.2). The region experiences a bimodal rainfall pattern, with the main rainy season, known as 'Kremt,' occurring from June to August, and a shorter rainy season, referred to as 'Belg,' taking place from March to

May. The primary crops cultivated in this area include maize (*Zea mays*), barley (*Hordeum vulgare*), sweet potato (*Ipomoea batatas*), enset (*Ensete ventricosum*), and common bean (*Phaseolus vulgaris* L.).

Hawassa Site

The Hawassa site is located within the main campus of Hawassa University, which is situated 273 km south of Addis Ababa in the Sidama Region of Ethiopia. It falls within the tepid moist mid-highlands agroecological zone (MoARD, 2005) at coordinates 07º3'3.2``N and 38º30'23.2``E, with an altitude of 1,694 meters above sea level (Fig. 1.2). The site experiences annual rainfall ranging from 900 to 1,100 mm, with minimum and maximum temperatures of 12°C and 33°C, respectively. The area features a bimodal rainfall pattern, with the main rainy season occurring from June to September and a shorter rainy season from March to May. Major crops cultivated in this region include maize (*Zea mays*), common bean (*Phaseolus vulgaris* L.), bread wheat (*Triticum aestivum* L.), enset (*Ensete ventricosum*), and hot pepper (*Capsicum frutescens* L.).

Alage site

The Alage site is located 217 km south of Addis Ababa and 38 km west of Bulbula town, near the Rift Valley Lakes (Abijata and Shaalla). It lies within the tepid semi-arid mid-highlands agroecological zone (MoARD, 2005) at coordinates 7°35`30``N and 38°24`59``E, with an altitude of 1,585 meters above sea level (Fig. 1.2). The mean annual rainfall in Alage is 693 mm, with an average annual temperature ranging from 17°C to 34°C. Major crops and vegetation in the region include maize (*Zea mays*), bread wheat (*Triticum aestivum* L.), common bean

(*Phaseolus vulgaris* L.), hot pepper (*Capsicum frutescens* L.), papaya (*Carica papaya*), mango (*Mangifera indica*), and banana (*Musa acuminata*), with Acacia as the dominant vegetation.

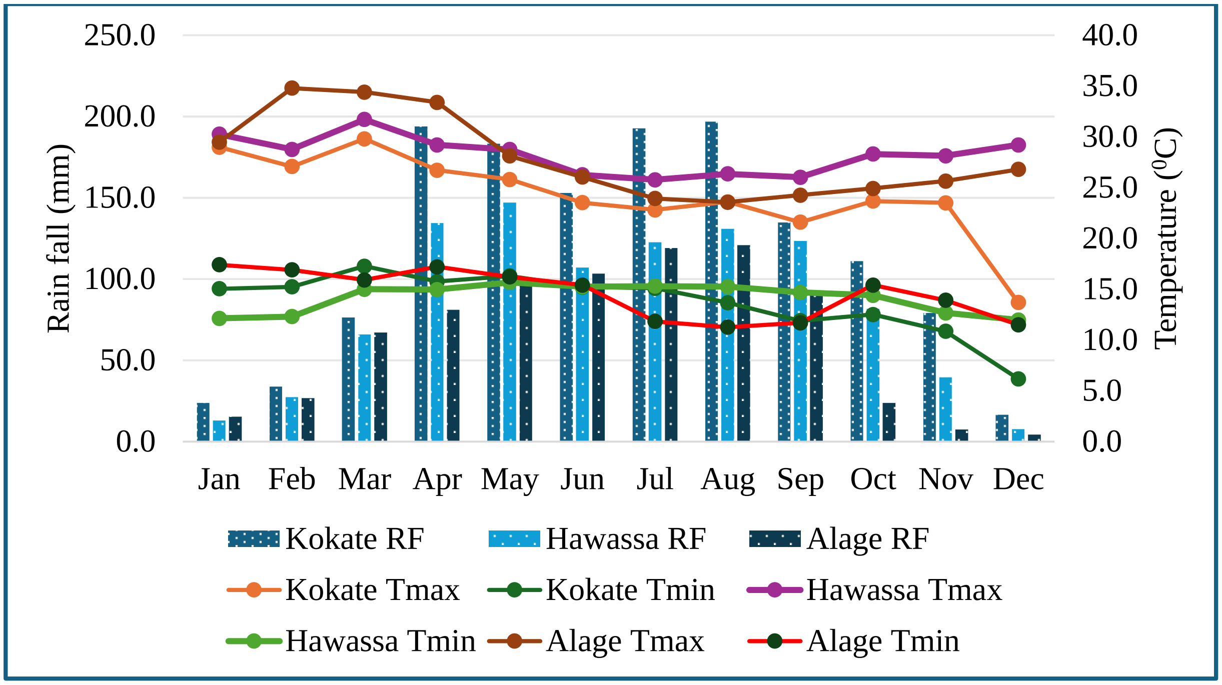

Figure 1.2. Mean annual rainfall and average minimum and maximum temperatures at three sites.

1.2.2. Soil sampling

For the soil characterization and classification study, both disturbed and undisturbed soil samples were collected from the identified horizons for physicochemical analyses. Additionally, to assess the initial soil fertility status, surface soil samples (0-20 cm depth) were collected from all directions surrounding each profile. This resulted in three representative composite soil samples for each site. All site information and soil description were recorded, and representative soil samples was collected from every identified horizon.

The collected soil samples were individually packed, labeled, and transported to the soil science laboratory at Hawassa University College of Agriculture. In the laboratory, each sample was adequately air-dried and crushed to pass through a 2 mm sieve for the analysis of most soil properties. A 0.5 mm sieve used for determining SOC and TN.

1.2.3. Soil laboratory analysis

Analysis of soil physical properties

Particle size distribution of the soil samples was analyzed using a modified sedimentation method with a hydrometer method (Bouyoucos, 1962). The bulk density (BD) of the soil sample was determined using core sampling methods (Blake and Hartge, 1986). Particle density was measured using the Pycnometer method (Blake and Hartge, 1986). Total porosity was computed from soil dry bulk density (BD) and particle density (PD) using the following formula.

$$\mathrm{TP} = 1 - (\mathrm{BD}/\mathrm{PD}) * 100$$ ------------- equation 1

Analysis of soil chemical properties

Soil pH was measured using a pH meter in suspensions of a 1:2.5 soil-to-water ratio. Electrical conductivity (EC) was measured using a conductivity meter on saturated soil paste extracts by Sahlemedhin and Taye (2000). Soil organic carbon (SOC) was determined by the wet oxidation method (Walkley and Black, 1934). The total nitrogen (TN) content in the soil samples was determined using the Kjeldahl procedure (Sahlemedhin and Taye, 2000). The available phosphorus (avail. P) in the soil samples was determined by the Olsen method (Olsen, 1954) and measured by spectrophotometer at 882 nm. Exchangeable cations (Ca, Mg, K, and Na) were extracted by 1 *M* NH_4OAc at pH 7.0. Exchangeable K and Na were determined using a flame photometer, while exchangeable Ca and Mg were determined using an atomic absorption spectrophotometer (AAS) (Sahlemedhin and Taye, 2000). The CEC was determined by the ammonium saturation method (Sahlemedhin and Taye, 2000). Percent base saturation (PBS) was calculated as the sum of exchangeable bases as a percentage of the sum of CEC

$$PBS = \frac{(Ca+ Mg+ K+ Na)}{CEC} * 100 \text{ ------------ equation 2}$$

The exchangeable sodium percentage (ESP) the ratio of exchangeable sodium (Exch. Na) to the cation exchange capacity of the soil (CEC) (Richards, 1954).

Exchangeable sodium percentage was calculated from the exchangeable sodium

$$ESP = \frac{(exch\ Na)}{CEC} * 100 \text{ ----------- equation 3}$$

The soil calcium carbonate equivalent (CCE) was determined using the trimetric method (FAO, 2020). The available micronutrients content (Fe, Cu, Mn and Zn) was extracted following the Diethylene Triamine Pentaacetic Acid (DTPA) method as described by Lindsay and Norvell (1978), and the contents in leachate were measured using AAS. Lanthanum was added during the analysis to prevent condensed phase interference.

1.2.4. Experimental procedure for phosphorus sorption characteristics study

The study was conducted in the soil laboratory at Hawassa University College of Agriculture to determines P sorption characteristics using batch equilibrium methods (Nair et al., 1984). Nine composite soil samples were collected from three experimental sites: Kokate, Hawassa, and Alage, with three samples from each site. A single composite soil sample was collected from twenty points at three sites, while a total of nine composite soil samples collected from 180 points. This soil sample is utilized for incubation as well as laboratory analyses. For each sample, one gram of air-dried soil (< 2 mm) was placed in a 50 ml plastic bottle with 25 ml of the prepared solution. Seven initial phosphorus (P) concentration levels were prepared (0, 2, 4, 10, 20, 30, and 40 mg P L^{-1}) by dissolving 0.441 g of KH_2PO_4 in a 0.01 *M* calcium chloride ($CaCl_2$) solution at a soil-to-solution ratio of 1:25 (w/v) in triplicate. The $CaCl_2$ solution served as the aqueous solvent phase to enhance centrifugation and reduce cation exchange, following the method outlined by Nega and Heluf (2009). The mixture was shaken at 380 rpm for 30 minutes and allowed to equilibrate for 24 hours. After equilibration, the suspension was filtered using Whatman No. 42 filter paper, and the P concentration in the clear extract was determined using the ascorbic acid method (Mamo et al., 2002). The sorbed P was calculated as the difference between the initial and final phosphorus concentrations in the solution, and a P sorption isotherm was created by plotting sorbed P against P concentration in the solution. A blank control was run for each soil sample using the same amount of soil and 25 ml of 0.01 *M* $CaCl_2$ solution (without added P) following the same procedure. The amount of sorbed P was calculated–using the formula established by Fox and Kamprath (1970).

$$\text{P adsorbed} = \frac{(\text{Co} - \text{Cf}) \text{ x V}}{\text{weight of soil (kg)}} \quad \text{------------equation 4}$$

Where, C_o = initial P concentration (mg L^{-1}), C_f = final concentration of P (mg L^{-1}) in the soil solution and V = volume of solution (L).

Soil P sorption data are fitted to linearized Langmuir and Freundlich.

$$\text{Langmuir equation: } \frac{C}{x} = \frac{1}{bXm} + \frac{C}{Xm} \quad \text{------------ equation 5}$$

Where, C (mg l^{-1}) is the equilibrium concentration, X (mg kg^{-1}) is the amount of P adsorbed per unit mass of adsorbent, b (L mg^{-1}) a constant related to the energy of sorption, and X_m (mg kg^{-1}) is P sorption maximum

$$\text{Freundlich equation: LogX = Logkf + } \frac{1}{n}\text{logC} \quad \text{------------ equation 6}$$

Where, X = the amount of P sorbed per unit mass of soil (mg kg^{-1}), and C is the equilibrium P concentration (mg L^{-1}), K_f is a measure of sorption surface coverage or capacity factor (mg kg^{-1}) and n = a constant related to bonding energy. Linear regression was obtained by plotting Log_C vs Log_X. The slope represents n, and the intercept represents Log K_f.

An incubation study was determining the impact of ISFM on soil properties and P sorption characteristics of soils collected from three sites. The experiment involved fifty-four soil samples from six treatments, with three replications in all three soil types. The treatments included: control, 20 kg ha^{-1} inorganic P fertilizer, 5 t ha^{-1} biochar (BC), 5 t ha^{-1} compost (Com), 5 t ha^{-1} biochar + 20 kg ha^{-1} inorganic P fertilizer (BP), and 5 t ha^{-1} compost + 20 kg ha^{-1} inorganic P fertilizer (CP). The experiment was arranged in a completely randomized design (CRD) with three replications for each soil type. Inorganic P fertilizer was sourced from triple superphosphate (TSP) (46 % P_2O_5), while compost (Com) and biochar (BC) served as organic fertilizers. The amount of P applied was based on the blanket recommended P fertilization rate, and the application rate of BC and Com were based on literature from other sites in southern Ethiopia.

1.2.5. Experimental procedure and design for soil rhizobia population study

To evaluate the abundance of native rhizobia populations, two experiments were conducted in 2021 and 2022, one in the laboratory and the other in a lath house. In order to minimize the confusing effect, the soil samples were collected from the field which had the same cropping history within the site. Accordingly, nine composite soil samples were collected from each site, labeled, and transported to the Soil Microbiology Laboratory at the College of Agriculture, Hawassa University. The soil samples were taken from the top 0-20 cm layer before planting common beans, with one composite sample collected from 27 auguring points at each site. These samples were obtained from farmers' fields which had no history of rhizobia inoculation to determine the rhizobia population. The remaining soil samples were divided for soil propeties analyses and pot experiments.

The lath house experiment was conducted in two stages. In the first stage, the abundance of rhizobia nodulating common bean was assessed. Following this, the effect of native rhizobia population on the symbiotic effectiveness of commercial rhizobia and N fertilizer were evaluated. The most probable number (MPN) method was used to determine the populations of native rhizobia present in the soils that could potentially nodulate common beans, following the procedures outlined by Vincent (1970). Representative subsamples of 1 kg were prepared for the most probable number (MPN) assay and stored in a refrigerator at 4°C until the initial rhizobia population could be enumerated. A tenfold serial dilution was prepared by diluting 10 g of soil samples were thoroughly mixed with 90 ml of sterile water. The common bean seeds (*Hawassa Dume variety*) were surface sterilized with 95% alcohol and 3.5% sodium hypochlorite for four minutes. The seeds were washed many times with distilled sterilized water before being germinated in sterile petri dishes containing 1% water agar. The pregerminated seedlings were aseptically transplanted into modified Leonard jars containing pre-treated river sand as a plant supporting media. Surface sterilized seeds were planted in acid-treated and sterilized sand using 300 ml plastic pots in a lath house. One ml of the soil serial suspension was inoculated to the root of the seedlings growing on the jars and serially diluted up to 10^{-10}. Uninoculated seedlings were considered as negative controls while seedlings weekly supplemented with quarter strength of 0.05g/ml of KNO_3 were considered as positive controls. Each treatment was replicated four times and weekly supplemented with Jenson’s N-free nutrient solution and sterilized distilled water as needed. The seedlings were grown in the lath house for 45 days and then harvested to assess nodulation, root and shoot biomass. A single nodule in a Leonard jar was considered a positive score. Nodulation was recorded as “+” for the presence of nodulation or “-” for no nodulation and the number of nodulated (+) plants (units) was recorded beside each dilution. The total number of nodulated units was calculated by summing up the nodulated units at each dilution level. The rhizobial population in each soil sample site was then estimated. The number of nodules for each replicate and serial dilutions were counted and tabulated to estimate MPN, according to the specified formula:

$$X = \frac{m \times d}{V} \text{-------------equation 7}$$

Where: X = MPN per gram of soil m=Likely number from the MPN table for the lower dilution of the series (Somasegaran, and Hoben, 1994); d = Lowest dilution (the first unit used in the tabulation) and V = Volume of aliquot applied to plants. The five-year cropping history of the sampling sites was evaluated through interviews with the farmers (personal communication) and questioners. Based on the results, rhizobia populations in the soil samples were categorized into three groups: (i) low ($<10^2$ rhizobia g^{-1} of soil), (ii) medium (10^2 to 10^3 rhizobia g^{-1} of soil), and (iii) high ($>10^3$ rhizobia g^{-1} of soil) (Howieson and Dilworth, 2016).

A pot experiment was carried out in a lath house in Hawassa University College of Agriculture from October to December 2022. The lath house was enclosed with metal wire and covered with transparent polycarbonate. The plastic pots used in this study had an upper diameter of 23 cm, a lower diameter of 19.2 cm, a depth of 19.5 cm, and were perforated at the bottom for drainage.

Each pot was filled with 2 kg of air-dried soil that had been sieved through a 6 mm sieve. The soil rhizobia population results indicate that Alage and Hawassa soils had high rhizobia populations, while Kokate soil had a low rhizobia population. The treatments were uninoculated and unfertilized (negative control), commercial rhizobium (500 g ha^{-1}HB-429) inoculation, and inorganic N fertilizers (20 kg N ha^{-1}) arranged in a completely randomized design (CRD) with three replications. All treatments were applied to each soil type, which had varying native rhizobia populations.

Four common bean (*Phaseolus vulgaris* L**.**) seeds of var. Hawassa Dume were sown per pot at a depth of 3 cm. Thinning of the crop was done about eight days after sowing keeping two plants per pot to maintain a uniform plant stand in all experimental units. Crop was irrigated carefully and other crop management practices were made uniformly on all pots to keep away from the competition of weeds and keep free from insects, pests, and disease attacks. Moreover, the visual observation was used to identify any ordinary signs and symptoms.

Relative Symbiotic Effectiveness (RSE) and Absolute Symbiotic Effectiveness (ASE) are key indices used to evaluate the symbiotic efficiency of rhizobia strains (Somasegaran and Hoben, 1985; dos Santos et al., 2011; Drew et al., 2012). These metrics were chosen because they offer comprehensive plant level assessments of nitrogen fixing performance based on easily measurable growth parameters, particularly shoot dry weight (Kebede et al., 2020). The RSE and ASE are commonly used in rhizobia-legume research to accurately assess rhizobia effectiveness in controlled condition (Somasegaran and Hoben, 1985; Kebede et al., 2020). They strike a balance between scientific rigor and operational feasibility, allowing for effective comparison across treatments with minimal technical complexity (Somasegaran and Hoben, 1985). Given the scope and goals of this study, RSE and ASE were suitable and robust tools for capturing the functional outcomes of the symbiosis.

The relative symbiotic effectiveness percentage (RSE%) of the inoculant for atmospheric nitrogen fixation was determined following the procedures outlined by Purcino et al. (2000). This involved comparing the performance of the inoculated plants with that of the nitrogen-fertilized positive control, using the formula:

$$\text{RSE (\%)} = \frac{\text{Inoculated shoot dry weight}}{\text{N fertilized shoot dry weight}} * 100 \text{............Equation 8}$$

RSE was categorized as highly effective (SE > 80%), effective (SE = 50- 80%), poorly effective (SE = 35-50% and ineffective (SE <35%) (Purcino et al., 2000).

The Absolute Symbiotic Effectiveness Percentage (ASE %) was determined following the method described by dos Santos et al. (2011), which involved comparing the inoculated plant with the uninoculated and unfertilized negative control using the formula:

$$\text{ASE(\%)} = \frac{\text{SDW from inoculant} - \text{shoot dry weight without N}}{\text{Shoot dry weight without N}} * 100 \text{............Equation 9}$$

1.2.6. Experimental set up and design for field experiment

The field experiments, soil samples were collected twice from the surface (0–20 cm). Before and after applying the treatment, three representative sub-samples were collected at each experimental site in 2021, following standard soil sampling procedures. The experiments were carried out at all sites for two consecutive cropping seasons (2021 and 2022). The experiments involved three levels of inorganic P fertilizer and three levels of organic inputs, arranged in a randomized complete block design (RCBD) with three replications at each site. Three levels of inorganic fertilizer (0, 8.5, and 17 kg P ha^{-1} for KK; 0, 5.8, and 11.6 kg P ha^{-1} for HW, and 0, 7.1, and 14.2 kg P ha^{-1} for AL) and three level of organic fertilizer (0, 5 t B ha^{-1}, 5 t C ha^{-1}) and 500 g ha^{-1} of RI were used as treatments. The phosphorus fertilizer rates were tailored for each site based on the EPR study results of chapter three, resulting in varying levels of inorganic P fertilizer used in the current studies. However, the quantities and types of organic fertilizers and *Rhizobium* inoculation were consistent in all sites. Details of treatment combinations are summarized in Table 1.1.

Table 1.1. Arrangement of experimental treatments.

Treatment No.	Inorganic P fertilizer (IF)	Organic fertilizer (OF)	Treatment combinations
1	Zero	Zero	Zero + Zero
2	Zero	Com	Zero + Com
3	Zero	BC	Zero + BC
4	Zero	RI	Zero + RI
5	½ RP	Zero	½ RP + Zero
6	½ RP	Com	½ RP + Com
7	½ RP	BC	½ RP + BC
8	½ RP	RI	½ RP + RI
9	RP	Zero	RP + Zero
10	RP	Com	RP + Com
11	RP	BC	RP + BC
12	RP	RI	RP + RI

*Where RP = recommended P fertilizer, Com = compost, BC = biochar and RI = Rhizobium inoculation

1.2.6.1. Preparation and analysis of organic fertilizers

Maize cobs were chosen for BC production because to their abundance in the study areas. They were collected from farmers' fields, dried in the air, and processed using traditional earth-mound technology. Specifically, the maize cobs were burned in a pit with limited air supply, reaching a temperature of 300 ºC for two hours at the College of Agriculture, Hawassa University.

Compost was prepared from locally available crop residues, such as maize and millet residues, as well as leaves, grasses, fresh and dry cow dung, and wood pieces at the Farmers Training Center in the Hulbarage district of the Siltie Zone. The composting materials were layered alternately, starting with chopped maize residues at the bottom. All recommended management practices were followed until the materials were ready for use.

The soil, BC, and Com samples used for this study were collected, air-dried, ground, and sieved (< 2 mm and 0.5 mm sieve) for the analysis of pH, EC, SOC, TN, Avail-P, and CEC at the Soil Laboratory at the College of Agriculture, Hawassa University. Three representative biochar and compost samples were collected. The pH was determined in a sample: water ratio of 1:2.5 using a pH meter. The EC was measured by a conductivity meter on saturated soil paste extracts (Sahlemedhin and Taye, 2000). The SOC was determined by the Walkley and Black (1934) wet digestion method. The TN was determined following the Kjeldahl digestion (Sahlemedhin and Taye, 2000). The avail P was determined by the Olsen extraction method (Olsen et al., 1954). The cation exchange capacity (CEC) was determined using the 1*M* NH_4OAc (pH 7) method (Sahlemedhin and Taye, 2000).

1.2.6.2.Experimental land preparation, application of input, and the common bean variety

The experimental land was plowed three times using a traditional oxen-drawn "local maresha" as per the usual planting schedule. Three weeks (21 days) before sowing the seeds, organic inputs like BC and Com were applied based on the treatments and incorporated into the top 20 cm of soil. Common bean seeds were inoculated with *Rhizobium* inoculum (strain RI: HB-429) at a rate of 500 g per 15 kg of seeds, following the supplier's recommendations. During planting, the site recommended rate of TSP was applied in rows according to the treatment, and starter nitrogen application of 18 kg N ha^{-1} from urea (46% N) was equally applied all plots.

The common bean variety "Hawassa Dume," released in 2008 by the Hawassa Agricultural Research Centre (MoARD, 2008), was chosen as the test crop. The seeds were sown at a spacing of 10 cm between plants and 40 cm between rows. The experimental plots were separated by 0.5 m, and the blocks were separated by 1 m. The total experimental area was 342.2 m² (29.5 m x 11.6 m), with each plot measuring 6.4 m² (3.2 m x 2 m). Each plot consisted of eight rows, with six rows used for data collection and two rows serving as borders. All recommended management practices were applied uniformly to all experimental units.

1.2.6.3. Yield and yield components

The yield and yield attributes were measured throughout the entire duration of the experiment using standard procedures. The number of pods per plant (NPP) was determined at harvest by averaging the total number of pods from five plants in each plot. The number of seeds per pod (NSP) was recorded by examining five pods from each of the five plants per plot at harvest. The number of nodules (NN) was evaluated by uprooting five common bean plants, washing them thoroughly to remove excess soil, and counting all the nodules on each plant to calculate the average. The hundred seed weight (HSW) was determined by weighing 100 randomly selected seeds from each plot's total harvest, with the weight adjusted to a moisture level of 10%. To calculate the total above-ground biomass yield (BY), five sample plants per plot were collected, oven-dried at 72 ºC for 48 hours, and their weight was converted to t ha^{-1}. The grain yield (GY) was measured from the six central rows and adjusted to 10% moisture. content.

1.2.7. Statistical analysis

The soil properties and phosphorus sorption parameters were analyzed using SAS software version 9.4 (SAS, 2012). Significance was determined using the LSD method at $p \leq 0.05$. A two-way ANOVA was conducted using the General Linear Model (GLM) to compare mean values. Pearson correlation coefficients used to evaluate the relationships among soil properties, phosphorus sorption parameters, and MPN based on cropping history. Bartlett's test showed significant differences among parameters, indicating heterogeneous variances across sites and necessitating separate analyses. Data were evaluated for homogeneity of variance across sites and years. Consistent data between seasons allowed for combined analyses of inorganic, organic, and biofertilizers on common bean yield. Duncan's Multiple Range Test was used to compare significant two-way interaction effects.

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CHAPTER TWO

"Essentially, all life depends upon the soil ... There can be no life without soil and no soil without life; they have evolved together."

— Charles E. Kellogg, USDA Yearbook of Agriculture, 1938

2. CHARACTERIZATION AND CLASSIFICATION OF SOILS FOR SELECTED SITES IN SOUTHERN ETHIOPIA

Abstract

Soils in southern Ethiopia are extensively cultivated but face a significant challenge from low fertility, and limited information on their properties constrains effective management. This study characterized and classified soils from three sites Kokate, Hawassa, and Alage through field description and laboratory analysis of surface and profile samples. Three profiles, one from each experimental site, were excavated and characterized in terms of their morphological, physical, and chemical properties. Soil samples were collected from the surface composite soil and each genetic horizon with their physicochemical properties. The results showed distinct differences among the sites: Kokate soils were very strongly acidic with clay texture, high micronutrients, base saturation and CEC, but low SOC and avail P; Hawassa soils were neutral, loamy texture, with high base saturation and CEC but low SOC, avail P, and micronutrients and Alage soils were moderately alkaline, silt clay loam texture, with high base saturation, CEC, and sodium content, but low SOC, avail P, and micronutrients. Based on the World Reference Base (WRB), the soils were classified as Vertic Luvisols (Kokate), Haplic Cambisols (Hawassa), and Calcaric Fluvisols (Alage). These variations highlight the importance of site-specific soil fertility management to enhance land productivity.

Keywords: Soil horizons; soil profile; soil properties; soil types

2.1.Introduction

Soil is a valuable natural resource essential for supporting plant life (Juilleret et al., 2016). It serves as a foundation for agricultural productivity and plays a critical role in maintaining ecosystem services. The formation of soil is influenced by various factors such as parent materials, climate, topography, biological components, and time (Jenny, 1994). These factors interact differently across landscapes, leading to the development of various soil types (Moustakas and Georgoulias, 2005). While it takes thousands of years for soil to form, it can degrade rapidly due to poor land use and mismanagement (Jonsson and Davíðsdóttir, 2016; Santos-Frances et al., 2021).

Despite its importance, soil is a complex and often underestimated environment that is under increasing pressure from human activities (Saljnikov et al., 2021; Balestrini et al., 2024). In Ethiopia, soil resources are particularly at risk due to population growth, rising food demand, land use competition, vegetation clearing, desertification, and unsustainable farming practices (Jónsson and Davíðsdóttir, 2016; Conijn et al., 2019; Gupta, 2023). These pressures have led to widespread land degradation as soils exceed their capacity to function effectively (Saljnikov et al., 2021; Chen et al., 2022). As a result, improving soil management is critical for ensuring long-term agricultural productivity.

Proper soil characterization is fundamental for sustainable agricultural practices (Tenga et al., 2018). It provides valuable information about soil fertility, mineralogical composition, and microbiological characteristics. Soil characterization includes the study of morphological traits, and physicochemical properties (FAO, 2006; Saether and De Caritat, 2020). Understanding these characteristics enables the development of effective soil management strategies and supports improved crop production (Onyekanne, 2012; Dessalegn et al., 2014; Fekadu et al., 2018).

Tropical soils, including those in sub-Saharan Africa (SSA), face significant fertility challenges due to continuous cultivation, inadequate fertilizer application, and declining organic matter content. These conditions contribute to the degradation of soil health and productivity. In the Ethiopian highlands, the average soil organic carbon balance is decreasing at a rate of -3.7 t $ha^{-1}year^{-1}$ (Van Beek et al., 2018). These trends underscore the urgent need for informed and location-specific soil management practices.

Soil classification is equally important, as it organizes knowledge and facilitates the transfer of scientific understandings across regions (Adhanom and Toshome, 2016). The World Reference Base (WRB) for Soil Resources is a widely accepted classification system used globally (IUSS Working Group WRB, 2022). Combined with detailed soil characterization and classification helps inform sustainable land use planning and supports better decision-making for resource management (Esu et al., 2008; Rabia et al., 2013).

In Ethiopia, integrated soil fertility management (ISFM) is increasingly recognized as a key strategy for reversing soil degradation and enhancing agricultural production (Hörner and Wollni, 2021). To address this, a study on ISFM was conducted in common bean-growing areas in southern Ethiopia (Kokate, Hawassa, and Alage). The aim of this study is to characterize and classify the soils of these selected sites to provide site-specific soil management recommendations.

2.2.Materials and Methods

2.2.1. Soil profile description and soil sampling

A representative profile was selected from each experimental site based on landforms and other physiographic features. Prior to excavating the pits, thirty soil auger observations were conducted using an Edelman auger to assess variations in soil depth and texture, thereby determining typical profiles at each site. Points sharing the same depth and textural class were grouped as a profile. A total of three profiles, one per site, each measuring 2 m x 2 m x 2 m, were hand-excavated at representative spots and then the soil profiles were described *in situ* following the guidelines for soil description (FAO, 2006). Data regarding the biophysical characteristics of the experimental sites, including morphological, meteorological, elevation, slope gradient, vegetation, and land use or dominant crop coverage, were collected and documented. The points of soil profiles were geo-referenced using the Global Positioning System (GPS).

Morphological soil characteristics like soil color was determined using Munsell Soil Color Charts (Munsell Color, 2009). The sequence, grade, size, and type (shape) of aggregates were used to characterize the soil structure, while the depth and distinctness of horizon borders were used to define the horizon boundaries. The consistency of the soil was determined in dry, moist, and wet moisture conditions. Detailed the soil samples are indicated under chapter one section 1.2.2.

2.2.2. Soil laboratory analysis

Particle size distribution

The particle size distribution (percentage of sand, silt, and clay) was determined using the modified sedimentation hydrometer method (Bouyoucos, 1962) following Bouyoucos' procedure. A 50 g air-dried soil sample (< 2 mm) was placed in a one-liter plastic bottle, and 100 ml of dispersing agent (sodium hexametaphosphate) was added to disperse aggregates. The bottle was shaken on an end-to-end shaker for 3 hrs. The soil and solution were then transferred to a mixer cup, washed, and stirred for 5 minutes. The suspension was poured into a graduated cylinder, and hydrometer readings were taken at 40 seconds and 2 hrs to determine the remaining particle concentration in suspension.

- First reading: sand has settled → estimate silt + clay.
- Second reading: silt has settled → estimate clay.

The temperature was recorded, and the temperature correction factor was taken into account for the calculation of the three particles size fractions.

Soil bulk density

The bulk density (BD) of the soil sample was determined using core sampling methods (Blake and Hartge, 1986). Undisturbed soil samples were collected using core samplers with a coring cylinder approximately 5 cm long and 5 cm in diameter. The cylinder was inserted horizontally for profiles sampling and vertically for field experiment soil sampling until it was level with the soil surface inside the core. The cylinder was then carefully extracted after excavation around the core, and the samples were trimmed to be level with the ends of the cylinder. The samples collected were dried in an oven at 105°C for 24 hrs, and the dry weight of the soil was measured with a precise balance. It was then calculated by dividing the dry weight of the sample by the volume of the cylinder Soil chemical analysis.

Soil pH and electrical conductivity

The soil pH was measured using a pH meter in a 1:2.5 soil to water suspension. Initially, 10 g of air-dried soil (< 2 mm) was placed in a 100 ml beaker and 25 ml of distilled water was added. The mixture was stirred for 30 minutes using an automatic stirrer. After allowing the solution to settle for 1 hour, the pH was measured at the top of the suspension using a glass electrode pH meter. Electrical conductivity (EC) was measured using a conductivity meter on saturated soil paste extracts by Sahlemedhin and Taye (2000).

Soil organic carbon, total nitrogen and available phosphorus

Soil organic carbon (SOC) was determined by the wet oxidation method (Walkley and Black, 1934). A 2 g soil sample was placed in a 500 ml Erlenmeyer flask. Then, 10 ml of 1 *N* $K_2Cr_2O_7$ solution was added using a pipette to both the samples and the blank. Subsequently, 20 ml of concentrated H_2SO_4 was poured into the flask, which was then swirled for 30 minutes. Afterward, 200 ml of distilled water was added and allowed to cool before adding 10 ml of concentrated orthophosphoric acid. Just before titration, 0.5 ml of barium diphenylamine sulphonate indicator was introduced. The samples and blanks were titrated with 0.5 N ferrous sulfate solution until the color changed to purple or blue. The ferrous sulfate solution was then added drop by drop until the color transitioned to green, and the titration continued until a light green endpoint was reached. The titration values were recorded to calculate the soil organic carbon content using the following equation:

$$\%OC = N \times \frac{V1 - V2}{S} * 0.39 * mcf \text{ ---------------- equation 1}$$

Where:

N= normality of ferrous sulfate solution (from blank titration)

V1= ml ferrous sulfate solution used for blank.

V2= ml ferrous sulfate solution used for sample.

S= weight of air-died soil samples in gram

0.39 = 3 x 10^{-3} x 100 x 1.3 (3 = equivalent weight of carbon).

mcf = moisture correction factor.

The total nitrogen (TN) content in the soil samples was determined using the Kjeldahl procedure (Sahlemedhin and Taye, 2000). A 1g air-dried soil sample was placed in a digestion tube along with 2g of catalyst mixture and boiling stones. Then, 7 ml of concentrated H_2SO_4 was added, and the mixture was digested for 3 hours at 300°C. After cooling, 50 ml of distilled water was added, and the acid digest was transferred to macro-Kjeldahl flasks. A boric acid solution and indicator were added, followed by 75 ml of 40% NaOH for distillation. The distillate was collected, and the endpoint was titrated with 0.1 *N* H_2SO_4. Finally, the volume was recorded for analysis.

$$\%TN = \frac{a-b}{s} * N * 0.014 * 100 * mcf$$ ---------------- equation 2

Where:

a= ml of H_2SO_4 required for titration of sample

b= ml of H_2SO_4 required for titration of blank

S= weight of air-died soil samples in gram

N= normality of H_2SO_4 (0.1 N)

mcf = moisture correction factor.

The available phosphorus (avail. P) in the soil samples was determined by the Olsen method (Olsen, 1954) and measured by spectrophotometer at 882 nm. Add five grams of soil samples and 50 mL of 0.5 *M* $NaHCO_3$ solution at pH 8.5 were shaken with 100 ml of the extraction solution for 30 minutes on an orbital shaker, filtered through Whatman no. 42 filter paper, and analyzed by mixing 3 ml of the filtrate with 3 ml of a mixed reagent. Use the molybdenum blue color method: add reagents to the extract to develop a blue color proportional to P concentration. Finaly, measure absorbance at 882 nm with a spectrophotometer. Use a calibration curve prepared with known phosphate standards to calculate P concentration in mg/L. Convert to mg P/kg soil based on soil weight and extraction volume.

Cation exchange capacity and exchangeable bases

The CEC was determined by the ammonium saturation method (Sahlemedhin and Taye, 2000). The soil's cation exchange capacity (CEC) was determined by saturating 5 grams of air-dried soil with 100 ml of 1 *M* NH_4OAc (ammonium acetate) solution at pH 7 in a 250 ml beaker. The suspension was filtered and washed with 100 ml of 1 *M* NH_4OAc to a volume of 200 ml. The soil was then washed with 25 ml ethanol three times and saturated with sodium by washing with 20 ml aliquots of sodium chloride (NaCl) five times. The filtrate was collected for CEC determination using the distillation method. The leachate was transferred to a 500 ml Kjeldahl flask, and 15 ml of 0.20 *N* H_2SO_4 was added to the distillate receiver in a 250 ml Erlenmeyer flask. The distillation apparatus was connected, and the distillate was back titrated with 0.1 *N* NaOH using methyl red as an indicator until the color changed from purple to yellow.

The exchangeable bases in the ammonium acetate leachate were determined using an atomic absorption spectrophotometer (AAS) following the methods described by Sahlemedhin and Taye (2000). A 0.5 ml sample of the leachate was mixed with 4.5 ml of distilled water in a test tube. Then, 5 ml of 0.5% La suppressant solution was added and thoroughly mixed. The Ca and Mg concentrations were measured using AAS at wavelengths of 422.7 nm and 285.2 nm, respectively. Exchangeable K^+ and Na^+ were analyzed using a flame photometer at wavelengths of 768 nm and 598 nm or K and Na, respectively. The percent base saturation was calculated using the formula:

$$PBS = \frac{(Ca+Mg+K+Na)}{CEC} * 100 \text{ ---------------- equation 3}$$

Available micronutrients

The available micronutrients (Fe, Mn, Zn, and Cu) were determined using the Lindsay and Norvell (1978) procedure. Soil samples weighing 20 g were mixed with 40.0 ml of diethylene triaminepentaacetic acid (DTPA) in a 100 ml polythene bottle and shaken for 2 hours at 150 rpm at 20°C. The mixture was then filtered through Whatman no. filter paper. Subsequently, 10 ml of the sample extract was combined with 0.1% lanthanum solution and homogenized. The micronutrients extracted using this method were analyzed by AAS at wavelengths of 248.3 nm for Fe, 279.5 nm for Mn, 324.7 nm for Cu, and 213.9 nm for Zn.

2.2.3. Soil classification

Based on the field description and laboratory analysis of soil properties, the soil profiles were classified according to WRB (IUSS Working Group WRB, 2022) and Soil Taxonomy (2006). The presence or absence of specific diagnostic horizons, properties and materials were detected and used to distinguish Reference Soil Groups (RSGs) according to the classification rules of the above-mentioned classification system.

2.2.4. Statistical analysis

The data from laboratory analyses were subjected to simple correlation analysis to distinguish functional relationships among and within selected soil physicochemical properties using SAS software 9.4 (SAS, 2012).

2.3. Results and Discussion

2.3.1. Characteristics of soils of the study area

The site characteristics of the profiles indicated that the study area was located on level to sloping (Table 2.1) and the profiles represented different land position: Kokate site slope, Hawassa and Alage sites nearly flat and flat sites respectively. The profiles were also representatives of different land use/cover: farm land (Kokate and Alage) and fallow land (Hawassa). The variations in soil properties could be attributed to different soil management practices across land use types (Kebebew et al., 2022). Kokate profile was well drained, while Hawassa and Alage profiles, which was on level slope positions and imperfectly drained. Furthermore, the existing land use/cover at the area has also contributed to the erosion process. Cultivated land of Kokate and Alage soils of the landscape, which is highly exposed to rainfall effect. The removal of surface soil on the Kokate land has reduced the soil profile development when compared to the Hawassa soil. Soil properties can also vary with land use and management system (Haile et al., 2022; Abebe, 2023; Beyene et al., 2023). Land management and its various uses for crop production in mountain areas influence runoff and erosion, which in turn results in varying properties of the soils under cultivation and grazing lands (Belayneh, 2009). Parent material determines certain soil properties and drainage condition, which is among other factors that also determine the type of soil (Wilson, 2019; Akinwa, 2023).

Table 2.1. Site characteristics, altitudes, geographic coordinates and land use of the study area

Locations	Altitudes (m)	GPS coordinate		LF	SD	Erosion	PM	Slope	LU
		Latitude	Longitude						
Kokate	2143	06º49’17.6``N	37º44’56.2``E	S	WD	WE	B	5	CL
Hawassa	1694	07º03'53.8``N	38º28'59.2``E	NF	PD	WE	A	2	FL
Alage	1585	7°35`30``N	38°24`59``E	F	PD	WIE	A	1	CL

Where: LF = land form; S = sloping; NF = nearly flat; F = flat; SD = surface drained; WD = well drained; PD = poor drained; WE = water erosion; WIE = wind erosion; PM = parent materials; B = basalt; A = alluvium; LU = land use; CL = cultivated land; FL = Fallow land

2.3.2. Soil morphological characteristic of the profiles

The morphological properties of soils; depth, horizon, color, structure, consistency and horizon boundary varied within soil depth at the studied sites. All soil profiles were very deep (>200 cm; Table 2.2). The number of genetic horizons per profile was two in Kokate, three in Hawassa and Alage soils. The Kokate site was characterized by Ap-AB-Bt1-Bt2-Bt3 sequence of horizons. The Hawassa site was characterized by A-Bw1-Bw2-Bw3-BC-C, while the Alage site was characterized by Ap-BC-C-2B1-2B2-2C-3B sequence of horizons showing deposition of materials resulting in lithological discontinuity. The surface horizon of the Kokate site was thinner as compared to other profiles. The relatively thin topsoil of Kokate could be attributed to the influence of runoff (Kiflu et al., 2016; Gebrehanna et al., 2022; Abuye et al., 2023). The flat slope at Alage site could be the result of accumulation of the soil deposits eroded from the surrounding. Furthermore, the continuous deposit of materials from the present flat slope on the profile at Alage site might have resulted in development of soils from different geological origin causing lithological discontinuities in the soils (Kiflu et al., 2016). The soil horizon thickness generally increased with soil depth indicating the increase in the movement of small-size material in profile within the depth (Kiflu et al., 2016; Yitbarek et al., 2016; Seid et al., 2018). However, soil depth showed inconsistent trend in the Alage site. The A horizons were formed as a consequence of incorporation of humified organic materials from agricultural crops in the Kokate and Alage sites, while Hawassa site from grass. The B horizons are the result of *in situ* weathering of the parent material and formed by the illuviation of clay minerals from the upper horizons. Variation in soil depth, particle size distribution, structure, and color could also be due to the difference in parent material (Gebrehanna et al., 2022; Abuye et al., 2023).

Table 2.2. Soil morphological properties

Depth (cm)	Horizon	Moist Color	Structure Grade/Size/Type	Consistency Dry/Moist/Wet	Horizon Boundary
			Kokate		
0-21	Ap	2.5YR2.5/1	WE, FC, GR	HA, FR, S/P	D, S
21-45	AB	2.5YR2.5/2	MO, ME, AB	SHA, FI, S/P	G, S
45-85	Bt1	10R3/3	MO, ME, SAB	SHA, FI, VSVP	G, S
85-150	Bt2	10R3/3	WE, ME, SAB	SHA, FR, VSVP	G, S
150-200^{+}	Bt3	10R3/4	WE, F, SAB	SHA, FR, VSVP	
			Hawassa		
0-27	A	10YR2/2	WE, FC, GR	SHA, FR, S/P	D, S
27-50	Bw1	10YR3/3	WE, ME, SAB	HA, VFR, S/P	G, S
50-90	Bw2	10YR3/3	WE, ME, SAB	HA, FI, S/P	G, S
90-110	Bw3	10YR4/2	WE, ME, SAB	SHA, FR, S/P	C, S
110-150	BC	10YR6/2	WE, ME, SAB	HA, FI, SS/SP	G, S
150-200+	C	10YR6/2	WE, ME, SG	HA, FI, NS/NP	
			Alage		
0-35	Ap	7.5YR3/2	WE, F, GR	SHA, FR, S/P	C, S
35-70	BC	7.5YR3/4	WE, FC, SAB	HA, VFI, SS/PP	A, W
70-80	C	7.5YR6/3	ST, ME, SG	HA, VFI, NS/NP	A, W
80-105	2B1	7.5YR4/4	WE, F, SAB	SHA, FR, SP	C, S
105-130	2B2	7.5YR4/6	WE, F, SAB	SHA, FR, SP	A, S
130-160	2C	7.5YR6/4	ST, ME, SG	HA, VFI, NS/NP	A, S
160-200+	3B	7.5YR4/4	WE, VF, SAB	SHA, VFR, SP/SP	

Where, WE = Weak; MO = Moderate; ST = Strong; FC = Fine to coarse; ME = Medium; F = Fine; VF = Very fine; GR = Granular; AB = Angular blocky; SAB = Sub angular blocky; SG = single grain; SHA = Slightly hard; HA = Hard; FR = Friable; FI = Firm; VFR = Very friable; VFI = Very firm; NS/NP = non-stick, non-plastic; SS/SP = Slightly sticky and slightly plastic; S/P= Sticky and plastic; VSVP = Very sticky and very plastic; G, S = Gradual and smooth; D, S = diffuse and smooth; C, S = Clear and smooth; A, W = Abrupt and wave; A, S = Abrupt and smooth

The study found that the moist colors of the soils varied within and between profiles of different sites, as shown in Table 2.2. The Kokate site's surface horizon's moist soil color was reddish black (2.5YR 2.5/1), while its subsurface horizons' colors dusky red (10R 3/3). The Hawassa site's surface horizons' soil was very dark brown (10YR2/2), while its subsurface horizons' colors dark brown (10YR 3/3). The Alage site's surface horizon soil was dark brown (7.5YR 3/2), while its subsurface horizons brown (7.5YR 4/4). The color of surface horizons also varied from reddish black (2.5YR2.5/1) in Kokate to very dark brown (10YR2/2) in Hawassa, whereas the color of the subsurface horizons varied from dusky red (10R3/3) in Kokate to dark grayish brown (10YR4/2) in Hawassa. The color variations between surface and subsurface layers are primarily due to biological processes, particularly those influenced by soil organic matter. In the Kokate, Hawassa, and Alage, the surface horizon had darker color as compared to subsurface horizons which could be due to the relatively higher organic matter contents in the surface horizons (Yitbarek et al., 2016; Yacob and Nigussie, 2022). Similarly, the difference in color among the profiles and within profile can be due to variations in forms of iron oxide and the types of parent material (Nahusenay, 2014; Dinssa and Elias, 2021).

The surface soil horizon at the Kokate site had a weak, fine to coarse, and granular structure that changed into moderate, medium and sub-angular blocky structure with depth (Table 2.2). The surface soil horizon of the Hawassa site had a weak, fine to coarse and granular structure changing into a weak, medium, and sub-angular blocky structure in the subsurface horizon. The surface horizon at the Alage site had a weak and fine structure, changing into a weak, very fine, and subangular blocky structure with increasing depth. Granular soil structures form with higher organic matter levels on surface horizons, while blocky structures form in subsurface horizons due to overlying layers, reduced organic matter, higher clay content, and reduced plant root abundance. According to Dinssa and Elias (2021) and Yitbarek et al. (2016), the granular soil structure present in the upper horizons changes to angular and sub-angular structures in the subsurface profile. Soil organic matter and particle size distribution have the greatest influence on aggregate dynamics (Tobiasova et al., 2013). A better structural development down the profiles except the 'C' horizon was due to the relatively higher clay content of the subsurface horizons than their respective surface horizons (Kiflu and Beyene, 2013; Gebrehanna et al., 2022; Yacob and Nigussie, 2022). Organic matter and microbial exudates serve to form and temporally stabilize the granular aggregates (Buol, 2011), although physical disruption of surface horizons reduces the microbial activity and aggregate stability as the stabilizing organic compounds are decomposed.

The dry consistency of the surface horizons of Kokate, Hawassa, and Alage was slightly hard to hard. All studied sites had soils with moist consistencies, showing variation within and between profiles. The three profiles showed friable moist consistency across most surface and subsurface layers, making them suitable for soil work. Similar study by, Ali et al. (2010) and Ayalew et al. (2015) also reported that the friable consistency of the soils indicates workability of the soils at appropriate moisture content. The wet consistency is also in the range of non-sticky/non-plastic in the Alage soil profile to very sticky/very plastic in the Kokate soil profile (Table 2.2). The subsurface layers exhibit sticky, very sticky, and plastic, very plastic consistency due to decreased organic matter content, increased clay particles, and difficulty in working with soils. Kiflu et al. (2016) and Dinssa and Elias (2021) reported similar results in that the sticky and plastic consistency indicates the existence of high clay content and difficulty in working. The increase in clay content with depth may explain the change in the consistency of the soil at different moisture levels. The variations in moist and wet consistencies are most likely explained by differences in OM and clay content (Moradi, 2013; Gebrehanna et al., 2022; Yacob and Nigussie, 2022). The friable, non to slightly sticky, and non-to-slightly plastic consistencies could be attributed to the low clay contents of the soils (Kiflu, 2016; Yacob and Nigussie, 2022). In contrast, the sticky, very sticky, plastic, and very plastic consistencies show the presence of high clay and low OC contents and difficulty to till (Yacob and Nigussie, 2022). The very sticky and very plastic consistency could be attributed to the presence of smectitic clays in the soils (Ali et al., 2010; Ayalew et al., 2015). The friable and very friable consistency observed in the surface horizons of the profiles (Table 2.2) could be attributed to the higher organic matter contents, which reduces the stickiness of clay soils (Demis and Beyene, 2010; Ayalew et al., 2015; Fekadu., et al., 2018).

The distinctness of horizon boundary between surface and subsurface horizons were diffuse smooth boundary (D, S) in Kokate, diffuse smooth boundary (D, S) in Hawassa and clear smooth boundary (C, S) in Alage profiles, while gradual smooth boundary (G, S) in Kokate, gradual smooth boundary (G, S) in Hawassa and abrupt smooth boundary (A, S) in Alage were observed subsurface profiles (Table 2.2). Variation of the boundaries might be due to anthropogenic interferences in addition to the natural phenomena. The lateral and vertical variations in master soil horizons are driven by factors like landscape position, parent material, vegetation, fertilization, tillage, drainage, and time (Hartemink et al., 2020). A biological activity was relatively higher in the surface horizons and decreased with increasing soil depth might be due to the abundance of roots and having favorable soil conditions (Abuye et al., 2023).

2.3.3. Physical properties of the soil profiles

The study revealed that the distribution of soil particle size in the soil horizons of the profile varied with soil depth (Table 2.3). At the Kokate site, the surface soil particle size fractions of clay, silt, and sand were 46, 28, and 26%, respectively. The surface soil was clayey in texture, and it was similar to throughout the profile. At Hawassa site, the surface soil particle size fractions of clay, silt, and sand were 24, 33, and 43%, respectively, and the surface soil texture was loam, but it changed with depth to clay loam. Whereas the surface soil particle fractions at Alage site were 36% clay, 46% silt, and 18% sand, and the surface soil texture was silt clay loam, but the profile showed textural variation with depth (Hazelton and Murphy, 2016). In the Kokate site, clay content of the soil increases with depth. It revealed most subsoil horizons are argic (Bt), which were formed by the illuviation of clay minerals from the upper horizons. This finding was in line with Ghonamey et al. (2020) and Abuye et al. (2023), who state that clay particle might be present as a result of clay movment from upper layer to lower layer. Other studies have also shown that the clay content of their study soils increased with depth (Dinssa and Elias, 2021; Yacob and Nigussie, 2021).

The silt/clay ratio of the surface and subsurface soils in the profiles varied across different depths: 0.61 to 0.26 in Kokate, 1.38 to 1.14 in Hawassa, and 1.28 to 3.00 in Alage (Table 2.3). There was no consistent trend of decreasing or increasing silt/clay ratio with depth in all soil profiles. According to Ahukaemere et al. (2017), soils with a silt/clay ratio < 0.15 are considered weathered, while those with a ratio > 0.15 are younger and have a higher weathering potential. In this study, all soils examined had silt/clay ratios greater than 0.15, indicating that they were young and less weathered. The BD of Kokate, Hawassa, and Alage sites ranged from 1.23 to 1.33, 1.10 to 1.44, and 1.20 to 1.70 gcm^{-3}, respectively (Table 2.3). The BD values of the surface horizon 1.23 in Kokate, 1.10 in Hawassa and 1.20 gcm^{-3} in the Alage sites, respectively. The study found that cultivated land in Kokate and Alage sites had higher surface horizon bulk density, possibly due to compaction, while in fallow land in Hawassa site low bulk density was recorded; it increased with soil depth, which is in agreement with other studies (Abayneh, 2005; Adhanom and Toshome, 2016; Mohamed et al., 2021). Surface horizons have low BD due to higher SOC content and abundant root systems, while subsurface horizons have high BD due to decreasing SOC content, few roots, and soil depth (Adhanom and Toshome, 2016; Yacob and Nigussie, 2021). The total porosity in Kokate, ranged from 50 to 54%; in Hawassa, it ranged from 46 to 59%; and in Alage, it ranged from 36 to 55% (Table 2.3**)**. The total pore space in the surface layer ranged from 54 to 59. The values were within the range (36 to 59%) and showed decreasing trend with soil depth except Alage soils showed inconsistence trend. This could be related to the distribution of organic matter content and natural compaction of the subsurface soils by the load of surface soils (Abayneh, 2005; Yitbarek et al., 2016; Gebrehanna et al., 2022). As the soil OM contents decreased, the soils would be less aggregated, and the bulk density would be increased.

Table 2.3. **Selected physical characteristics of the soil profiles at different sites**

Depth (cm)	Horizon	Particle size (%)			Textural class	Si/C	BD (g cm^{-3})	TP (%)
		Clay	Silt	Sand				
Kokate profile								
0-21	Ap	46	28	26	C	0.61	1.23	54
21-45	AB	48	32	20	C	0.67	1.25	53
45-85	Bt1	68	18	14	C	0.26	1.27	52
85-150	Bt2	78	16	6	C	0.21	1.30	51
150-200$^+$	Bt3	78	15	7	C	0.19	1.33	50
Hawassa profile								
0-27	A	24	33	43	L	1.38	1.10	59
27-50	Bw1	28	32	40	CL	1.14	1.25	53
50-90	Bw2	29	36	35	CL	1.24	1.27	52
90-110	Bw3	36	30	34	CL	0.83	1.34	49
110-150	BC	27	37	36	CL	1.37	1.36	49
150-200$^+$	C	26	32	42	L	1.23	1.44	46
Alage profile								
0-35	Ap	36	46	18	SiCL	1.28	1.20	55
35-70	BC	22	62	16	SiL	2.82	1.35	49
70-80	C	6	16	78	LS	2.67	1.48	44
80-105	2B1	16	48	36	L	3.00	1.22	54
105-130	2B2	20	64	16	SiL	3.20	1.22	54
130-160	2C	12	22	66	SL	1.83	1.70	36
160-200$^+$	3B	26	64	10	SiL	2.46	1.27	52

Where: C = clay; L= loam; CL= clay loam; SiCL = silt clay loam; SiL= silt loam; LS = loam sand; SL= sandy loam; Si/C = silt clay ratio; BD = bulk density; TP = total porosity

2.3.4. Chemical properties of the soil profiles

The soil pH in Kokate, Hawassa, and Alage ranged from 4.6 to 5.0, 6.8 to 7.1, and 7.9 to 9.4, respectively. For Kokate, Hawassa, and Alage profiles, the surface soil pH values were 4.6, 6.8, and 7.9, respectively. Following Hazelton and Murphy (2016), the surface soil was very strongly acidic in Kokate, neutral in Hawassa, and moderately alkaline in Alage (Table 2.4). The soil pH (H_2O) revealed slightly increasing trend within depth in all profiles. The low pH of the surface and subsurface soil of Kokate could be attributed to the removal of base cations because of the high rainfall and humid climate of the study area (Mohammed et al., 2017; Mohamed et al., 2021; Abuye et al., 2023). According to Beyene et al. (2023), soil acidity, which is either severely or moderately acidic, affects broad regions of the highlands, and salinity and/or sodicity affects around 10% of the total land area. This is important: significant: amounts of fertile topsoil at the Kokate site are being lost as a result of water erosion. This is supported by a significant and positive association with the Olsen-P (r = 0.95), SOC (r = 0.97), TN (r = 0.82), Ca (r = 0.98), K (r = 0.96), and Na (r = 0.83), while a significant and negative association with the Fe (r = 0.93), Zn (r = 0.88) and Mn (r = 0.87; Table 2.6). The EC determination is often sufficient for diagnosing, surveying and monitoring soil salinity, and for assessing the adequacy of leaching and drainage (FAO, 2021). The EC in the study area was very low in Kokate, low in Hawassa and high in Alage soils its surface value varied between 0.08 (Kokate) and 1.20 dS/m (Alage), which means that the soils are not affected by salinity (FAO, 1988). The very low electrical conductivity could be due to higher rainfall levels in the Kokate site and allowable drainage situations favoring leaching of drained bases with infiltrating water.

The surface SOC contents were 1.65, 2.58, and 2.15% for Kokate, Hawassa, and Alage, respectively, and were rated as medium by Tadesse et al. (1991). Similarly, the TN contents of the surface layer at Kokate, Hawassa, and Alage were 0.14, 0.23, and 0.20%, respectively, and were rated as low to medium by (London, 2014). In our study, SOC and TN in all profiles were higher in surface soils and decreased with depth. The higher soil organic carbon (SOC) content in the surface layer compared to the subsurface layer is due to the increased organic matter input from plants and biological activity in the surface layer (Ayalew et al., 2015; Mohammed et al., 2017; Dinssa and Elias, 2021; Yacob and Nigussie, 2021). Among the three study sites, the surface profile at the Hawassa site had higher levels of surface SOC and TN compared to the cultivated soil at Kokate and Alage. This difference could be attributed to inadequate application of organic material and complete removal of total biomass from the cultivated soils (Beyene et al., 2023). The levels of SOC and TN decreased consistently with depth at all sites, consistent with findings from previous studies (Demiss and Beyene, 2010; Ayalew et al., 2015; Alemayheu et al., 2017). Therefore, organic matter input integrated with mineral fertilizers could improve the SOC and TN status of soils. The C: N ratio shows the quality of organic matter in relation to nitrogen content (Msanya et al., 2001; Landon, 2014; Hazelton and Murphy, 2016). Soil OC is an important parameter that shows the effect of the mineralization of applied crop residues on soil nitrogen levels (Hazelton and Murphy, 2016). The C: N ratio of surface soil ranged from 10.8 in Alage to 11.8 in Kokate, reflecting good-quality organic matter (C: N ratio 8–13) (Msanya et al., 2001). According to some workers (Zhang et al., 2020), the C: N ratio might not be a good parameter to evaluate soil fertility, and therefore it is suggested in this regard to use the N and C values separately for more useful interpretation. The C:N ratio values at most study sites ranged from 8.9:1 to 12.3:1, indicating an optimal level of mineralization.

The avail P contents of Kokate, Hawassa, and Alage ranged from 1.3 to 3.4, 1.4 to 6.5, and 1.3 to 6.0 mg kg^{-1}, respectively (Table 2.4). For Kokate, Hawassa, and Alage, the surface avail P levels were 3.4, 6.5, and 6.0 mg kg^{-1}, respectively. The avail P content of the soils in all the sites was very low to low, despite the difference in soil properties (Olsen, 1954). Kokate soil, characterized by high clay content and low pH, has been found to promote P fixation in a study conducted by Mohammed et al. (2017), Kassa et al. (2020), and Laekemariam and Kibret. (2020). This soil type exhibits lower levels of avail P compared to sites with neutral soil pH, where P fixation is minimal (Yitbarek et al., 2016). In addition, P availability is limited because of $CaCO_3$ and the high pH of the Alage soil, which favors phosphate precipitation (Brindhavani et al., 2022). During the cultivation period, the use of both organic and inorganic fertilizers with low phosphorus content may have also contributed to the low availability of phosphorus in the Kokate and Alage sites. Moreover, the avail P showed a decreasing trend with increasing depth in all profiles because of the decreasing SOC level and increasing fixation by clay minerals. This observation is in agreement with other studies (Ayalew et al., 2015; Kiflu et al., 2016; Yacob and Nigussie, 2021). The low level of avail P observed in the study soils indicated that P availability limits crop productivity. This study is comparable with the findings of Melese et al. (2015); Adhanom and Toshome (2016), and Mesfin et al. (2017) that state P is deficient in Ethiopian soils. Therefore, external P supply, as ISFM, is required to restore the P status of soils. According to FAO (2006), the $CaCO_3$ contents of soils of Kokate and Hawassa were low (<2%), while in Alage soil, it ranges from medium to high (Table 2.4).

Table 2.4. **Chemical properties of the soil profiles at different sites**

Depth (cm)	Horizon	pH (H_2O)	EC (dSm^{-1})	SOC (%)	TN (%)	C: N Ratio	Avail. P ($mg\ kg^{-1}$)	$CaCO_3$ (%)
Kokate profile								
0-21	Ap	4.6	0.08	1.65	0.14	11.8	3.4	0.35
21-45	AB	4.8	0.09	1.20	0.13	9.2	2.9	0.49
45-85	Bt1	5.0	0.09	1.30	0.11	11.8	1.9	0.61
85-150	Bt2	4.9	0.08	1.20	0.12	10.0	1.6	0.86
150-200+	Bt3	4.9	0.07	0.80	0.09	8.9	1.3	1.20
Hawassa profile								
0-27	A	6.8	0.21	2.58	0.23	11.2	6.5	0.51
27-50	Bw1	6.8	0.24	2.00	0.19	10.5	4.2	0.67
50-90	Bw2	6.9	0.24	1.60	0.13	12.3	2.9	0.83
90-110	Bw3	7.1	0.28	1.20	0.11	10.9	3.0	0.95
110-150	BC	6.7	0.24	1.20	0.10	12.0	1.6	1.30
150-200+	C	6.4	0.20	1.10	0.09	12.2	1.4	1.99
Alage profile								
0-35	Ap	7.9	1.2	2.15	0.20	10.8	6.0	9.5
35-70	BC	8.2	1.2	1.40	0.12	11.7	3.0	15.5
70-80	C	8.5	1.1	0.60	0.05	12.0	1.5	21.5
80-105	2B1	9.4	1.7	1.20	0.11	10.9	2.7	17.4
105-130	2B2	9.4	1.7	1.20	0.10	12.0	3.6	8.9
130-160	2C	9.4	1.2	0.98	0.08	12.3	2.9	23.6
160-200+	3B	9.4	1.7	0.98	0.09	10.9	1.3	12.5

Where: EC = electrical conductivity; SOC= soil organic carbon; TN= total nitrogen; C: N = carbon nitrogen ratio; Avail. P = available phosphorus; $CaCO_3$ = calcium carbonate

The cation exchange capacity (CEC) in the three profiles varied from 25.7 to 33.6 in Kokate, 17.2 to 31.6 in Hawassa, and 15.5 to 29.5 cmol (+) kg^{-1} in Alage (Table 2.5). The surface CEC of the soils at the three sites 25.7 in Kokate, 28.0 in Hawassa and 27.0 cmol (+) kg^{-1} in Alage, which could be categorized as high (Landon, 2014). The soil's CEC was determined to be medium to high, with values ranging from 15.5 to 33.6 cmol kg^{-1} (Landon, 2014). The high amount of CEC in the soils of the study area may due to the presence of active clay mineralogy especially Kokate site. The CEC increased with increasing soil depth except C horizons, which could be attributed to their exchangeable base leaching from the surface horizon down to the sub-surface, and clay content increased downward (Dessalegn et al., 2014; Debele et al., 2018; Yacob and Nigussie, 2021) (Table 2.5). The high CEC values indicated that the soil in the study area had sufficient nutrient holding and buffering capacities (Gebrehanna et al., 2022).

The study found that exchangeable Ca, Mg, Na, and K contents varied from 3.5 to 12.9, 1.2 to 5.7, 0.38 to 5.90 and 0.4 to 3.5 cmol kg^{-1}, respectively (Table 2.5). The highest Ca^{2+} content (12.9 cmol (+) kg^{-1}) was found in the surface horizon of Alage soil, while the lowest (6.5 cmol (+) kg^{-1}) was found in the surface horizon of Kokate soil. This highest concentration of Ca^{2+} indicates the degree of weathering (less intensive) and the pH (H_2O) value of 5–9 was the more optimum pH range for the availability of Ca^{2+} (Hazelton and Murphy, 2016). Exchangeable Mg in the topsoil ranged from 3.0 in Kokate to 5.3 cmol (+) kg^{-1} in Alage. According to the FAO (2006) assessment revealed that both exchangeable Ca^{2+} and Mg^{2+} were found in medium to high ranges. The surface soil of exchangeable Na between 0.38 in Kokate to 0.90 cmol (+) kg^{-1} in Alage, and K between 0.4 in Kokate to 1.9 cmol (+) kg^{-1} in Alage. According to the FAO (2006) assessment, both exchangeable K^+ and Na^+ were rated as medium to very high. With the exception of the Alage profile, the exchangeable bases of the soils in the studied profiles were dominated by Ca, followed by Mg, K, and Na, making them ideal for plant growth, and deviations from this order can create ion-imbalance problems for plants (Bohn, 1986) (Table 2.5). The high presence of calcium at all studied sites compared to other cations could be due to the nature of the starting material. The Na content in all profiles, except for the Alage profile, was found to be low, indicating no sodicity problem.

The Ca: Mg ratio of surface to subsurface horizons varies from 1.7:1 to 2.2:1 in Kokate, it varies from 1.9:1 to 2.2:1 in Hawassa and it varies from 2.4:1 to 3.0:1 in Alage profiles. The Ca: Mg ratio of surface horizons varies from 2.2:1 in Kokate profile to 2.4:1 in Alage profile which is below 4:1 Ca: Mg value for most crop production. As rated by Hazelton and Murphy (2016), the Ca: Mg ratio below 4:1 resulted in low availability of Ca that shows the probable shortage of Ca uptake because of surplus amount of Mg or leaching out of basic cations by the high amount of rainfall especially Kokate profile. The approximate optimum range of Ca: Mg ratio for most crops is between 3:1 and 4:1 (Landon, 2014). If it is less than 3:1, P uptake may be inhibited. Across the soil depth, the Ca: Mg ratio was irregularly distributed for all three profiles. The study found percent base saturation, with surface soil horizons 40% in Kokate, 52% in Hawassa and 78% in Alage (Table 2.5). As rated by Hazelton and Murphy (2016), PBS in surface horizons ranged from moderate (40, 52% in Kokate and Hawassa) to high (78% in Alage), indicating Alage soils poor leaching, while Kokate soil moderately leaching and potential for leaching due to high rainfall. Consequently, soils in Alage area could be categorized as fertile soil in line with the assessment of Landon (2014), who suggested soils with more than 60% base saturation as fertile. The variation observed in PBS indicates the degree of leaching, which was used as a diagnostic character for classifying soils (Meena, 2014).

Soil sodicity measures the amount of exchangeable sodium in the soil, which can cause problems like low infiltration, dense subsoils, clay dispersion (Msanya et al., 2001; Hazelton and Murphy, 2016). Kokate and Hawassa profiles have non-sodic soil suitable for crop production, while Alage profile has a range of 3.3 to 36.5, indicating it can be used without reducing crop yield, especially in the upper 35 cm of the profile (Table 2.5).

The surface soil of micronutrients varied across all studied profiles. The site and depth of the soil influenced the level of micronutrients (Table 2.5). This could be because of the effect of soil pH on micronutrient availability (Ayalew, 2016; Mohamed et al., 2021). In the topsoil, micronutrient levels were classified as low or insufficient in Hawassa and Alage, but as high or sufficient in Kokate (Jones, 2003). Fertilizer response is unlikely for values greater than 10.0, 3.0, 1.5, and 1.0 for Fe, Mn, Zn, and Cu, respectively (Hartz, 2007). The study revealed that, except for Cu, soils in the Kokate site have sufficient levels of Fe, Mn, and Zn, while lower levels in the Hawassa and Alage sites suggest the requirement for micronutrient containing fertilizer (Ali et al., 2010).

Table 2.5. **Chemical characteristics of soil from different horizons and sites**

Depth (cm)	Horizon	CEC	Ca	Mg	K	Na	Sum	Ca: Mg	PBS	ESP	Fe	Mn	Zn	Cu
			(Cmol (+) kg^{-1} of soils					ratio		%		mg kg^{-1}		
						Kokate profile								
0-21	Ap	25.7	6.5	3.0	0.4	0.38	10.3	2.2	40	1.5	22.3	16.9	2.30	0.29
21-45	AB	25.9	6.7	3.3	0.4	0.39	10.8	2.0	42	1.5	18.6	15.0	1.20	0.31
45-85	Bt1	31.9	8.9	5.1	1.5	0.54	16.0	1.7	51	1.7	13.1	11.7	1.70	0.15
85-150	Bt2	32.5	10.1	5.0	1.1	0.62	16.8	2.0	52	1.9	12.2	11.3	1.40	0.12
$150\text{-}200^{+}$	Bt3	33.6	11.5	5.3	2.1	0.63	19.5	2.2	58	1.9	12.1	11.3	1.20	0.17
						Hawassa profile								
0-27	A	28.0	8.5	3.8	1.5	0.70	14.5	2.2	52	2.5	2.5	2.3	0.39	0.49
27-50	Bw1	26.8	8.7	3.9	1.3	0.90	14.8	2.2	55	3.4	3.1	0.5	0.19	0.35
50-90	Bw2	31.6	10.3	5.4	3.5	1.20	20.4	1.9	65	3.8	2.4	0.8	0.10	0.13
90-110	Bw3	30.6	12.7	5.7	2.3	1.50	22.2	2.2	73	4.9	2.3	1.2	0.11	0.40
110-150	BC	25.6	9.2	4.4	1.9	1.10	16.6	2.1	65	4.3	1.1	1.3	0.05	0.41
$150\text{-}200^{+}$	C	17.2	4.3	2.8	1.3	1.10	9.5	1.5	55	6.4	1.9	1.1	0.06	0.42
						Alage profile								
0-35	Ap	27.0	12.9	5.3	1.9	0.90	21.0	2.4	78	3.3	1.2	1.0	0.21	0.15
35-70	BC	25.6	11.0	4.7	1.8	2.60	20.1	2.3	79	10.2	0.7	0.8	0.13	0.12
70-80	C	15.6	4.7	2.2	1.1	5.70	13.7	2.1	88	36.5	0.9	0.9	0.13	0.12
80-105	2B1	28.6	11.7	3.9	1.8	5.90	23.3	3.0	81	20.6	0.4	0.4	0.10	0.22
105-130	2B2	29.5	9.2	2.4	2.5	5.40	19.5	3.8	66	18.2	2.4	1.3	0.21	0.10
130-160	2C	15.5	5.4	1.2	1.6	3.70	11.9	4.5	77	23.9	0.7	0.9	0.11	0.06
$160\text{-}200^{+}$	3B	20.6	3.5	1.9	1.7	3.70	10.8	1.8	52	18.0	1.3	1.1	0.23	0.20

Where: CEC = Cation exchange capacity; Ca = Calcium; Mg = Magnesium; Na = sodium; K = potassium; Ca: Mg = Calcium magnesium ratio; PBS = Percent base saturation; ESP = Exchangeable sodium percentage; Fe = Iron; Mn = manganese; Zn = Zinc and Cu = Cupper

Table 2.6. Correlation among the soil parameter across sites

	Clay	**Bd**	**pH**	**Olsen P**	**SOC**	**TN**	**CEC**	**Ca**	**Mg**	**K**	**Na**	**Fe**	**Zn**	**Cu**	**Mn**
Clay	1														
Bd	0.64^{ns}	1													
pH	-0.67^{ns}	-0.14^{ns}	1												
Olsen P	-0.86**	-0.40^{ns}	0.95***	1											
SOC	-0.59^{ns}	-0.06^{ns}	0.97***	0.90***	1										
TN	-0.47^{ns}	0.09^{ns}	0.82**	0.73*	0.82**	1									
CEC	0.71*	0.27^{ns}	-0.57^{ns}	-0.68*	-0.60^{ns}	-0.65^{ns}	1								
Ca	-0.56^{ns}	-0.03^{ns}	0.98***	0.89***	0.98***	0.79*	-0.48^{ns}	1							
Mg	0.24^{ns}	0.17^{ns}	0.31^{ns}	0.09^{ns}	0.31^{ns}	0.30^{ns}	0.14^{ns}	0.37^{ns}	1						
K	-0.75*	-0.24^{ns}	0.96***	0.96***	0.92***	0.67*	-0.57^{ns}	0.93***	0.10^{ns}	1					
Na	-0.14^{ns}	0.31^{ns}	0.83**	0.62^{ns}	0.85**	0.72*	-0.25^{ns}	0.89**	0.55^{ns}	0.73*	1				
Fe	0.89**	0.40^{ns}	-0.93***	-0.99***	-0.86**	-0.71*	0.67*	-0.86**	-0.05^{ns}	-0.95***	-0.57^{ns}	1			
Zn	0.93**	0.50^{ns}	-0.88**	-0.98***	-0.82**	-0.68*	0.71*	-0.80**	0.05^{ns}	-0.92***	-0.47^{ns}	0.98***	1		
Cu	0.37^{ns}	0.65^{ns}	0.44^{ns}	0.15^{ns}	0.50^{ns}	0.44^{ns}	0.10^{ns}	0.55^{ns}	0.57^{ns}	0.31^{ns}	0.86**	-0.08^{ns}	0.02^{ns}	1	
Mn	0.93^{ns}	0.43^{ns}	-0.87**	-0.96**	-0.81**	-0.63^{ns}	0.67^{ns}	-0.80**	-0.03^{ns}	-0.91**	-0.47^{ns}	0.98**	0.96**	0.029^{ns}	1

*, **, *** *and ns refer to* $p \leq 0.05$, *0.01, 0.001, and not significant, respectively.*

2.3.5. Classification of the soils

The studied soils were classified; according to World Reference Base Legend IUSS Working Group (IUSS, 2022) and Soil Taxonomy (2006). The morphological, physical and chemical characteristics of the soils were used for classification purposes.

The Kokate surface soil had 21 cm thick having color values and chroma of less than 3 when moist, dark moist coloured, moderate, fine and granular structure, friable consistency, less than 50 percent base saturation, and contain more than 0.6 percent organic carbon fulfilling all the requirements of an umbric epipedon in the surface horizon. The loam sand or finer and greater than 8% clay, indication of clay illuviation but doesn't form part of natric horizon. Furthermore, the subsurface horizon of this profile contained more clay compared to the overlying soil horizon, which started at less than 100 cm soil depth fulfilling the criteria of the argic horizon (Table 2.7). The soils in the argic horizon had CEC greater than 24 cmol (+) kg^{-1}, PBS of greater than 50% at certain depth, and high-activity clay throughout the argic horizon and hence could be classified as Luvisols. The soils also exhibited vertic properties, qualifying vertic prefix qualifiers. The soils contained more than 1 per cent organic carbon in the fine earth fraction to a depth of 50 cm from the mineral soil surface and hence considered as humic suffix qualifier. Moreover, the soils had clay textural class was the dominant throughout the profile, and thus qualify clayic supplemental qualifier. Accordingly, the soils of the Kokate site were classified as Vertic Luvisols (Pantoclayic, Aric, Cutanic, Differentic and Humic).

The surface soil of Hawassa site had 27 cm thick, well-structured, very dark moist colored, high percent base saturation, high biological activity, and moderate organic matter content indicating mollic diagnostic surface horizon. The granular and sub-angular blocky structures were the dominant at the surface and subsurface horizons, respectively. The subsurface horizon was greater than 15 cm in thickness with clay loam texture. The soils in the cambic subsurface horizon showed evidence of pedogenetic alteration the overlying horizon, and hence could be classified as Cambisols. Moreover, the soils did not have principal qualifiers, contained more than 1 percent OC throughout the soil profile, texture class of clay loam in a layer ≥ 30 cm thick within ≤ 100 cm of the mineral soil surface, humic and loamic supplementary qualifier. Therefore, the soils in the Hawassa area were classified as Haplic Cambisols (Pantoloamic and Humic).

The surface layer of Alage soil profile had 35 cm thick, dark-coloured, high base saturation, moderate content of organic matter. The soils in the surface horizons of the Alage profile fulfill all the requirements of the mollic epipedon, whereas the subsurface diagnostic horizon is formed from fluvic material. The exhibited stratified layers of sand, silt, clay, SOC and avail P etc. The fluvic material of lacustrine deposit, and the horizon was with obvious stratification and weak sub angular blocky in structure and contained more than 1 percent OC throughout the soil profile. The soils of calcic subsurface horizon contained substantial accumulation of calcium carbonate, which is designated by C horizon (Table 2.5). The profile had Calcaric and Panofluvic principal qualifier and textural and aric, supplementary qualifiers. Consequently, the soil of Alage was classified as Calcaric Panofluvic Fluvisols (Endoarenic, Katoloamic, Katosiltic, Aric, Humic).

Table 2.7. Diagnostic horizons and soil types of studied areas according to WRB and Soil Taxonomy at each site

Profiles	Soil classification based on WRB			Soil classification based on soil taxonomy		
	Diagnostic horizon		Soil type	Diagnostic horizon		Soil type
	Surface	Subsurface		Surface	Subsurface	
Kokate	Umbric	Argic	Luvisols	Umbric	Argillic	Alfisols
Hawassa	Mollic	Cambic	Cambisols	Mollic	Cambic	Inceptisols
Alage	Mollic	Calcic	Fluvisols	Mollic	Calcic	Fluvents

2.4.Conclusions

Field and laboratory analyses were conducted to characterize and classify soils in the Kokate, Hawassa, and Alage areas of southern Ethiopia. One representative soil profile was opened at each study site, and soil properties were evaluated to understand variations caused by differences in soil-forming processes.

The soils showed clearly differentiated physical and chemical characteristics.The Kokate soil was very strongly acidic, with low SOC and avail P, but high micronutrient content. The Hawassa soil had neutral soil pH, low SOC, avail P, and low micronutrient content. The Alage soil was moderately alkaline, with high sodium content and low SOC, avail P, and micronutrients.

The study revealed significant variations in morphological, physical, and chemical properties both within and among the study sites, indicating differences in productive potential and management requirements. To improve soil fertility and agricultural productivity, particular attention should be given to managing SOC, TN, avail P, and micronutrients. The diverse soil properties and types identified in the study provide valuable information for developing site-specific integrated soil fertility management strategies**.**

Based on the WRB soil classification system, the surface horizons of the Kokate, Hawassa, and Alage soils were classified as umbric, mollic, and mollic epipedon, respectively, while the subsurface diagnostic horizons were identified as argic, cambic, and calcic, respectively. Consequently, the soils of Kokate, Hawassa and Alage were classified as Vertic Luvisols, Haplic Cambisols, and Calcaric Fluvisols, corresponding to Alfisols, Inceptisols, and Fluvents in the Soil Taxonomy system respectively.

2.5.Reference

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CHAPTER THREE

3. EFFECTS OF INTEGRATED SOIL FERTILITY MANAGEMENT ON SOIL PROPERTIES AND PHOSPHORUS SORPTION CHARACTERISTICS IN THREE SOIL TYPES IN SOUTHERN ETHIOPIA

Abstract

Low phosphorus (P) availability, largely due to sorption, is a major constraint on crop productivity in Ethiopian soils. This study evaluated P sorption and the effects of integrated soil fertility management (ISFM) on Luvisols, Cambisols, and Fluvisols in southern Ethiopia. Phosphorus sorption was determined using batch equilibrium methods fitted to Langmuir and Freundlich models, and ISFM effects were evaluated in incubation experiment involving control, inorganic P, BC, Com, and their combinations, arranged in completely randomized design (CRD) with three replications. Results showed that Luvisols had the highest P sorption capacity, requiring more fertilizer than Cambisols and Fluvisols. The Freundlich model best described sorption (R^2 = 0.82–0.98), indicating heterogeneous adsorption sites. The incubation experiments revealed that integrated applications of inorganic P and organic fertilizer reduced P sorption and increased avail P compared to control and sole inorganic fertilizer treatment. The combined use of 5 t ha^{-1} biochar + 20 kg ha^{-1} inorganic P fertilizer most effective in acidic Luvisols, and 5 t ha^{-1} compost + 20 kg ha^{-1} inorganic P fertilizer best in Cambisols and Fluvisols. Overall, ISFM improved soil properties, P availability, and offers a sustainable strategy for smallholder systems in southern Ethiopia.

Keywords: Available phosphorus, external phosphorus requirement, Freundlich Model, phosphorus fixation.

3.1.Introduction

Phosphorus (P) is a vital nutrient essential for energy transfer, fruiting, seed production, and early plant growth and development. Next to nitrogen, P deficiency in plants creates the most important soil fertility problem throughout the world, particularly in tropical and subtropical acidic and alkaline soils (Islam et al., 2024; Teressa et al., 2024; Nambafu et al., 2025). Many tropical soils lack avail P for plants due to limited fertilizer use and strong P sorption (Hanyabui et al., 2020; Lambano et al., 2022).

In Ethiopia, agricultural soils are generally low in avail P (Bereket et al., 2018), making P deficiency one of the major constraints to crop production. Soil acidity and alkalinity strongly influence P dynamics: acidic soils typically contain Fe and Al oxides that adsorb P (Bekele et al., 2020; Warke, 2024), while alkaline soils contain calcium carbonate, which binds P with Ca and Mg (Hopkins and Ellsworth, 2005; Mwende, 2019; Alemayehu and Haile, 2022). The limited availability of P may also result from inherently low P in parent materials, high weathering intensity, soil erosion losses, long-term mismanagement, and strong fixation processes (Andualem, 2021; Jiang et al., 2025). In particular, soils of volcanic ash and acidic origin in Ethiopia are expected to exhibit high P sorption, but P fixation varies among soil units due to mineral composition, soil properties, and management practices (Lambano et al., 2022).

Inorganic fertilizers supply nutrients rapidly and correct deficiencies, but they often have low fertilizer use efficiency and limited residual effects. Less than 20% of applied P may be recovered by crops during a single growing season, while the rest becomes lost by leaching and runoff or immobilized through adsorption and precipitation (Helfenstein et al., 2018; Maluf et al., 2018). Consequently, only a small fraction of the total P in the soil is accessible to plants (Harrell and Wang, 2006). However, applying large amounts of inorganic fertilizers is not economical or environmentally friendly for smallholder farming systems (Hossain et al., 2022).

Organic amendments such as compost and biochar play a complementary role by improving soil organic matter, nutrient cycling, and microbial activity, thereby enhancing P availability (Han et al., 2022; Yan et al., 2023). It has high fertilizer use efficiency for long term and high residual effects for the season. Compost can lower soil P sorption capacity and reduce the need for external fertilizers (Monteiro, 2019), while biochar improves soil structure, nutrient retention, and P availability due to its porous structure (Bai et al., 2022). These organic resources are cost-effective, locally available, and particularly important in soils with strong P fixation (Rakotoson and Tsujimoto, 2020; Teshale et al., 2025). However, organic inputs alone release nutrients slowly and may not fully meet crop demand.

The best practice: integrated use of inorganic + organic fertilizers usually give the highest fertilizer use efficiency → inorganic provides quick nutrients, while organic improves soil and reduces nutrient losses. The ISFM involves tailoring combinations of fertilizers and management practices to local conditions to enhance nutrient utilization efficiency and sustainability (Doldt et al., 2023). Recent evidence indicates that combining organic and inorganic fertilizers provides greater benefits than applying either alone (Bai et al., 2022; Yan et al., 2023). Therefore, ISFM which combines inorganic fertilizers with organic amendments, has emerged as an effective strategy to enhance soil fertility, crop yields, and nutrient-use efficiency (Elka and Laekemariam, 2020; Gebrekidan et al., 2025). The studies on the integrated effects of inorganic fertilizers with organic inputs such as compost and biochar on soil properties and P sorption remain limited in southern Ethiopia. This study was conducted to evaluate the effects of ISFM on soil properties and P sorption characteristics in three soil types in southern Ethiopia.

3.2. Materials and Methods

3.2.1. Soil phosphorus sorption characteristics

Soil P sorption data were analyzed using linearized Langmuir and Freundlich models. The goodness-of-fit of the data to the equations was evaluated using the coefficient of determination (R^2) for each soil amendment. A higher R^2 value suggests a better fit of the model to the data.

3.2.2. Soil sampling, treatments and experimental design

The soil was collected from the surface layer (0-20 cm depth) of the three sites (Kokate, Hawassa, and Alage) using an auger by random sampling technique and nine composite soil samples were made. The composite soil samples were crushed and passed through a 0.5 mm sieve for SOC and TN, while 2 mm sieve for other soil properties. The treatments were arranged in a completely randomized design (CRD) with three replications. Six different combinations of ISFM (0, P, BC, Com, P with BC, and P with Com) were used as treatments. Triple superphosphate (TSP) (46% P_2O_5) was used as inorganic P fertilizer, and compost (Com) and biochar (BC) were used as organic fertilizer. In this study, the amount of phosphorus was based on the blanket recommended P fertilization rate, whereas that of BC and Com was based on literature for other sites in Southern Ethiopia. Accordingly**,** the application rates of BC and Com were set at 5 t ha^{-1}**.**

3.2.3. Incubation experiment

Experiments on soil incubation were conducted in a controlled environment at 25^oC. The air-dried soil (<2 mm) was thoroughly mixed with different combinations of amendments. Plastic pots (10 cm internal diameter and 30 cm height), each containing 3 kg of soil, were filled with ISFM-treated soil samples and incubated for 21 days in a closed system without leaching or periodic sampling.The moisture contents of the incubated soils were maintained by addition of distilled water. Soil samples were collected after 21 days of incubation period for determinations of selected physicochemical properties.

3.2.4. Determination of external phosphorus requirements

The external P-requirement of each soil or the amount of P required for each soil at 0.2 mg P L^{-1} equilibrium solution of P was calculated based on Langmuir and Freundlich models/equations developed for each soil types.

3.2.5. Statistical analysis

The soil properties and P sorption parameters data were analyzed using Statistical Analysis Systems (SAS version 9.4) (2012). A two-way analysis of variance (ANOVA) was conducted with the General Linear Model (GLM). To determine significant differences in mean values of soil and P sorption parameters, the least significant test at $p \leq 0.05$ was used. Pearson correlation analysis was performed to assess the relationship between P sorption parameters and selected soil properties.

3.3. Results and Discussion

3.3.1. Biochar, compost, and selected soil properties before the soil amendment

The Luvisols were the most acidic, the Cambisols were neutral, and the Fluvisols were moderately alkaline. The soil at Luvisols, Cambisols, and Fluvisols has medium SOC and TN as rated by Tadesse et al. (1991)**,** low avail P as rated by Olsen (1954), and high CEC as rated by Hazelton and Murphy (2016) (Table 3.1). The CEC of the soils was almost similar for all soil types. Biochar and compost were alkaline and neutral pH, respectively. They have high SOC, TN, avail P and CEC as rated by Hazelton and Murphy (2016) (Table 3.1).

Table 3.1. **Selected chemical properties of soil, biochar and compost before experiment**

Items	Ash Content (%)	pH (H_2O)	Avail P (mg kg^{-1})	SOC	TN	CEC (cmol (+) kg^{-1})
				%		
Biochar	25.7	8.3	31.7	53.9	0.97	43
Compost	-	6.5	27.2	42.7	1.27	37
Luvisols	-	4.8	3.5	1.7	0.16	26
Cambisols	-	6.6	6.5	2.6	0.22	28
Fluvisols	-	7.9	6.2	2.1	0.19	27

3.3.2. Effects of soil amendments on selected soil properties under incubation

The study found that soil texture was not significantly ($p<0.01$) affected by soil amendment, but other soil properties like Bd, soil pH, SOC, avail P, exchangeable bases, and CEC were significantly ($p<0.01$) influenced by BC, Com, BP, and CP soil amendments compared to the control and sole inorganic P fertilizer in all soil types (Table 3.2). The biochar, compost and their combined with inorganic fertilizer application reduced bulk density by 10.6, 33.6 and 21.3% for Kokate, Hawassa and Alage, respectively. This decline in bulk density may be related to the increase in SOC which modify the porosity through aggregate stabilization and formation. This result, was in line with Gudadhe et al. (2015) who found decrease in soil bulk density as a result of farm yard manure (FYM) and compost application (Tesfaye, 2019). The significant decrease in bulk density also agrees with Omondi et al. (2016) who reported that biochar application reduced bulk density. However, the bulk density of the studied soils did not change with the application of sole inorganic P fertilizer. This agreed with Wondimu et al. (2024) who showed that mineral fertilizers application did not affect soil bulk density.

The soil pH of Luvisols, Cambisols, and Fluvisols increased significantly by 1.9, 0.8, and 0.8 units, respectively. The highest increase in soil pH of 1.9 units in Luvisols was observed with BP application compared to sole inorganic P fertilizer (Table 3.2). It was also increased by 39%, 12%, and 10% in Luvisols at Kokate, Cambisols, and Fluvisols at Hawassa and Alage, respectively, due to the BP amendment. Previous studies also showed that the pyrolysis preparation process of corn cob BC for soil amendment (Shareef et al., 2018). Consistent with our results, BC application led to higher pH changes compared to Com (Mensah and Frimpong, 2018), possibly due to the higher pH value and ash content of BC in our experiment. This influence on soil pH was consistent with other studies for either organic or organic combined with inorganic fertilizer (Apori et al., 2021; Nigussie et al., 2021).

The soil organic carbon (SOC) increased by 26% from BP application in Luvisols, 13% from CP application in Cambisols, and 26% from CP application in Fluvisols. This increase might be due to the application of organic inputs (biochar, and compost) which have high SOC contents. Previous studies have shown that the application of biochar to agricultural fields can increase SOC levels (Mavi et al., 2023; Bekele and Swaren, 2025). Other studies have also shown increased SOC due to the application of biochar (Lulu et al., 2022) and compost (Getachew et al., 2016; Tucho et al., 2024). Similar findings after the application of compost with inorganic fertilizer (Tesfaye, 2019). The highest TN contents, 0.33, 0.34 and 0.27 % were recorded in BP and CP with Kokate, Hawassa and Alage, respectively. The lowest TN contents, 0.16% for Kokate, 0.22% for Hawassa and 0.19% for Alage were recorded in the control and P treated soils. It occurs through increased microbial population diversity (Li et al., 2020). The biochar pores allow populations to grow and fix nitrogen for plant uptake (Ameloot et al., 2013). Additionally, for crops unable to fix nitrogen on their own, biochar increases the amount of nitrogen available for plant absorption (Xia et al., 2020; Preza Fontes et al., 2024). This study was in agreement with Yuan et al. (2023) and Tazebew et al. (2024) who stated that biochar addition to the soil resulted in a significant in increasing TN. Hence, it was clear that the application of integrated soil fertility management increased the TN, which may be attributed to the mineralization of N from organic components (Tesfaye, 2019).

The avail P levels in all soil types before the experiments were very low to low. This could be attributed to the continuous cultivation of the farms with minimal external P input and P fixation (Jalali, 2020; Antonangelo et al., 2025). The low availability of P in the experimental soils clearly indicates that P is a limiting factor for crop productivity. However, the application of all the amendments significantly increased the avail P in the soil ($p \leq 0.001$). In Luvisols at Kokate, the avail P increased by 95% with the BP amendment, while in Cambisols and Fluvisols at Hawassa and Alage, respectively, there was a 59% and 49% increase with the CP amendment compared to the respective sole P fertilizer application. The soil amendments could have resulted in decreased P sorption and increased avail P due to their influence on soil pH, particularly for acidic Luvisols. Hence, application of BP was more efficient in increasing avail P in acidic Luvisols, while CP was more efficient in neutral Cambisols and moderately alkaline Fluvisols. This suggests that additional P might be released from BC and Com through mineralization and ash, respectively (Naeem et al., 2018; Ahmed et al., 2021). Consistent with the present findings, the combined application of sole organic or combined organic and inorganic fertilizers significantly improved soil avail P (Hu et al., 2023). Moghimi et al. (2018) also reported that the addition of vermicompost (VC) increased avail P by 37% in calcareous soils in central Iran. The increase in avail P indicates that the combined fertilizers enhance P availability through the release of avail P, improvement of Ca^{2+}, and/or modification of soil pH (Naeem et al., 2018). Li et al. (2020) suggested that BC addition to soils can increase avail P by enhancing CEC or altering soil pH. Studies have shown that the avail P content in soil has a significant positive correlation with CEC (Shah et al., 2019). Organic fertilizers provide abundant C sources to stimulate soil microbial degradation of SOM that enhances the avail P (Ibrahim et al., 2021). Therefore, the increase in avail P due to the application of BC, Com, BP, or CP in the present study could be attributed to the releasing of P through various mechanisms from added organic components in the soils or increasing P desorption by chelation of OC with Fe and Al oxides in acidic or Ca in alkaline soils (Lin et al., 2020; Bekele and Swaren, 2025). Thus, the contents of avail P in the soil were raised from low to improve after applications of BC, Com, BP, and CP, indicating that the use of the amendments may lead to improved P availability. In a long-term study, Ahmed et al. (2021) found a significant increase in soil total P and avail P concentrations in soils of three sites when amended with NPK mineral fertilizer and manure. The high SOC content of BC and Com in both sole and combined amendments could highly contribute to the avail P in the present study (Lulu et al., 2022).

The organic amendments (BC and Com) and combination between organic amendments and inorganic P fertilizer applications (BP and CP) significantly affected the CEC of the three soil types. The lowest CEC of 32, 33 and 33 cmol (+) kg^{-1} were recorded in Kokate, Hawassa and Alage soils under P and control treated soils, respectively. The highest increase in CEC was 22% in Kokate, 21% in Hawassa and 21% in Alage soils due to sole biochar, compost and combination of organic and inorganic fertilizer (BP and CP) (Table 3.2). This could be attributed to the high SOC content of soils after application of these amendments. The results are also in agreement with previous findings (Gautam et al., 2017; Kätterera et al., 2019) who found increased CEC and SOC of the soils treated with organic fertilizers. Similar studies, organic fertilizer can increase the CEC of the soils (Harden et al., 2018). The inorganic P and the control treatments had no significant difference on the exchangeable bases in the soil (Table 3.2). The present study showed that high SOC content of BC and Com in both sole and integrated amendments could highly contribute to exchangeable bases. Similar study the integrated amendments could highly contribute to exchangeable bases (Lulu et al., 2022). Other study reported that the effects of BC and FYM application enhanced soil K content by 18.41% and 9.0%, respectively over the control treatment (Lulu et al., 2022; Nega et al., 2025). Li et al. (2022) and Frąc et al. (2023) have shown that soil Mg increased after applying organic fertilizer alone or in combination with mineral fertilizers.

Table 3.2. **Influence of soil amendments on physicochemical properties of the soils**

Amendment	Clay	Bd	pH H_2O	Avail P mgkg^{-1}	SOC	TN	CEC	Ca^{2+}	Mg^{2+}	K^{+}	Na^{+}
					(%)			cmol (+) kg^{-1}			
Luvisols											
Control	56	1.25^{a}	4.8^{d}	3.5^{e}	1.65^{c}	0.16^{b}	26^{c}	7.9^{d}	2.9^{c}	0.39^{c}	0.38^{b}
P	57	1.22^{ab}	4.9^{d}	3.9^{d}	1.67^{c}	0.16^{b}	27^{c}	10.1^{c}	5.1^{b}	0.42^{bc}	0.39^{b}
BC	57	1.13^{abc}	6.1^{b}	5.4^{c}	1.88^{b}	0.29^{a}	33^{b}	15.3^{a}	5.5^{a}	0.45^{b}	0.45^{ab}
Com	57	1.20^{ab}	5.8^{c}	5.3^{c}	1.85^{b}	0.32^{a}	32^{b}	11.7^{b}	5.7^{a}	0.43^{b}	0.41^{bc}
BP	57	1.03^{c}	6.8^{a}	7.6^{a}	2.10^{a}	0.33^{a}	36^{a}	16.5^{a}	5.5^{a}	0.49^{a}	0.48^{a}
CP	58	1.09^{bc}	6.0^{bc}	5.9^{b}	2.05^{a}	0.33^{a}	35^{a}	13.2^{b}	5.8^{a}	0.50^{a}	0.43^{b}
$LSD_{t0.05}$	2.3	0.15	0.28	0.39	0.09	0.07	1.4	1.6	0.34	0.04	0.04
CV (%)	2.3	6.9	2.7	4.1	2.50	13.5	2.4	6.9	3.7	4.6	5.3
Cambisols											
Control	22	1.1^{a}	6.6^{c}	6.5^{c}	2.55^{d}	0.22^{d}	28^{c}	9.3^{d}	4.2^{c}	1.2^{bc}	0.68^{c}
P	24	1.0^{a}	6.7^{c}	6.8^{c}	2.56^{d}	0.23^{cd}	28^{c}	14.0^{c}	4.9^{b}	1.2^{bc}	0.69^{c}
BC	23	0.97^{a}	7.3^{a}	7.0^{c}	2.67^{c}	0.26^{bcd}	33^{b}	19.9^{ab}	5.1^{bc}	1.21^{abc}	0.81^{b}
Com	23	0.93^{ab}	6.9^{b}	8.5^{b}	2.74^{b}	0.27^{bc}	34^{b}	17.3^{b}	5.3^{abc}	1.21^{abc}	0.82^{b}
BP	23	0.87^{ab}	7.5^{a}	8.1^{b}	2.78^{b}	0.28^{b}	34^{b}	21.5^{a}	5.4^{ab}	1.24^{a}	0.92^{a}
CP	24	0.73^{b}	7.1^{b}	10.8^{a}	2.90^{a}	0.34^{a}	38^{a}	22.7^{a}	5.5^{a}	1.23^{ab}	0.82^{b}
$LSD_{t0.05}$	2.4	0.21	0.19	0.69	0.07	0.05	2.4	3.1	0.41	0.04	0.06
CV (%)	5.7	12.5	1.5	4.7	1.40	9.5	4.1	9.7	4.5	6.9	4.5
Fluvisols											
Control	36	1.22^{a}	7.9^{c}	6.2^{d}	2.14^{d}	0.19^{b}	27^{c}	14.3^{c}	5.3^{c}	1.5^{b}	1.2^{b}
P	37	1.13^{ab}	7.9^{c}	6.5^{cd}	2.19^{cd}	0.19^{b}	27^{c}	18.7^{c}	5.3^{c}	1.5^{b}	6.2^{a}
BC	38	1.15^{ab}	8.4^{b}	6.7^{c}	2.20^{cd}	0.21^{b}	33^{b}	22.1^{b}	5.4^{b}	2.0^{ab}	6.3^{a}
Com	37	1.0^{abc}	8.0^{c}	7.6^{b}	2.29^{bc}	0.23^{ab}	35^{ab}	20.0^{bc}	5.7^{ab}	2.2^{a}	6.3^{a}
BP	38	0.97^{bc}	8.7^{a}	7.5^{b}	2.40^{b}	0.23^{ab}	37^{a}	26.1^{a}	5.5^{ab}	2.3^{a}	6.3^{a}
CP	38	0.96^{c}	8.3^{b}	9.7^{a}	2.75^{a}	0.27^{a}	36^{ab}	20.2^{bc}	5.9^{a}	2.5^{a}	6.5^{a}
$LSD_{t0.05}$	2.1	0.19	0.27	0.41	0.12	0.05	2.5	2.7	0.39	0.67	0.44
CV (%)	3.1	9.5	1.8	3.1	2.80	12.9	4.2	7.3	3.8	17.3	4.4

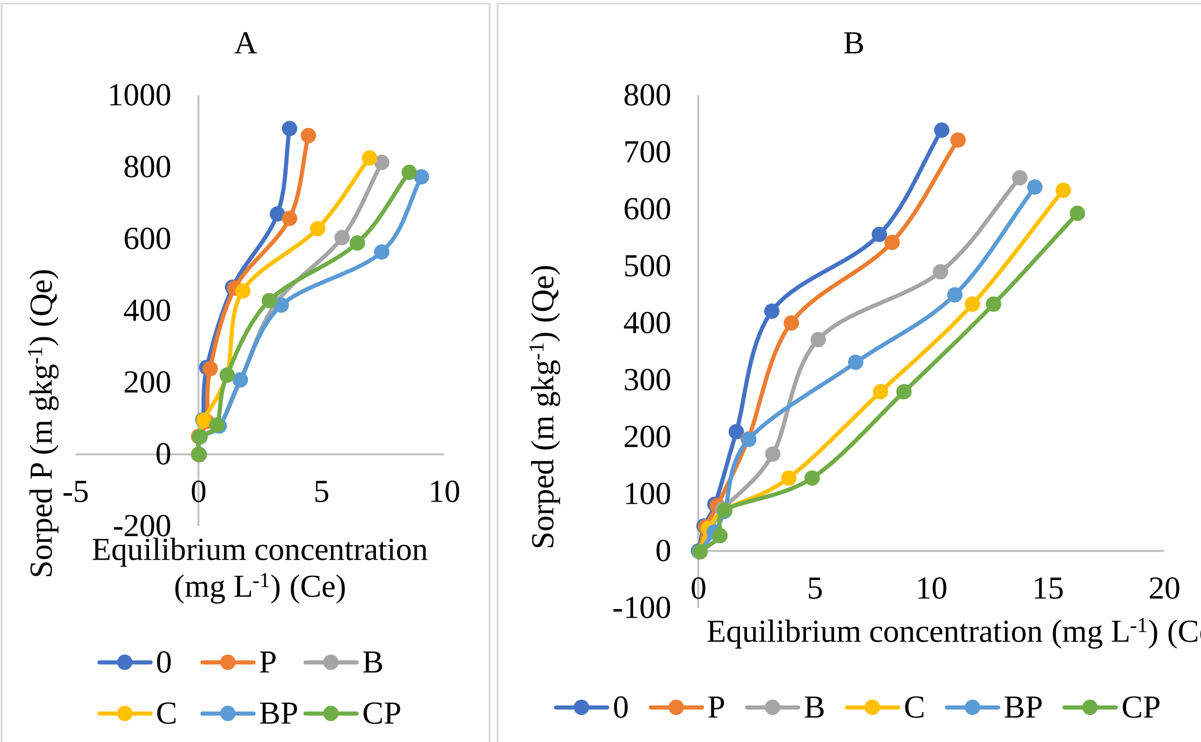
Where**:** P = inorganic phosphorus; BC = biochar; Com = compost; BP = biochar with inorganic P; CP = compost with inorganic P; avail P = available phosphorus (mg kg^{-1}); SOC = Soil organic carbon (%); CEC = cation exchange capacity (cmol (+) Kg^{-1}); and Ca^{2+} = exchangeable calcium (cmol (+) kg^{-1}); Mg^{2+} = exchangeable magnesium (cmol (+) kg^{-1}); K^{1+} = exchangeable potassium (cmol (+) kg^{-1}), and N^{1+} = exchangeable sodium (cmol (+) kg^{-1})

3.3.3. Phosphorus sorption characteristics and the effect of soil amendments on it

Phosphorus sorption isotherms

The phosphorus (P) sorption isotherm is a fundamental concept in soil science, especially particularly in the study of how P interacts with soil particles, biochar, compost, or other amendments. It helps to determine the soil's capacity to retain P at different concentrations and the amount of avail P in the soil solution for plant uptake.

The P sorption isotherms show distinct variations among different soil types and when influenced by amendments (Figure 3.1). In all soils studied, the amount of sorbed P increased gradually as the P concentration in the soil solution, increased, in line with established principles of P sorption dynamics (Barrow, 1983; Milham et al., 2025). At lower P concentrations in the solution, there were significant spikes in P sorption in all soil types, especially in unamended soils, indicating a strong affinity for P when sorption sites are abundant. However, at higher P concentrations, sorption in amended soils reached a relatively steady state, suggesting that amendments reduced the number or reactivity of sorption sites, limiting further P fixation. Prior to amendment, Cambisols exhibited the lowest steep slope of P sorption at lower concentrations compared to Luvisols and Fluvisols, due to their lower inherently lower P sorption capacity. After amendment, the slope decreased in all soil types compared to the control, highlighting the role of amendments in reducing P fixation and enhancing P availability in the soil solution. Consistent findings from previous studies also support the lower sorption affinity and capacity after amendment (Iyamuremye et al., 1996; Dossa et al., 2008; Gutema et al., 2023).



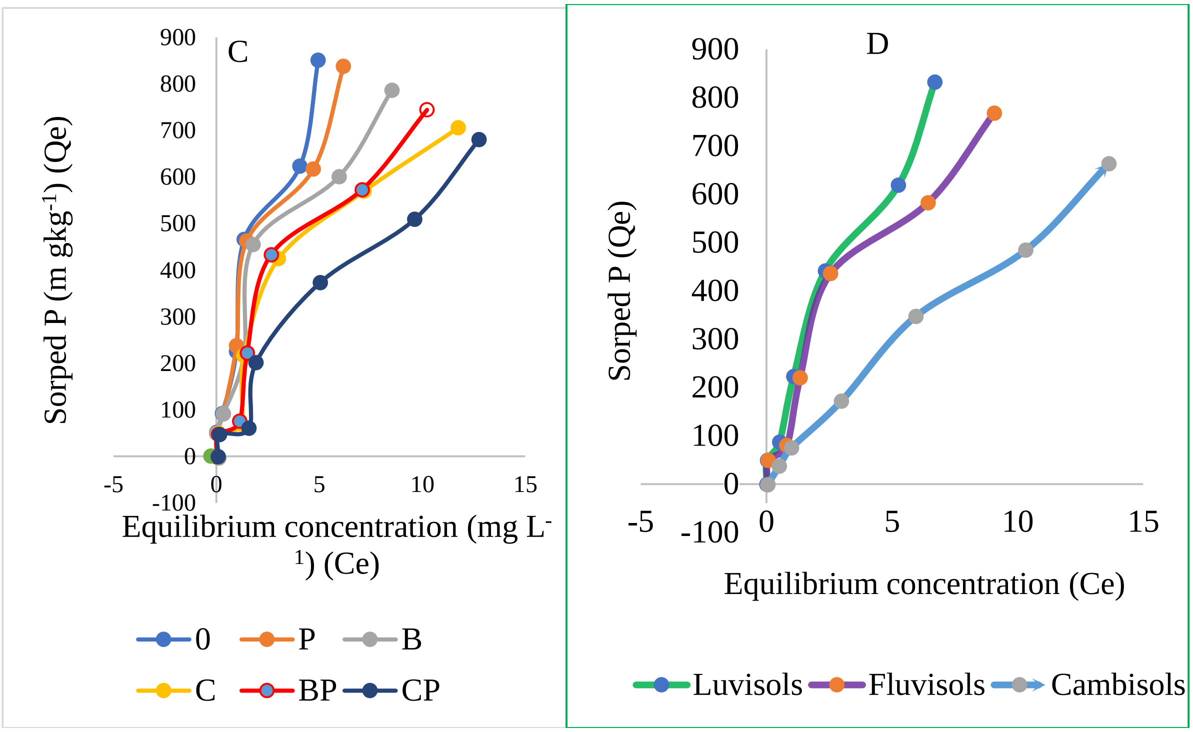
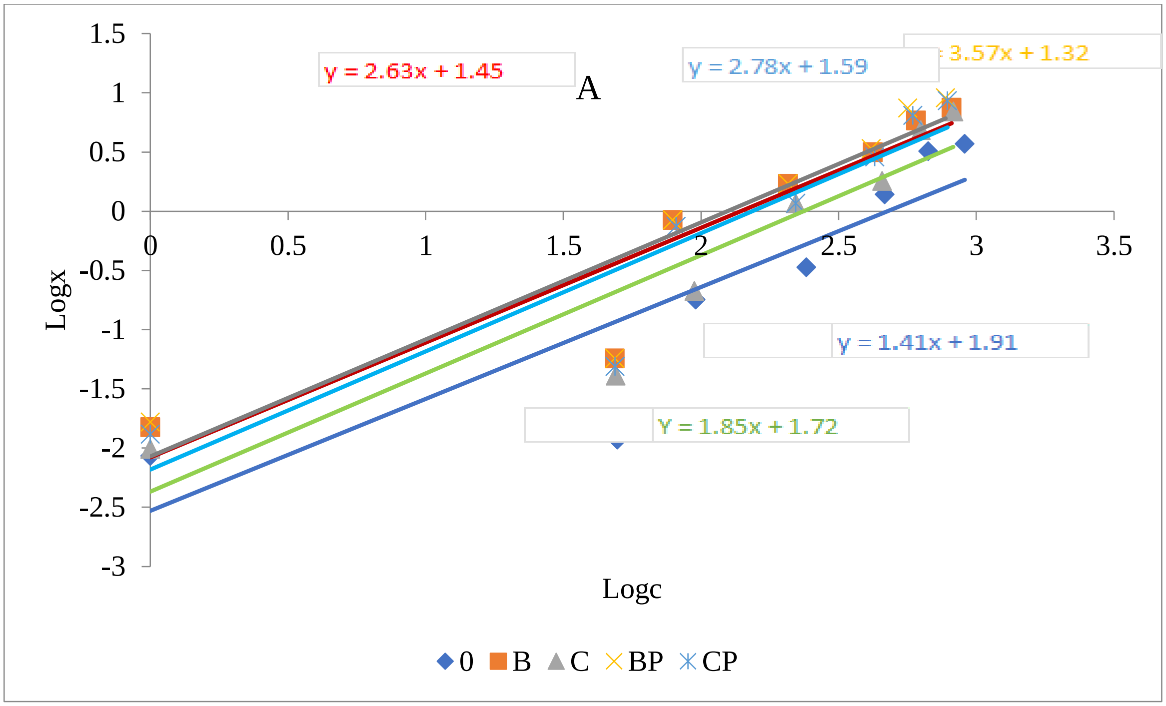
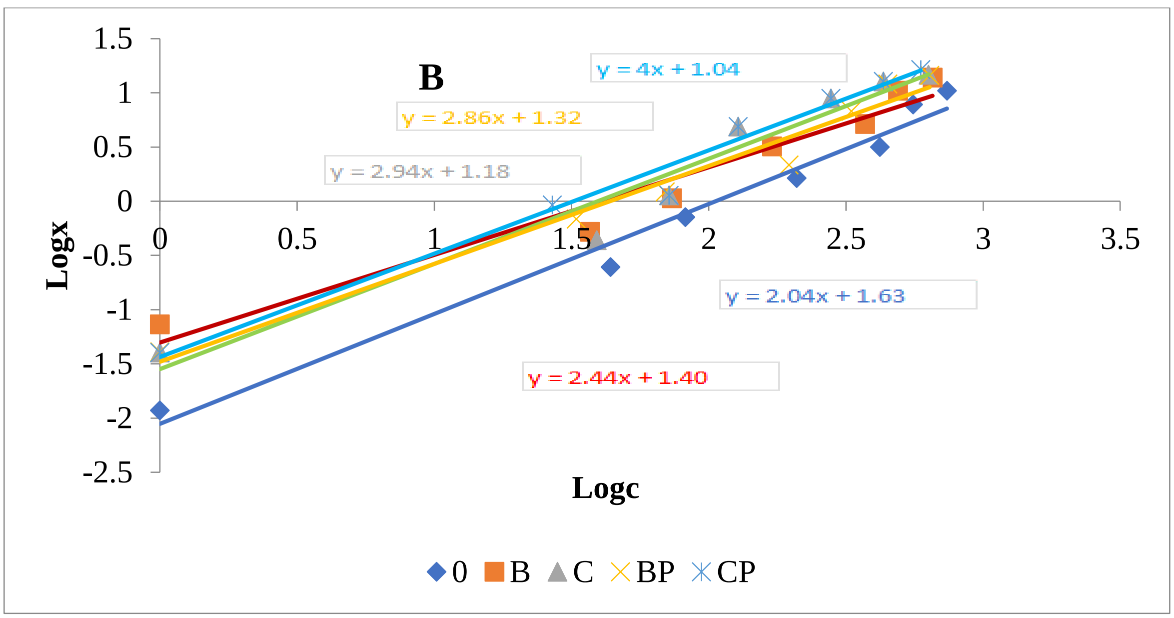


Figure 3.1. Adsorption isotherms for soils of A. Luvisols at Kokate, B. Cambisols at Hawassa, C. Fluvisols at Alage and D. All soil types

3.3.4. Phosphorus sorption characteristics and sorption parameters

The P sorption data fitted with the linearized Langmuir and Freundlich models are shown in Table 3.3 and Figure 3.2. The goodness of fit of the models was evaluated using the coefficients of determination (R^2) values, which ranged from 0.37 to 0.89 for the Langmuir model and 0.82 to 0.98 for the Freundlich model. The P sorption characteristics of the three soil types, with and without amendments were discussed based on the Freundlich model parameter, which provided a better fit. The Freundlich parameter Logk_f is practical tool for summarizing soil sorption properties across a wide range of equilibrium concentrations (Bereket et al., 2018). The variation in P sorption among the soils may be attributed to difference in soil types and clay mineralogy, consistent with the findings of Wang et al. (2021).


A
y = 2.63x + 1.45
y = 2.78x + 1.59
3.57x + 1.32
y = 1.41x + 1.91
Y = 1.85x + 1.72
Logx
Logc
0 B C BP CP


B
y = 4x + 1.04
y = 2.86x + 1.32
y = 2.94x + 1.18
y = 2.04x + 1.63
y = 2.44x + 1.40
Logx
Logc
0 B C BP CP

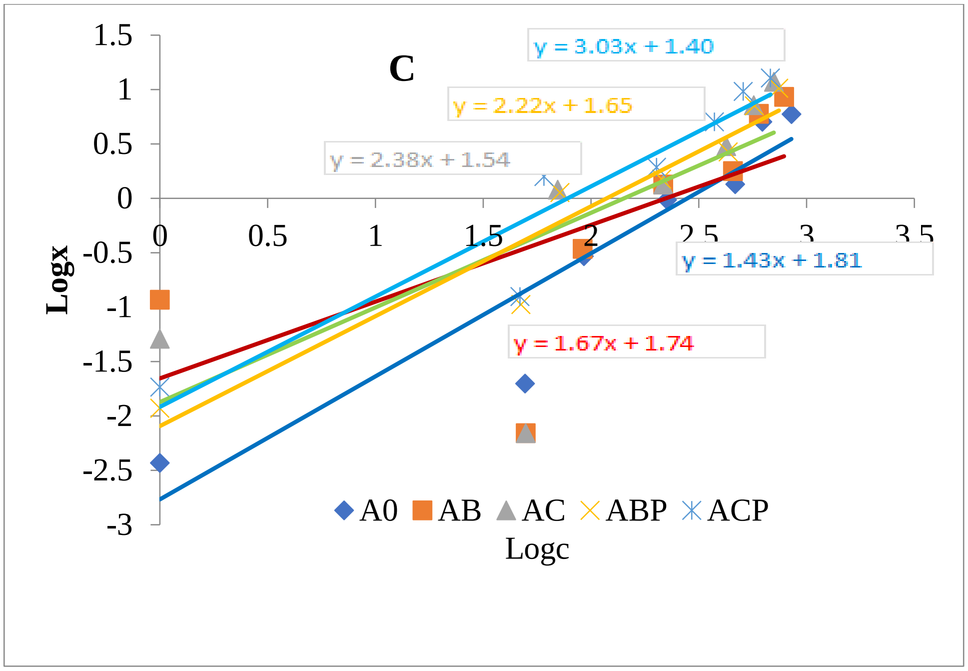


Figure 3.2. Freundlich adsorption isotherms for P adsorption for soils of Kokate (A), Hawassa (B), and Alage (C)

The Freundlich sorption capacity (Kf), P sorption energy (n), P buffering capacity (PBC), and external P requirement (EPR) varied significantly across soil types (Table 3.3, Figure 3.3). Among the studied soils, Luvisols exhibited the highest Kf value (81 mg kg^{-1}), indicating the strongest P sorption capacity, while Cambisols recorded the lowest value (43 mg kg^{-1}), indicating the lowest P sorption capacity. The application of organic and integrated amendments including BC, Com, BP, and CP significantly reduced Kf ($p \leq 0.05$). The highest declines occurred in Luvisols, from 81 to 21 mg kg^{-1} with BP (74% reduction), in Cambisols from 43 to 11 mg kg^{-1} (74% reduction), and in Fluvisols from 64 to 25 mg kg^{-1} with CP (61% reduction). These values are lower than the sorption capacities reported for southern Ethiopian soils (237–1200 mg kg^{-1}; Zinabu, 2015), suggesting that organic amendments are highly effective in reducing P fixation and enhancing availability.

Several studies support these findings. Organic amendments such as BC and Com consistently decrease Kf and increase avail P (Andualem, 2021; Hu et al., 2023). Similarly, the combination of Com or BC with inorganic fertilizers has been shown to lower P sorption and significantly reduce P bonding energy compared with sole inorganic P fertilizer treatment (Monteiro, 2019; Nobile et al., 2020; Teressa et al., 2024; Teshale et al., 2025). These results imply that integrating organic amendments with mineral fertilizers reduces soil P sorption strength, consistent with lower Freundlich Kf values. Other stud also biochar application has been shown to decrease P sorption and increase avail P (Hu et al., 2023).

The variation in P sorption among soil types is strongly influenced by soil properties. In this study, Kf correlated significantly with clay content, SOC, pH, and CEC, in agreement with earlier findings (Table 3.4; Bereket et al., 2018; Naeem et al., 2018). Differences in clay content, SOC, CEC, and soil pH likely explain the variation in sorption between Luvisols, Cambisols, and Fluvisols (Getie et al., 2021). In acidic soils ($pH < 5.5$), protonation of soil surfaces and Al release enhance P sorption, but organic matter can mitigate this by forming stable complexes with Al and by inhibiting Fe and Al oxide crystallization. Such mechanisms reduce P sorption by chelation, supporting the role of organic amendments in improving P availability (Getie et al., 2021).

Table 3.3. **The soil P sorption parameters as influenced by amendments**

Amendment	Freundlich					Langmuir				
	N	Kf (mg kg^{-1})	PBCf $_{(0.2)}$ (mL kg^{-1})	EPRf $_{(0.2)}$ (mg kg^{-1})	R^2	b (L mg^{-1})	X_m (mg kg^{-1})	$PBC_{L\,(0.2)}$ (mL kg^{-1})	$EPR_{L\,(0.2)}$ (mg kg^{-1})	R^2
Luvisols										
Control	0.71^{a}	81^{a}	128^{a}	87^{a}	0.94	0.52^{a}	975^{a}	460^{a}	152^{a}	0.86
P	0.68^{a}	71^{b}	85^{b}	84^{a}	0.92	0.48^{b}	972^{a}	425^{b}	144^{b}	0.51
BC	0.38^{c}	28^{e}	77^{c}	52^{d}	0.90	0.33^{cd}	912^{b}	285^{d}	34^{d}	0.87
Com	0.54^{b}	53^{c}	87^{b}	78^{b}	0.93	0.36^{c}	917^{b}	327^{c}	44^{c}	0.89
BP	0.26^{d}	21^{f}	49^{d}	43^{e}	0.88	0.23^{e}	875^{c}	195^{e}	34^{d}	0.50
CP	0.36^{c}	39^{d}	75^{c}	71^{c}	0.89	0.32^{d}	887^{bc}	266^{d}	44^{c}	0.59
$LSD_{0.05}$	0.07	5.3	6.1	4.5		0.04	34.4	32.2	1.9	
CV (%)	5.6	15.7	6.2	10.3		5.4	2.0	5.4	1.4	
Cambisols										
Control	0.49^{a}	43^{a}	64^{a}	63^{a}	0.98	0.23^{a}	616^{a}	135^{a}	61^{a}	0.87
P	0.44^{b}	29^{b}	53^{b}	47^{b}	0.97	0.19^{b}	611^{a}	114^{b}	49^{b}	0.79
BC	0.41^{b}	25^{bc}	41^{c}	42^{bc}	0.92	0.17^{c}	608^{a}	98^{c}	46^{c}	0.88
Com	0.34^{c}	15de	28^{e}	26^{d}	0.89	0.14^{de}	493^{b}	68de	41^{d}	0.85
BP	0.34^{c}	21^{cd}	36^{d}	36^{c}	0.96	0.15^{d}	570^{a}	81^{d}	46^{c}	0.73
CP	0.25^{d}	11^{e}	25^{e}	25^{d}	0.94	0.13^{e}	463^{b}	57^{e}	41^{d}	0.41
$LSD_{0.05}$	0.04	6.8	4.6	7.5		0.02	46.4	13.9	1.9	
CV (%)	5.6	15.6	6.7	10.1		6.1	4.6	8.3	5.9	
Fluvisols										
Control	0.70^{a}	64^{a}	72^{a}	72^{a}	0.93	0.51^{a}	737^{a}	339^{a}	76^{a}	0.84
P	0.67^{a}	43^{bc}	66^{ab}	65^{b}	0.87	0.46^{b}	733^{ab}	309^{b}	74^{a}	0.84
BC	0.60^{b}	55^{ab}	60^{bc}	60^{b}	0.91	0.37^{c}	717^{b}	249^{c}	57^{b}	0.81
Com	0.42^{c}	35^{cd}	61^{bc}	52^{d}	0.89	0.36^{cd}	670^{c}	219^{d}	49^{c}	0.79
BP	0.45^{c}	45^{bc}	56^{c}	55^{d}	0.88	0.35^{d}	629^{d}	211^{d}	57^{b}	0.48
CP	0.33^{d}	25^{d}	38^{d}	41^{d}	0.82	0.32^{e}	518^{e}	175^{e}	46^{c}	0.37
$LSD_{0.05}$	0.06	12.7	7.03	3.97		0.02	17.3	14.0	5.1	
CV (%)	6.3	15.7	6.6	3.8		2.9	1.4	3.0	4.7	

Where**:** b = Freundlich sorption energy; Kf = Freundlich sorption capacity; PBC_F = phosphorus buffering capacity; SPR_F = standard P requirement using Freundlich model; b = bonding energy; Xm = Adsorption maxima; PBC_L = phosphorus buffering capacity for Langmuir; SPR_L = standard P requirement using Langmuir model; LSD= least significance difference.

The sorption energy (n) of the soils ranged from 0.49 to 0.71 in the control treatments and decreased significantly ($p < 0.05$) with soil amendments at all sites (Table 3.3). This parameter is crucial for determining the mechanism of P sorption in soils (Beyene et al., 2022; Lambano et al., 2022). The largest reductions in n were observed in Luvisols amended with BP, where values declined from 0.71 to 0.26, followed by Cambisols from 0.49 to 0.25, and Fluvisols from 0.70 to 0.33 under CP application. These decreases represent reductions of 63%, 49%, and 53% for Luvisols, Cambisols, and Fluvisols, respectively. The control soils of this study fell within the range of n values (0.39–0.79 L kg^{-1}) reported for soils in the Bule and Wonago areas of southern Ethiopia (Zinabu, 2015). The decline in n values was most pronounced under CP in Cambisols and Fluvisols, while BC and CP produced comparable effects in Luvisols.

The consistent decrease in n following organic and combined amendments suggests that organic matter competes with phosphate ions for sorption sites, thereby lowering the affinity of P to soil particles (Monteiro, 2019; Teressa et al., 2024). Similar declines in n values have been reported after the application of BC and VC (Andualem, 2021; Modak et al., 2024; Teshale et al., 2025). This reduction in sorption strength may be attributed to the lower capacity of biochar to fix P compared with unamended soils (Baninajarian and Shirvani, 2020).

Correlation analysis further showed the importance of n in soil P dynamics. Sorption energy showed significant positive correlation with clay content ($r = 0.59^{**}$) and negative correlations with soil pH ($r = –0.80^{***}$), Olsen-P ($r = –0.96^{***}$), SOC ($r = –0.95^{***}$), and CEC ($r = –0.94^{***}$) (Table 3.4). The strong relationship between n and Kf highlights that sorption capacity and sorption strength are closely related, with both parameters jointly influencing soil P bonding and availability.

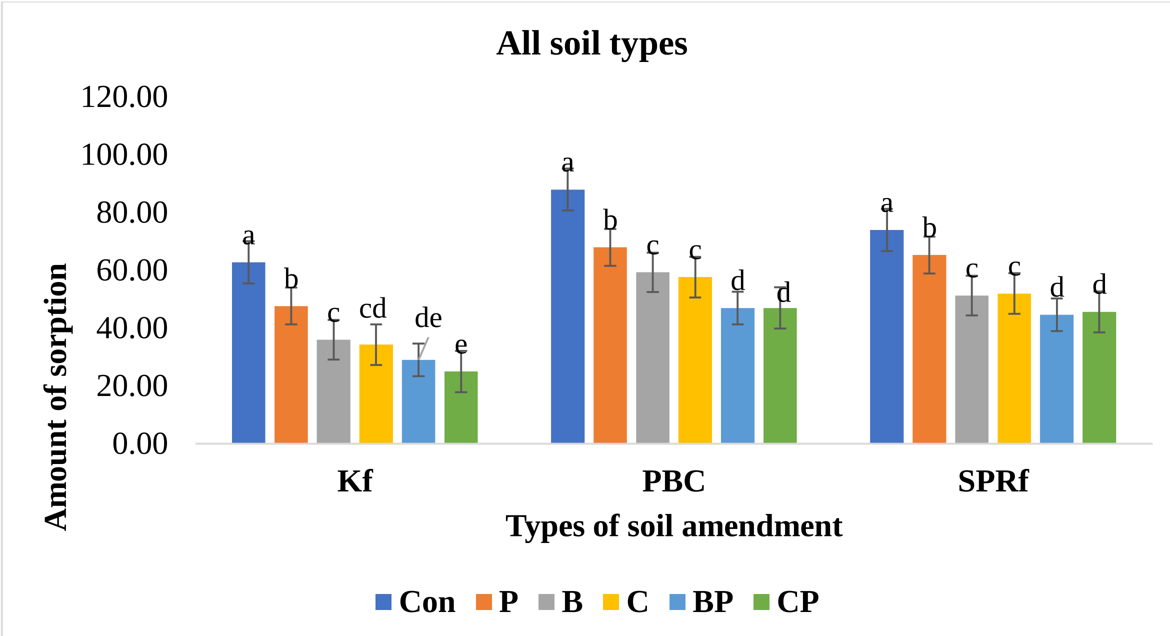


Figure 3.3. Freundlich adsorption isotherms across all soil types

Table 3.4. Correlation coefficient (r) for the linear relationship between the P adsorption parameters with selected soil properties across all soil types

Sorption parameters	Clay	pH	Olsen-P	SOC	CEC
N	0.59^{**}	-0.80^{***}	-0.96^{***}	-0.95^{***}	-0.94^{***}
Kf	0.64^{***}	-0.77^{***}	-0.88^{***}	-0.83^{***}	-0.90^{***}
PBSF	0.67^{**}	-0.81^{***}	-0.86^{***}	-0.85^{***}	-0.90^{***}
SPRF	0.67^{**}	-0.84^{***}	-0.84^{***}	-0.82^{***}	-0.91^{**}

3.3.5. Phosphorus buffer capacity and external phosphorus requirements

The P buffer capacity (PBC) values for control soils ranged from 64 to 128 mL kg^{-1} but decreased with soil amendment (Table 3.3 and Figure 3.2). The largest decline in PBCf value was observed in Luvisols, dropping from 128 to 49 with BP, from 64 to 25 in Cambisols, and from 72 to 38 in Fluvisols with CP applications. This resulted in a reduction of 62%, 61%, and 47% in PBCf values for Luvisols, Cambisols, and Fluvisols, respectively. The PBCf values are closely related to selected soil properties and are essential for managing P by measuring the soil's ability to replenish phosphate in soil solutions (Asmare, 2015; Baninajarian and Shirvani, 2020). The positive correlation between PBC_f and K_f values indicates that as Kf values decrease, the PBCf values also decrease.

Soil amendments, especially BP and CP, resulted in to a lower buffering capacity, indicating increased P availability in soil solutions and improved P mobility in these soils (Bereket et al., 2018). Similar decline reported in PBCf after BP and CP application may be attributed to the reduced retention strength of phosphate ions through the interaction of organic components with soil colloid, releasing phosphate ions into the soil solution (Baninajarian and Shirvani, 2020). Other study also organic matter can interfere with P adsorption on soil colloidal surfaces, reducing P adsorption and subsequently lowering PBCf values (Yu et al., 2013). A low PBCf value indicates a reduced need for external P application to maintain optimal P concentration in the soil solution for plant growth (Hafiz et al., 2016).

The external P requirement (EPR), determined using the Freundlich isotherm, varied among the studied soils, due to inherent differences in their soil properties. Control soils had EPR values ranging from 63 to 87 mg kg^{-1}, with Luvisols showing the highest values, followed by Fluvisols, while Cambisols had the lowest. Application of BP and CP significantly ($p \leq 0.05$) reduced EPR values across all soils by enhancing SOC and avail P. In Luvisols, BP reduced EPR values from 87 to 43 mg kg^{-1}, whereas CP lowered values from 63 to 25 mg kg^{-1} in Cambisols and from 72 to 41 mg kg^{-1} in Fluvisols. Similarly, combined fertilizer application further decreased EPRf values by 51%, 60%, and 43% in Luvisols, Cambisols, and Fluvisols, respectively. These consistent reductions with increasing amendment rates were comparable to declines observed in P adsorption parameters, as also reported by Teressa et al. (2024), Khan et al. (2025), and Zhang et al. (2025). Our findings are in agreement with previous studies where EPRf values declined following biochar additions (Baninajarian and Shirvani, 2020; Andualem, 2021; Beyene et al., 2022).

The estimated fertilizer consumption in SSA was 8 kg P ha^{-1} (Morris et al., 2007), while the blanket recommendation in Ethiopia was 20 kg P ha^{-1}. The EPRf for unamended soils in this study ranged from 69 to 107 kg P ha^{-1}, 3.4 to 5.4 times higher than the blanket P fertilizer recommendation rate. The EPRf values were influenced by the nature and type of parent materials in each soil, with soils like Luvisols requiring more P fertilizer, while Cambisols had lower EPRf values require less P fertilizer for optimal crop production. Similar studies, such as Lambano et al. (2022), also reported high EPRf values (59.4 mg kg^{-1} in Nitisols and 52.4 mg kg^{-1} in Luvisols before liming), confirming that soils in Ethiopia and SSA demand greater P inputs than currently applied.

Correlation analysis further showed that EPRf values were strongly and positively associated with clay content ($r = 0.67^{**}$), but negatively correlated with soil pH ($r = -0.84^{***}$), Olsen-P ($r = -0.84^{***}$), SOC ($r = -0.82^{***}$), and CEC ($r = -0.91^{***}$). These relationships indicate that higher clay and lower pH conditions exacerbate P sorption, increasing EPRf, while improvements in SOC, avail P, and CEC under amendment use help reduce fertilizer requirements. Therefore, integrating inorganic P fertilizers with organic amendments such as BC and Com can significantly lower soil P requirements, enhance P availability, and improve fertilizer use efficiency in Ethiopian soils.

3.4.Conclusions

Phosphorus sorption properties of soils are largely governed by sorption isotherm parameters. In this study, sorption data of the three soil types were better described by the Freundlich model than the Langmuir model. Among the soils, unamended Luvisols exhibited the highest P sorption parameters, indicating their strong P fixation capacity.

Application of BC, Com, and their combinations with inorganic P fertilizer (BP and CP) significantly improved Bd, soil pH, avail P, SOC, exchangeable bases and CEC across all soil types. As a result, the amendments consistently decreased Freundlich parameters (K, n, PBC and EPR), thereby reducing P fixation. Biochar and BC combinations were more effective in acidic soils, while Com and Com combinations showed more effective in neutral and moderately alkaline soils.

The EPRf values of the experimental soils were 3.4–5.4 times higher than the current blanket P fertilizer recommendation for Ethiopian soils, highlighting that existing application rates are insufficient to meet crop demand. Importantly, BP and CP amendments reduced PBCf and EPRf values by an average of 57% and 51%, respectively, suggesting that integrating organic with inorganic P fertilizers can substantially improve P availability and fertilizer use efficiency.

Overall, the results show that combining BC or Com with inorganic P fertilizers can mitigate P fixation and enhance P availability, although the effectiveness varies depending on soil type. We recommend that further studies address the long-term effect of combined organic and inorganic P fertilizer applications on soil properties and P sorption to support these findings and improve crop productivity.

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CHAPTER FOUR

4. EEEFECTS OF NATIVE RHIZOBIA POPULATION ON COMMERCIAL RHIZOBIUM INOCULATION AND YIELD OF COMMON BEAN (Phaseolus vulgaris L.) IN RELATION TO SYMBIOTIC EFFECTIVENESS

Abstract

This study was conducted in the lath house of Hawassa University, College of Agriculture, to assess native rhizobia populations nodulating common bean and their effects on commercial inoculation and yield components. The treatments consist of native rhizobia, commercial inoculants, and inorganic N fertilizer arranged in a completely randomized design (CRD) with three replications. Totally, t*wenty-seven composite soil samples were collected from Kokate, Hawassa, and Alage, serially diluted, and inoculated into seedlings. Native rhizobia populations were estimated using the most probable number (MPN) method. Results showed rhizobia counts ranged from* 5.8×10^{1} *to* 1.7×10^{6} *cells·*g^{-1} *of soil, with the lowest population in Kokate and the highest in Hawassa. Population size was influenced by soil pH and cropping history; Kokate soils had low legume history and suboptimal pH, while Hawassa and Alage had high legume history and favorable soil pH conditions. Commercial rhizobia inoculation had a nonsignificant effects on the most common bean yield components in both low and high native rhizobia soil, except in Hawassa with high rhizobia population size soil. In contrast, inorganic nitrogen application significantly (*$p \leq 0.001$*) improved yield traits, and its combination with rhizobia produced the highest values regardless of population size. Symbiotic efficiency indices showed that 47% of strains in Kokate, 67% in Hawassa, and 64% in Alage were effective, with absolute symbiotic efficiency of 76%, 144%, and 142%, respectively. Higher rhizobia populations*

(Hawassa and Alage) were more effective in supporting shoot biomass and yield components than low populations (Kokate). Overall, the results suggest that yield improvement in common beans depends on efficient and competitive rhizobia strains and their interaction with soil properties. Further research should assess the competitiveness, persistence, and potential of native rhizobia under field conditions.

Keywords: Effectiveness and competitiveness, most probable number, native rhizobia, nitrogen deficiency.

4.1.Introduction

Legumes like common beans (*Phaseolus vulgaris* L.) play a crucial role in smallholder farming systems by providing protein rich food and supporting sustainable agriculture through nitrogen fixation with rhizobia. The success of this symbiosis depends on the presence, abundance, and competitiveness of native rhizobia populations (Mendoza-Suárez et al., 2024). Recent studies in southern Ethiopia have revealed that native rhizobia are often abundant and effective, sometimes even outcompeting commercial inoculants (Geremu et al., 2025).

Nitrogen deficiency is a significant challenge for common bean production due to its high nitrogen requirements (Soratto et al., 2014; Maia et al., 2017; Jena et al., 2022). Biological nitrogen fixation (BNF) offers a sustainable solution to meet the nitrogen needs of legume crops, reducing costs and environmental impacts (Adams et al., 2016; Thilakarathna and Raizada, 2018; Khan et al., 2020). Despite its potential, common beans are considered relatively poor nitrogen fixers compared to other legumes due to their promiscuous nodulation with various rhizobia (Remans et al., 2008; Rahmani et al., 2011). Rhizobium inoculation is commonly used to enhance common bean growth and yield. However, the effectiveness of BNF can be limited by environmental stresses and competition from native strains (Lopez et al., 2016; Moreau et al., 2019; Basu et al., 2021).

The abundance and diversity of native rhizobia are influenced by soil properties, cropping history, and environmental conditions such as pH, salinity, and organic matter (Yan et al., 2014; Maluk et al., 2022; Nzeyimana et al., 2024; Geremu et al., 2025). In Ethiopia, soils often contain large populations of native rhizobia (Argaw, 2016; Nura and Belay, 2019; Hailu et al., 2021). While these strains are competitive, many are less effective at nitrogen fixation compared to commercial inoculants. Southern Ethiopia, with its diverse soils, climates, and farming practices, provides an ideal environment to study how native rhizobia impact the performance of inoculated strains.

Despite the widespread cultivation of common beans, there is limited knowledge about the abundance, diversity, and effectiveness of native rhizobia in southern Ethiopian soils. The research aims to assess the population size and effectiveness of native rhizobia nodulating common beans and to investigate how these native populations size influence yield responses to commercial rhizobium inoculation in different soil types in southern Ethiopia.

4.2. Materials and Methods

4.2.1. Cropping and inoculation history

The five years cropping history of the sampling sites were assessed by interviewing the farmers (personal communication) and questionnaires to the farmers. The questionnaires were designed to gather detailed information on crop types and inoculation practices. Closed and open-ended questions were prepared to capture specific details and quantifiable data. The questionnaires included types of crops grown, crop rotation, intercropping and inoculation practices for leguminous crops. Farmers were asked to list crops grown by type and year, as well as details on inoculant use.

4.2.2. Soil sampling and analysis of selected soil properties

The soil samples were collected during the 2021 cropping season from farmers' fields which had no history of rhizobia inoculation. A laboratory and pot trials were executed to assess the abundance of the native rhizobia population and evaluate their effect on commercial rhizobium inoculation. Details of soil samples and analysis are indicated under Chapter One Section 1.2.5.

4.2.3. Determination of the abundance of native rhizobia in the soil

The most probable number (MPN) method was used to estimate the populations of native rhizobia in the soil capable of nodulating common beans, as per Vincent (1970). This analysis was conducted before planting the common beans. For more information on the abundance of native rhizobia, refer to Chapter One, Section 1.2.5.

4.2.4. Rhizobium viability test

The commercial inoculant (*Rhizobium etli* strain HB-429) was checked for viability by inoculating a spoon of the inoculant powder in yeast mannitol broth and further streaking on yeast extract mannitol agar (YMA) plates containing Congo red dye (Somasegaran and Hoben, 1994). The growth of rhizobia in the broth and on agar plates were used to confirm their viability while the growth of uniform and single type colonies on YMA indicated the purity of the inoculants. Viable and pure strains were further multiplied in broth culture for further use.

4.2.5. Lath house experiment site and experimental design

A pot experiment was conducted under lath house conditions in 2021 at the experimental site of Hawassa University College of Agriculture as detailed in Chapter One Section 1.2.5.

4.2.6. Determination of symbiotic effectiveness indices of rhizobium inoculation

The relative symbiotic effectiveness percentage (RSE%) and Absolute symbiotic effectiveness percentage (ASE %) were determined as detailed in Chapter One Section 1.2.5.

4.2.7. Data collection

After 45 days of planting, the plants were carefully uprooted from the jars and pot. The root and shoot fractions were immediately separated at harvest. The nodule numbers per plant data was then recorded. The plants per pot were collected and oven-dried at 72 ºC for 48 h, and the weight was then converted to t ha^{-1} to estimate root, shoot dry weight (BY), and total N per plant (TNP).

4.2.8. Data analysis

All data including NN, NDW, RDW, SDW, and TPN were analyzed using the General Linear Models Procedure of SAS software version 9.4 (SAS, 2012) to conduct an analysis of variance (ANOVA). The means were then tested for significance using the least significant difference of means (LSD) at a significance level of $p \leq 0.05$. Pearson correlation coefficients were calculated to determine the relationship between MPN and cropping history, soil properties, and SE%, as well as the degree of association among selected common bean parameters.

4.3. Result and Discussion

4.3.1. Soil properties and rhizobia abundance

Assessing soil fertility is crucial for sustainable agriculture. This study examined soil properties to assess their influence on the abundance of native rhizobia and the efficacy of Rhizobium inoculation in common bean cultivation areas. Soil texture analysis showed clay in Kokate, loam in Hawassa, and silt clay loam in Alage (Hazelton and Murphy, 2016). These variations are likely influenced by factors such as topography, slope gradient, and parent material, as reported by Abate et al. (2016) and Ghonamey et al. (2020). Bulk density values ranged from 1.15 g cm^{-3} in Hawassa to 1.25 g cm^{-3} in Kokate, falling within the optimal range for most crops. The lower bulk density in Hawassa suggests fallow land use, higher organic matter content, and abundant root systems (Adhanom and Toshome, 2016; Mohamed et al., 2021; Wabela et al., 2024).

Soil pH varied among the sites: Kokate was strongly acidic (pH 4.7), Hawassa was near to neutral (pH 6.5), and Alage was moderately alkaline (pH 7.5) (Hazelton and Murphy, 2016). All pH levels were above the critical threshold of 4.5 for crop production (Tafesse et al., 2021). The high pH in Alage may be attributed to low rainfall and high evapotranspiration, which limit leaching and promote cation accumulation. The SOC and TN ranged from 1.60% and 0.15% in Kokate to 2.35% and 0.22% in Hawassa, respectively, while avail P was lowest in Kokate (3.1 mg kg^{-1}) and highest in Hawassa (6.3 mg kg^{-1}). The CEC values were relatively high in all soils (27–29 cmol(+) kg^{-1}). According to classification systems, the soils exhibited medium levels of SOC and TN (Tadesse et al., 1991), low availability of P (Jones, 2003), and high CEC (Table 4.1) (Hazelton and Murphy, 2016).

Table 4.1. The soil analysis of experimental sites before planting

Location	Textural class	Bd(g cm^{-3})	pH (H_2O)	Avail. P mg kg^{-1}	OC (%)	TN (%)	CEC cmol (+) kg^{-1}
Kokate	Clay	1.25	4.7	3.1	1.60	0.15	27
Hawassa	Loam	1.15	6.5	6.3	2.35	0.22	29
Alage	Silt clay loam	1.23	7.5	5.9	2.15	0.17	28

The native rhizobia populations varied significantly, ranging from 5.8×10^1 cells g^{-1}in Kokate to 1.7×10^6 cells g^{-1} in Hawassa (Figure 4.1). In Kokate, the soil had the lowest rhizobia population per gram of soil, with less than 100 cells g^{-1}, which is insufficient for reliable nodulation. On the other hand, Hawassa and Alage had populations exceeding 10^3 cells g^{-1}, consistent with findings that most cultivated tropical soils contain more than 100 cells g^{-1} (Howieson and Dilworth, 2016; Kebede et al., 2020). The abundance of rhizobia was significantly influenced by soil properties, particularly pH, SOC, TN, and CEC (Table 4.2).

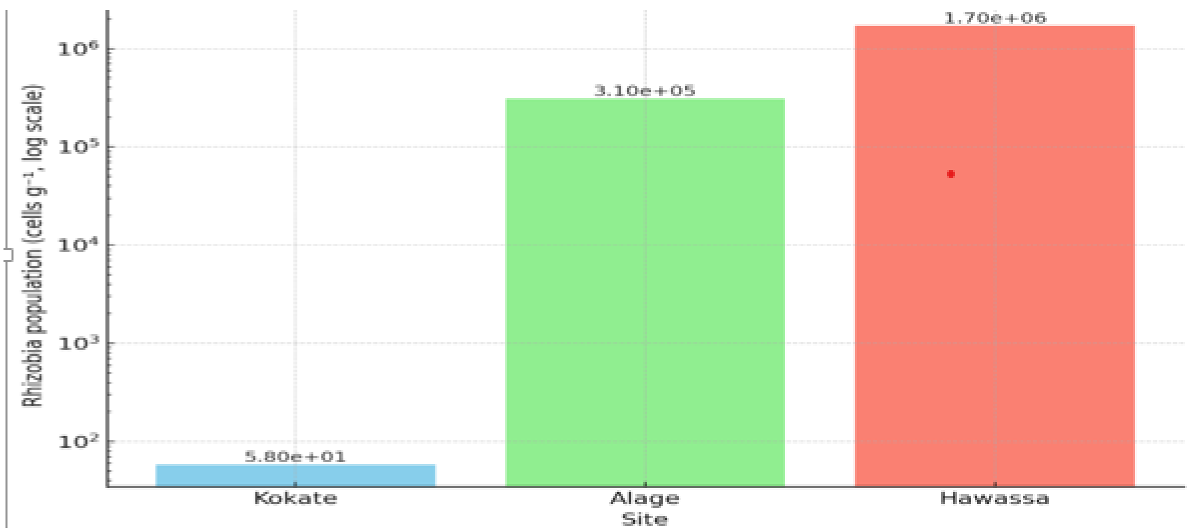


Figure 4.1. Native rhizobia population for the three studied sites

The abundance of rhizobia was positively correlated with soil pH, avail P, SOC, TN, and CEC (Table 4.2; Figure 4.2). The low rhizobia count in Kokate can be attributed to its acidic soil conditions, with a pH below 5.5, which hinders rhizobia survival and nodulation efficiency due to aluminum toxicity that affects membranes, enzymes, and root development (Martyniuk and

Oron, 2008; Ahmed et al., 2022). In contrast, Hawassa's neutral soils provide optimal conditions for rhizobia growth and symbiosis, while Alage's moderately alkaline soils also support higher populations (De Meyer et al., 2016; O'Callaghan et al., 2022). Although some acid-tolerant rhizobia and legumes can persist under low pH (Ferguson et al., 2019; Li et al., 2023), the results from Kokate underscore the challenges by soil acidity for successful inoculation.

The SOC serves as an energy source for microbial activity, improves soil structure and moisture, while TN enhances microbial turnover and nutrient availability (Bastianoni et al., 2010; Li et al., 2023; Geremu et al., 2025). The relatively low levels of SOC and TN in Kokate may have limited rhizobia survival compared to Hawassa and Alage. High nitrogen levels above the critical limit of 0.25% can hinder nodulation and nitrogen fixation (Santachiara et al., 2019), but the TN content in all study sites was below this threshold. Additionally, low avail P in Kokate may have limited nitrogen fixation, as P is essential for nodulation and symbiotic activity (Mitran et al., 2018). The CEC also showed a positive correlation with rhizobia abundance, as soils with high CEC retain essential cations (Ca, Mg, K) that support nodulation and nitrogenase activity (Drew et al., 2012).

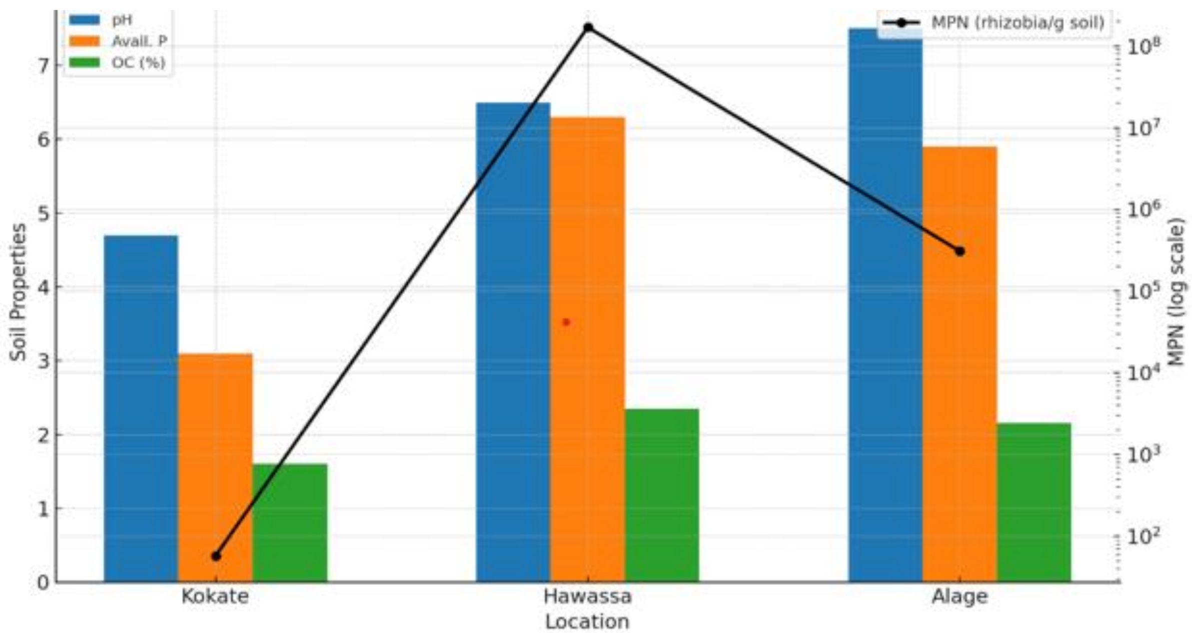


Figure 4.2. Effect of selected soil properties on native rhizobia abundance

Overall, the abundance and efficiency of native rhizobia are closely related to the soil environment. Successful legume-rhizobia symbiosis requires compatible strains and favorable soil conditions, including balanced soil pH and sufficient nutrient availability. Addressing soil acidity and nutrient deficiencies through integrated soil fertility management is crucial for enhancing inoculation response, legume productivity, and soil fertility in southern Ethiopian farming systems.

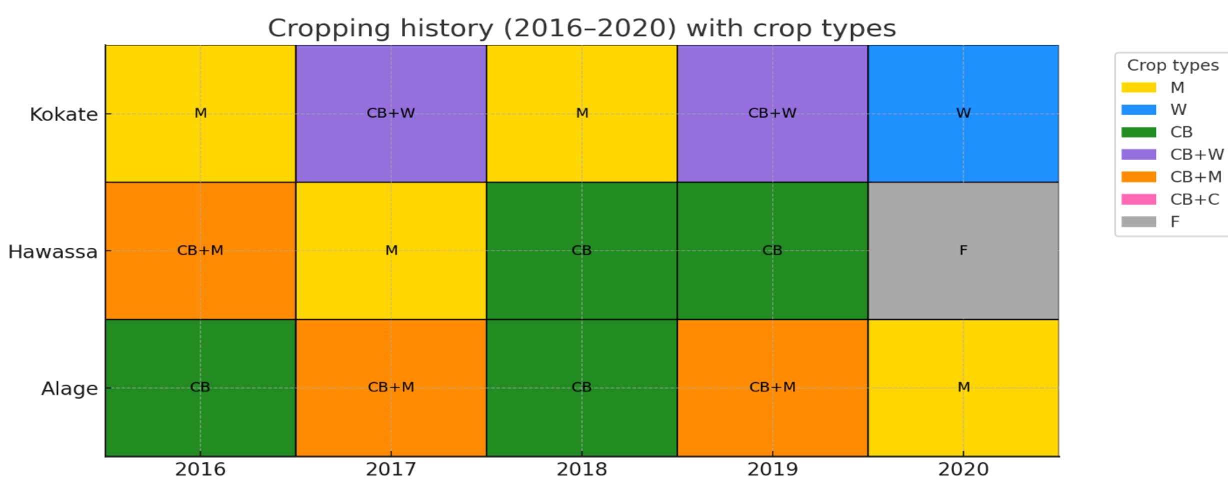
Table 4.2. Correlation among soil chemical properties and population of rhizobia across location

	MPN	pH	Avail P	SOC	TN	CEC
MPN	1					
pH	0.91***	1				
Avail P	0.76*	0.95***	1			
SOC	0.92***	0.97***	0.90***	1		
TN	0.80*	0.82**	0.73*	0.82**	1	
CEC	0.41*	0.57*	0.68*	0.60*	0.65*	1
HCO	0.87*	0.34*	0.67*	0.78*	0.98*	1

Where: MPN = most probable number, HCO = host crop occurrence

4.3.2. Cropping history and rhizobia abundance

In the study sites, common beans were the predominant crop, leading to higher rhizobia populations, especially in Hawassa and Alage (Figure 4.3). The lower population in Kokate could be attributed to limited bean cultivation and acidic soil conditions. The present study indicated that rhizobia abundance is significantly influenced by cropping history (Table 4.2). The previous research work also indicated that rhizobia populations are lower in non-legume crops like maize and potato compared to bean fields (Geremu et al., 2025), while continuous legume cultivation has been shown to greatly enhance rhizobia numbers (Vargas et al., 2000; Argaw and Tsigie, 2015; Argaw and Tesso, 2017; Kebede, 2020). For instance, Martins et al. (2003) reported a tenfold increase in rhizobia after the first legume crop and a hundredfold increase after the second, highlighting the role of common beans in promoting nodulation and rhizobia multiplication in the rhizosphere. Rhizobia populations are also influenced by land-use history, fertilizer application, and crop rotation (Yan et al., 2014). Therefore, the high rhizobia abundance observed in bean producing areas is primarily due to the incorporation of legumes into cropping systems, which sustain rhizobia populations through beneficial symbiotic interactions (Yan et al., 2014; Patil et al., 2017; Kebede et al., 2021).



Where: M = Maize; W = Wheat; CB + W = Common bean with wheat rotation; F = Fallow; CB = Common Bean; CB + M = Common bean intercropped with maize, CB + C = Common bean with cabbage, TCB = Total common bean occurrence with five years and IH = Inoculation history

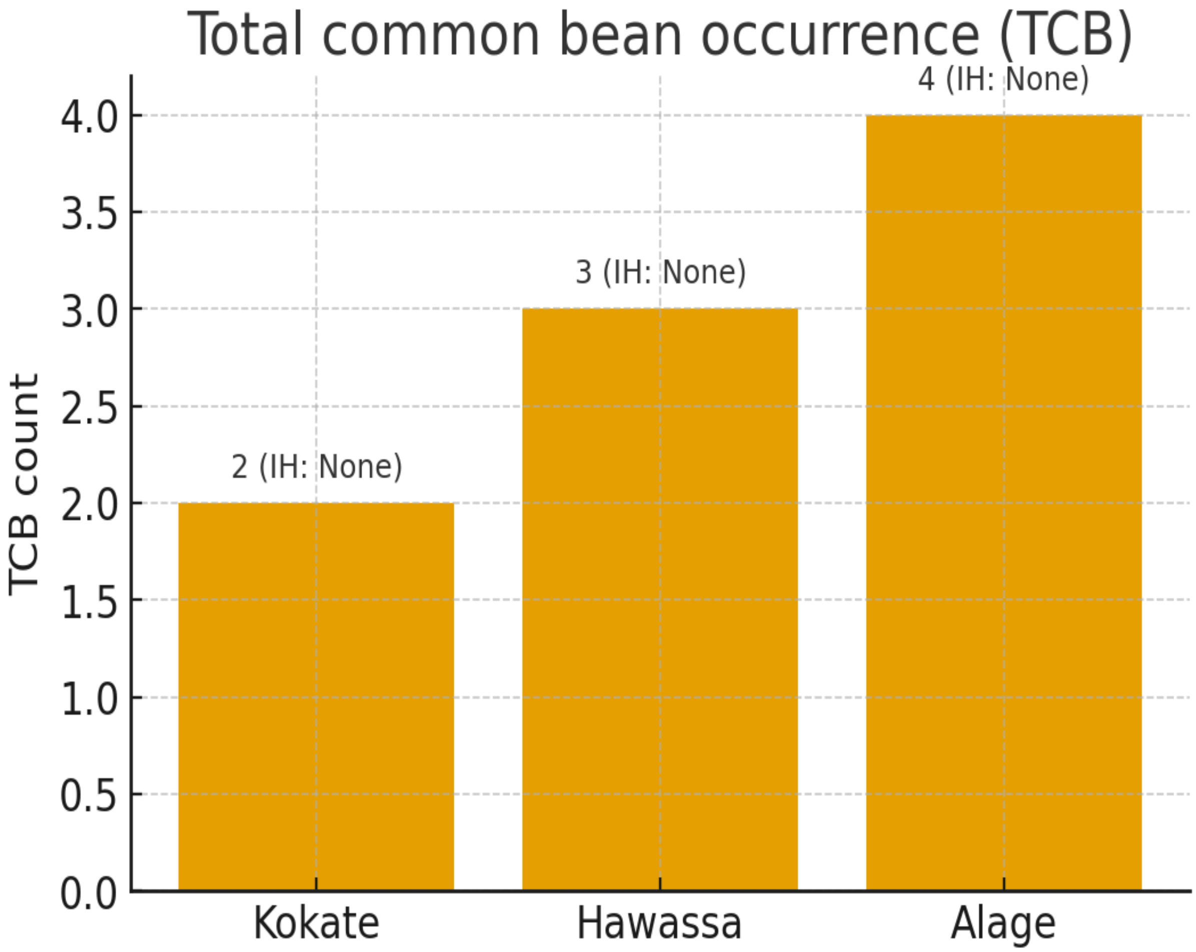


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Figure 4.3. Five years cropping histories in Kokate, Hawassa and Alage sites

4.3.3. Rhizobia inoculation and inorganic nitrogen application on common bean yield parameters

4.3.3.1. Nodule number (NN) and nodule dry weight (NDW)

The study revealed significant variations in nodule number (NN) and nodule dry weight (NDW) per plant ($p \leq 0.001$; Table 4.3; Figure 4.4) in response to rhizobial inoculation, nitrogen fertilizer, and their interaction. The highest NN (65) and NDW (3.0 g) were recorded in Hawassa soil, which had a high native rhizobia population and nearly neutral pH, indicating that both commercial Rhizobium inoculation and inorganic N fertilizer effectively promoted nodulation**.** In contrast, soils with low (Kokate) or highly efficient (Alage) native rhizobia populations compared to commercial inoculant showed lower NN and NDW**,** suggesting that soil acidity (pH 4.7 in Kokate) and the competitiveness of native strains in Alage limited inoculant performance. This is consistent with previous studies indicating that soil acidity inhibits nodulation and nitrogen fixation (Vargas and Graham, 1989; Bambara and Ndakidemi, 2010). The limited response in Alage soil, despite its high native rhizobia population, may be due to the greater effectiveness and competitiveness of native strains compared to the inoculant (Arora et al., 2010; Wabela et al., 2024; Geremu et al., 2025). The difference in NN could also be attributed to the competitiveness of the inoculated strain against the native rhizobia population (Zeng et al., 2007; Gan et al., 2009; Allito et al., 2021). Overall, the results confirm that nodulation response is strongly influenced by the size, effectiveness, and competitiveness of native rhizobia populations, with inoculation success depending not only on the abundance of native rhizobia but also their symbiotic efficiency and ability to compete with introduced strains (Thies et al., 1991; Gan et al., 2009; Wabela et al., 2024; Geremu et al., 2025).

Table 4.3. Nodulation status, root dry weight, shoot dry weight, TPN and relative symbiotic effectiveness of common bean (var. Hawassa Dume) Rhizobium inoculation and mineral N fertilizer application at different soil rhizobia size in shade house experiment

	Treatments	NN			NDW			RDW			SDW			TPN		
		KK	HW	AL	KK	HW	AL	KK	HW	AL	KK	HW	AL	KK	HW	AL
Pot experiment	Control	25[b]	42.0[b]	41.0[c]	0.23[c]	1.6[c]	0.7[c]	1.5[c]	2.1[c]	1.6[b]	2.1[c]	2.5[d]	2.5[b]	1.8[c]	2.4[b]	2.6[b]
	500 g RI	25[b]	55.3[a]	44.0[c]	0.27[c]	2.0[b]	1.9[b]	1.5[c]	2.5[b]	2.2[b]	2.5[c]	3.8[c]	3.4[a]	1.9[c]	3.2[a]	2.9[b]
	20 kg N ha^{-1}	28[a]	56.3[a]	48.0[b]	0.50[b]	2.6[a]	2.1[b]	1.7[b]	2.5[b]	2.3[b]	3.7[b]	4.7[b]	3.5[a]	2.5[b]	3.6[a]	3.1[b]
	500 g RI + 20 kg N ha^{-1}	35[a]	65.0[a]	59.0[a]	0.80[a]	3.0[a]	2.7[a]	2.6[a]	4.3[a]	3.5[a]	5.4[a]	6.0[a]	3.7[a]	2.9[a]	3.6[a]	3.9[a]
	p value	Ns	***	***	***	***	***	***	***	***	***	**	***	***	***	**
	LSD	7.3	12.1	3.8	0.2	0.6	0.5	0.2	0.2	0.2	0.5	0.6	0.5	0.3	0.5	0.5
	CV%	14.9	12.1	4.2	18.1	14.8	11.5	4.9	3.8	12.0	7.7	7.3	7.7	7.1	8.4	9.2

Where: N = Nitrogen; RI = *Rhizobium* inoculum (strain HB-429); means in the same column followed by the same letter are not significantly different at the 5 % probability level by Duncan test; NN = nodule number; NDW nodule dry weight; SDW shoot dry weight; TPN = total plant nitrogen, CV (%) = coefficient of variation; * significant at 0.05; ** significant at 0.01; *** significant at 0.001 and ns = non-significant

4.3.3.2.Root dry weight (RDW), and shoot dry weight (SDW)

The root dry weight (RDW) and shoot dry weight (SDW) were significantly influenced by Rhizobium inoculation (RI), nitrogen fertilizer (NF), and their interaction ($p \leq 0.001$; Table 4.3; Figure 4.4). The RI increased RDW and SDW by 20% and 36% compared to the control, NF by 21% and 68%, and their interaction resulted in the highest increases of 103% and 115%, respectively. These results show synergistic effect of integrating RI with NF on plant growth.

The increase in RDW and SDW is attributed to biological nitrogen fixation and plant growth promoting hormones from rhizobia (Gulati et al., 2008), along with the readily avail N supplied by NF. Inoculated plants developed more efficient nodules and greater biomass compared to uninoculated plants, consistent with previous studies (Kawaka et al., 2014; Wabela et al., 2024). However, RI alone resulted in 35% and 70% lower SDW compared to NF and the combined RI+NF treatment, indicating that inoculation alone may not fully meet nitrogen requirements under certain conditions.

Native rhizobia populations also played a role in biomass production., with symbiotic efficiency. The SDW and grain yield positively correlated with native rhizobia abundance (Kawaka et al., 2018; Wabela et al., 2024; Geremu et al., 2025). In Alage soils with high native populations, NF alone did not significantly differ from RI or the control, emphasizing the site-specific response to fertilizers. Overall, these findings highlight nitrogen as a major limiting nutrient in common bean production, as evidenced by the lowest RDW and SDW in control treatments. Combining RI with NF emerges as the most effective strategy for enhancing biomass accumulation and yield, particularly in soils with low native rhizobia, making it a promising approach for sustainable smallholder farming systems (Argaw, 2016; Samago et al., 2018).

4.3.3.3.Total Plant N Accumulation (TPN)

Rhizobium inoculation (RI), inorganic nitrogen fertilizer (NF), and their combination significantly influenced plant nitrogen accumulation in all soils ($p \leq 0.001$; Table 4.3; Figure 4.4). The effectiveness of RI varied depending on the native rhizobia population, their competitiveness, and efficiency. The highest total plant nitrogen (TPN) was observed under the combined application of RI and NF, reaching 2.9%, 3.6%, and 3.9% in Kokate, Hawassa, and Alage soils, respectively. This treatment consistently resulted in significantly higher TPN compared to RI or NF alone, confirming the synergistic effect of integrating biological and chemical N sources.

In Kokate (low rhizobia) and Alage (high rhizobia) soils, NF alone or NF+RI resulted in higher TPN than RI alone, while RI alone did not differ significantly from the control. This supports previous findings that inoculation may be ineffective in soils with suboptimal soil condition and efficient native rhizobia populations (Shutsrirung et al., 2002; Argaw and Tsigie, 2015; Geremu et al., 2025). In Alage, the lack of inoculation effect suggests that native rhizobia were more efficient in N_2 fixation than the introduced strain, and in some cases, RI may even inhibit nitrogenase activity (Sanginga et al., 1996; Zhou et al., 2024). Conversely, in Hawassa soil, RI alone resulted in significantly higher TPN than the control, possibly due to the lower effectiveness of native rhizobia in N_2 fixation (Thuita et al., 2012; Ntambo et al., 2017). The highest TPN was consistently obtained from the combined RI+NF treatment, which enhanced nodulation and N_2 fixation (Furseth et al., 2012; Mothapo et al., 2012), and benefitted from the synergistic effect of starter N application (da Silva et al., 1993; Wortmann, 2001).

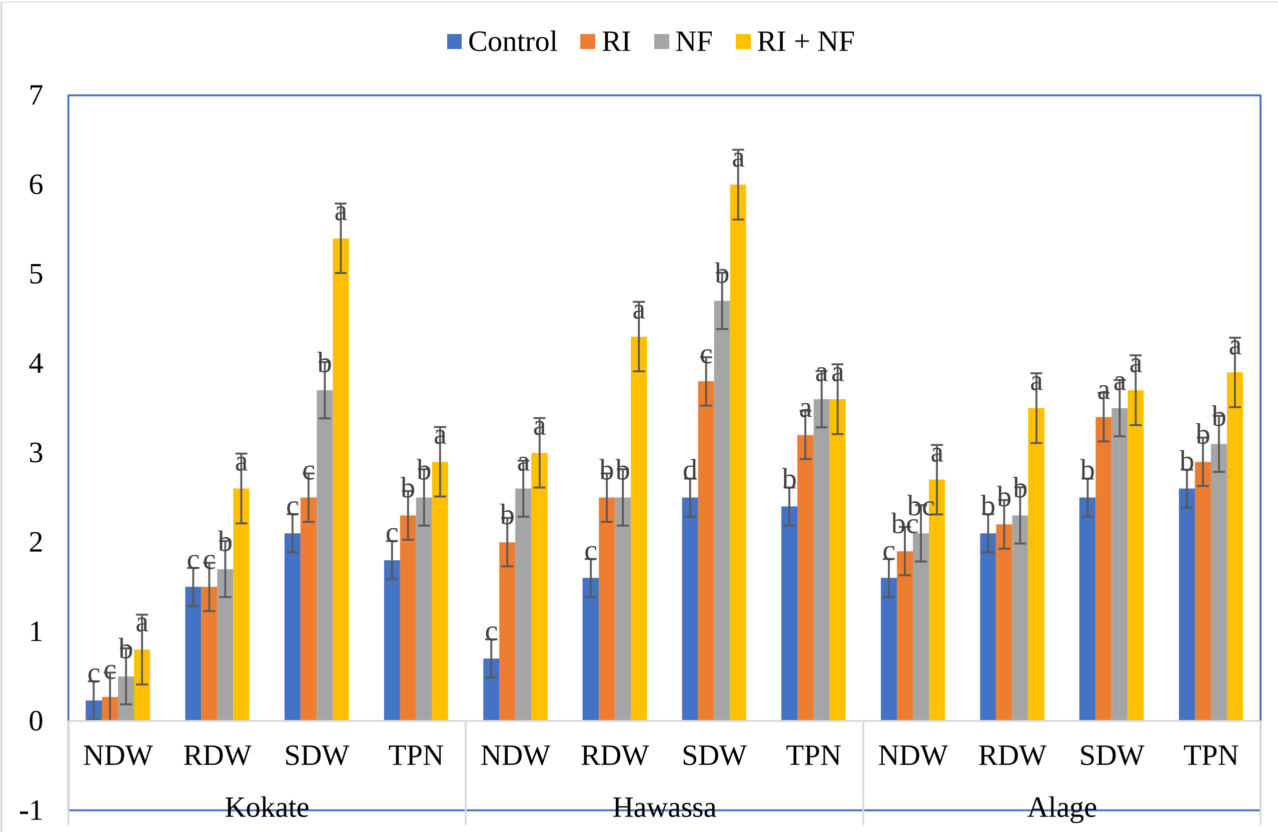

Figure 4.4. Rhizobium inoculation and inorganic N fertilizer application at different soil rhizobia size at lath house experiment

4.3.3.4.Symbiotic efficiency indices of common bean rhizobia inoculant

The effectiveness of the inoculant varied significantly, with relative symbiotic effectiveness (RSE) ranging from 47–67% and absolute symbiotic efficiency (ASE) from 76–144%, depending on soil rhizobia populations (Figure 4.5). These indices confirmed that the commercial rhizobia strain was effective compared to N-fertilized and uninoculated plants. Symbiotic effectiveness was positively and strongly correlated with SDW, NN, and RDW, while positively and weakly correlated with NDW (Table 4.4), indicating that inoculation with efficient strains enhances biomass accumulation and nitrogen fixation.

Soil conditions and native rhizobia populations strongly influenced inoculation outcomes. In Hawassa (neutral pH, high native population), commercial inoculation was effective, showing that introduced strains can still improve yield even in soils with abundant rhizobia, provided they are highly competitive and efficient (Argaw and Tsigie, 2015; Samago et al., 2018). In contrast, Alage soil (high native rhizobia, alkaline conditions) showed a weaker response to inoculation, this may be native strains were more effective than the introduced strain, reducing the benefit of commercial inoculants, which is consistent with reports that the external strains not significant than native rhizobia in yield parameter (Wabela et al., 2024; Geremu et al., 2025). In Kokate (acidic soil, low native rhizobia), inoculation was also less effective, suggesting that soil acidity constrained the performance of the commercial strain, which is consistent with reports that external strains often fail under acidic stress (Kawaka et al., 2014; Wekesa et al., 2023).

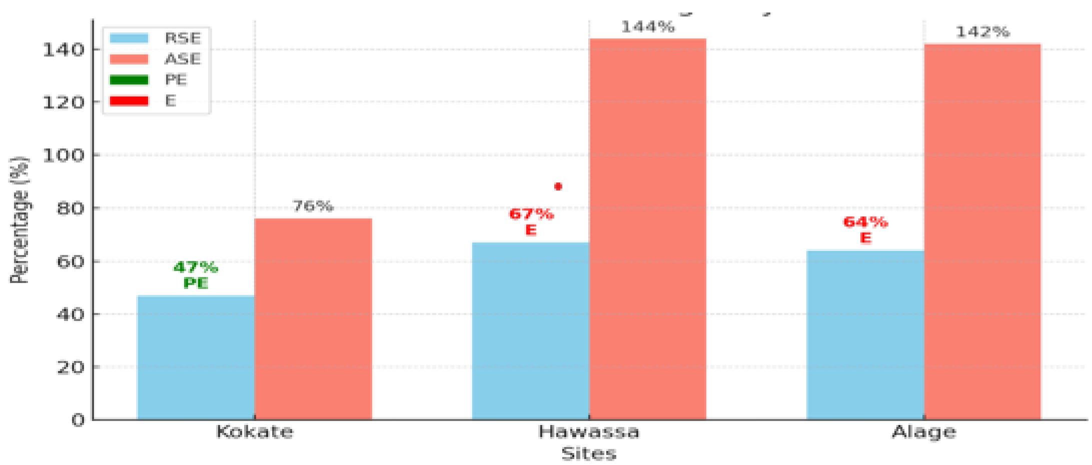

Figure 4.5. Commercial inoculation on RSE and ASE

Where: RSE% = Relative symbiotic effectiveness percentage; SER = Symbiotic effectiveness rating; ASE% = Absolute symbiotic effectiveness percentage; PE = Poorly effective and E = Effective

These results explain the inconsistent response of legumes to inoculants in soils with abundant or highly efficient native rhizobia, as previously reported (Thies et al., 1991; Segovia et al., 1991). However, in neutral soils such as Hawassa, commercial rhizobia can outcompete weaker native strains and significantly increase yield (Razafintsalama et al., 2022).

Overall, the findings indicate that commercial inoculants are most effective in favorable soil environments with neutral pH (e.g., Hawassa), while their performance is limited in acidic soils (Kokate) and in soils dominated by highly efficient native strains (Alage). The presence of effective native or commercial strains under suitable soil conditions highlights the potential of inoculation to enhance nodulation, nitrogen fixation, and yield in common bean (Table 4.3)**.**

Table 4.4. Correlation coefficients among nodule number, nodule dry weight, shoot dry weight, total plant nitrogen and symbiotic effectiveness

	NN	**NDW** (g)	**RDW** (g)	**SDW** (g)	**TPN**	**SE** (%)
NN	1					
NDW (g)	0.10*	1				
RDW	0.60*	0.20*	1			
SDW (g)	0.70**	0.20*	0.80***	1		
TPN	0.50*	0.10	0.50**	0.60***	1	
SE (%)	0.90***	0.02*	0.70***	0.80***	0.60*	1

4.4. Conclusion

The success of rhizobia inoculation and agricultural productivity is greatly influenced by soil properties, native rhizobia abundance, and their symbiotic efficiency. In this study, it was found that Kokate soils contained low rhizobia populations, while Hawassa and Alage had higher populations. The higher rhizobia abundance in Hawassa and Alage was associated with higher NN, NDW, RDW and SDW, resulting in higher bean yield. Conversely, the low rhizobia population in Kokate contributed to reduced bean yield components. These differences showed the combined effects of soil properties, cropping history, and symbiotic effectiveness. Symbiotic effectiveness showed a positive correlation with NN, NDW, RDW, and SDW, as well as rhizobia inoculation. Additionally, all yield parameters improved when rhizobia inoculants were used in combination with inorganic N fertilizer. Overall, the study suggests that higher and competitive native rhizobia populations support greater host plant productivity, while soils with low, high but ineffective rhizobia populations and favorable soil conditions benefit the most from inoculation. Therefore, promoting the use of inoculants in such soils is crucial for enhancing common bean production among smallholder farmers in southern Ethiopia.

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CHAPTER FIVE

5. EFFECTS OF INTEGRATED FERTILIZER APPLICATION ON SELECTED SOIL PROPERTIES AND YIELD ATTRIBUTES OF COMMON BEAN (*Phaseolus vulgaris* L.) ON DIFFERENT SOIL TYPES

Abstract

*In Ethiopia, the productivity of common beans remains low due to poor soil fertility. This study evaluated the effects of integrating inorganic, organic, and biofertilizers on selected soil properties and yield components of common bean. Field experiments were carried out during two consecutive cropping seasons (2021–2022) at three sites in southern Ethiopia (Kokate, Hawassa, and Alage). The experiment was laid out in a randomized complete block design (RCBD) with three replications. The treatments included three levels of inorganic P fertilizer, applied at 0, 8.5, and 17 kg P ha^{-1} for Kokate; 0, 5.8, and 11.6 kg P ha^{-1} for Hawassa; and 0, 7.1, and 14.2 kg P ha^{-1}for Alage, tailored to the specific conditions of each site. Additionally, the experiment incorporated organic inputs 0, 5 t biochar ha^{-1}, and 5 t compost ha^{-1} along with Rhizobium inoculation (HB-429) applied at 500 g ha^{-1}. Results showed that integrated applications significantly ($p \leq 0.05$) improved soil pH, organic carbon, and avail P compared to sole fertilizer and control treatment use. They also increased nodule number, hundred seed weight, grain yield, and biomass yield. We also found that 23 and 24% higher grain yield were obtained with integrated applications of 11.6 and 14.2 kg ha^{-1}inorganic P fertilizer with 5 t ha^{-1} compost on Hawassa and Alage sites and 18% higher grain yield were obtained from the integrated application of 17 kg ha^{-1}inorganic P fertilizer with 5 t ha^{-1} biochar than sole inorganic P fertilizer application. Economic benefits**:** Highest moneitary returns were obtained with 5.8 and 7.1 kg P ha^{-1} + 5 t ha^{-1} compost at Hawassa (69,460 ETB) and Alage (63,250 ETB* *per hectare), and 17 kg P ha*$^{-1}$ *+ 5 t ha*$^{-1}$ *biochar at Kokate (53,583 ETB). The study confirms that site-specific integrated soil fertility management enhances soil fertility, crop yield, and profitability common bean production in southern Ethiopia compared to sole fertilizer application. Long-term studies are recommended to optimize integration strategies for different soil types.*

Keywords: Biochar, Biofertilizers, Compost, Economic benefit, Inorganic fertilizer, Grain yield.

5.1.Introduction

Legumes play a vital role in Ethiopia's agricultural development by improving nutrition, enhancing the rural economy, enriching soil fertility, and contributing to sustainable and climate-resilient food systems through atmospheric nitrogen (N_2) fixation (Joep et al., 2014; Franke et al., 2018). Legumes cover around 12% of Ethiopia's cultivated area, with faba bean (4%), common bean (2.4%), chickpea (1.7%), and field pea (1.69%) being the most important crops (CSA, 2021).

Common bean (*Phaseolus vulgaris* L.) is a key food and cash crop for smallholder farmers, grown both as a sole crop and in rotation or intercropping with cereals (Asfaw et al., 2009; CSA, 2015; Araujo et al., 2020; Uebersax et al., 2023). They are adaptable to various soil conditions and climates, making them a versatile crop (Shamseldin and Velázquez, 2020). However, the national average yield remains around 1,700 kg ha^{-1}, far below the potential yield of 3,500 kg ha^{-1} (MoANR, 2016; Assefa et al., 2017; Zerihun, 2017). Low yields are attributed to soil fertility decline, limited fertilizer use, poor rhizobia technologies, and a lack of improved seed varieties (Mahmood et al., 2017; Rurangwa et al., 2020). Ethiopia's agricultural soils experience high nutrient depletion rates 122 kg N, 13 kg P, and 82 kg K ha^{-1} yr^{-1}, and these rates were twice as high as the average rate for Sub-Saharan Africa (Haileslassie et al., 2005). In addition, soil organic carbon (SOC) stocks in the highlands are declining at a rate of –3.7 t ha^{-1} yr^{-1} (van Beek et al., 2018), necessitating improved fertility management strategies (Aslani and Souri, 2018).

Judicious use of fertilizers, combined with improved agronomic practices, enhances crop productivity and nutrient use efficiency (Desalegn et al., 2017; Agegnehu et al., 2019; Deressa et al., 2020; GIZ, 2020; Erkossa et al., 2022). Phosphorus (P) is the second most essential nutrient after nitrogen and is particularly important for legumes, as it supports efficient N_2 fixation and grain quality. However, the high cost of inorganic fertilizers and the absence of site-specific recommendations limit farmers' access, leading to the application of suboptimal N and P rates (Tamene et al., 2017). Continuous use of inorganic fertilizers alone also risks soil acidification, SOC loss, and micronutrient depletion (Liu et al., 2010; Elias, 2017).

Organic fertilizers, such as compost and biochar, improve soil porosity, SOC, nutrient status, bulk density, and water retention (Agegnehu et al., 2016; Zhang et al., 2021; Yan et al., 2023). They enhance soil aggregation, reduce nutrient losses, and promote microbial activity (Zhang et al., 2019; Zhou et al., 2020; Dominchin et al., 2021). Biochar, in particular, can increase SOC storage, improve enzyme activity, release stored P, and reduce P fixation (Brassard et al., 2018; Mukherjee, 2020). However, smallholder adoption is limited by competing uses of crop residues, labor shortages, and the bulky nature of organic inputs (Abunyewa et al., 2007; Nigussie et al., 2015).

Rhizobium inoculants are another sustainable alternative, as they enhance soil fertility through N_2 fixation and can solubilize fixed P, reducing dependence on inorganic fertilizers (EIAR, 2016). Integrating inorganic fertilizers, organic amendments, and biofertilizers can therefore improve soil properties, enhance nutrient availability, and enhances crop yield. However, information on the integrated effects of inorganic, organic, and biofertilizers to understand the effect on soil properties and crop production is limited in the studied sites. Therefore, this study aimed to investigate the effects of integrated use of inorganic and organic fertilizers with Rhizobium inoculation on soil properties, yield, and yield components of common bean, and to determine the optimum combination of fertilizer management practices for each soil type.

5.2.Materials and Methods

5.2.1. Treatments and experimental design

The inorganic fertilizer treatments consisted of TSP application rates of 0, 8.5, and 17 kg P ha^{-1} for Kokate; 0, 5.8, and 11.6 kg P ha^{-1} for Hawassa; and 0, 7.1, and 14.2 kg P ha^{-1} for Alage. In addition, the experiment included organic inputs: 0, 5 t biochar ha^{-1}, and 5 t compost ha^{-1}, along with *Rhizobium* inoculation (HB-429) applied at 500 g ha^{-1}. The phosphorus fertilizer rates were tailored for each site based on the EPR study-results of chapter three, resulting in varying levels of inorganic P fertilizer used in the current studies. However, the quantities and types of organic fertilizers and *Rhizobium* inoculation were consistent in all sites. The experiment was laid out in a factorial arrangement within a randomized complete block design (RCBD) with three replications at each site, as described in Chapter One, Section 1.2.6**.**

5.2.2. Biochar production and compost preparation

Biochar production, compost preparation and the chemical characteristics of the biochar and compost used in the field experiment is presented in Table 3.2. Detailed descriptions are indicated under Chapter One Section 1.2.6.1.

5.2.3. Treatment application and planting of the test crop

The experimental land was plowed three times using an oxen-drawn "local maresha." Triple superphosphate was applied in row at planting time and organic fertilizers (BC and Com) were mixed with the soil 21 days before planting. A starter nitrogen rate of 18 kg N ha^{-1} was uniformly applied as urea (46% N) to all plots during planting.

Rhizobium inoculum (RI: HB-429 strain) obtained from Menagesha Biotechnology PLC in Addis Ababa, Ethiopia was used to inoculate the common bean seed at a rate of 500 g inoculum per 15 kg seed, as recommended by the company. Inoculation of seeds was performed following the standard procedure modified by MoA (2020). Before planting 100 g of sugar were dissolved in distilled water (10,000 ml) then add the Rhizobium inoculant to form a sticker solution and the seed of common beans were then mixed in sticker solutions until all seeds were evenly coated with the sticker. Finally, the seeds of the inoculated common bean were air dried for a few minutes under shade and planted as per treatment.

The common bean variety "Hawassa Dume" was used as a test crop, which was released in 2008 by the Hawassa Agricultural Research Centre (MoARD, 2008). It is medium-sized with a dark red bean, a white flower, and a maturity period of 85–90 days. Moreover, it is high-yielding, widely grown, well adapted and highly preferred by farmers in the study areas. The seeds were sown at 10 cm and 40 cm between plants and rows, respectively. The experimental plots and blocks were separated by 0.5 and 1 m, respectively. The total experimental area was 342.2 m^2 (29.5 m * 11.6 m), and each experimental plot had an area of 6.4 m^2 (3.2 m x 2 m). Every plot consisted of a total of eight rows, six of which were subjected to data collection, and the remaining two rows, one from each side, were considered borders. It is worth noting that the plots used in the 2021 cropping year were changed in 2022 in order to avoid the residual effects of fertilizers.

5.2.4. Soil, biochar, and compost analyses

Soils of each site, BC, and Com used for this study were collected dried, crused, and sieved (< 2 mm sieve) for laboratory analysis. Detailed selected chemical analyses are indicated under Chapter One Section 1.2.6.2.

5.2.5. Yield and yield components

The number of pods per plant (NPP) was determined at harvest by averaging the number of pods from five plants per plot. The number of seeds per pod (NSP) was recorded at harvest of five plants per plot and five pods per plant. The number of nodules (NN) was taken from the five common bean-uprooted plants, which were carefully washed in water to remove excess soil. The NN per plant was determined by counting all the nodules in each of the five plants and computing the average. Hundred seed weight (HSW) (g) was determined by weighing 100 randomly sampled seeds from the total harvest per plot, and the weight was adjusted to 10% moisture level. Five sample plants per plot were collected and oven-dried at 72 ºC for 48 h, and the weight was then converted to t ha^{-1} to estimate total above-ground biomass yield (BY). The grain yield (GY) (t ha^{-1}) was recorded from the six central rows and adjusted to 10% moisture.

5.2.6. Economic analysis

The economic analysis was computed based on the procedure provided by CIMMYT (1988). Total variable costs (TVC) were estimated by considering the current prices of TSP (38 Birr kg^{-1}), labor costs of BC, and Com preparation based on World Food Program work norms of 1,100 Birr for 5 t ha^{-1}, respectively. Then, the TVC was calculated as the sum of all costs that are variable or specific to a treatment against an unfertilized plot. The average yield was adjusted downward by 10% to reflect the farmers' field yields, as described by CIMMYT (1988). The adjusted yield was multiplied by the market price to obtain the gross field benefit. The gross benefit (GB) was calculated by multiplying common bean grain by 30 Birr kg^{-1} (current prices). The net benefits (NB) were calculated by subtracting TVC from GB for each treatment. Finally, a marginal rate of return (MRR) for the dominant treatments was estimated using the following formula:

$$MRR = \frac{(NB\ from\ superior\ dominant\ plot - NB\ from\ inferior\ dominant\ plot)}{TVC\ from\ superior\ dominat\ plot - TVC\ from\ inferior\ dominant\ plot} \times 100$$

5.2.7. Data analysis

The data recorded 3 sites and 2 seasons in two consecutive years were first checked for the assumption of homogeneity of variance to identify data requiring separate or combined analysis. Accordingly, Bartlett's test for homogeneity of variance for all parameters showed a significant difference, indicating their variances across sites are heterogeneous and suggesting separate analysis. The data for all parameters were similar between seasons; the interaction effect of inorganic, organic fertilizer and biofertilizer on common bean yield and yield components was combined because the variances among seasons were homogenous. Two-way analysis of variance (ANOVA) was determined by using Statistical Analysis Software (SAS version 9.4) (SAS, 2012). A mean comparison was performed using the least significant difference (LSD) test for the main effect significant parameters. Because this procedure has a high risk of committing a type I error rate when the number of treatments is large, Duncan’s Multiple Range Test (DMRT) was used to compare differences between means for all the two-way interaction effect significant parameters.

5.3. Results and discussion

5.3.1. Effects of soil amendments on selected soil properties

The sole applications of biochar (BC) and compost (Com), as well as the combined treatments of BC with inorganic P fertilizer (BP) and Com with inorganic P fertilizer (CP), significantly improved ($p \leq 0.05$) soil pH, SOC, and avail P compared to the control and sole inorganic P fertilizer treatments in the three soils (Figure 5.1). Thus, the avail P contents in the soil increased from low to moderate after the application of BC, Com, BP, and CP (Figure 5.1). Detailed effects of soil amendments on selected soil properties are indicated under chapter three section 3.3.2.

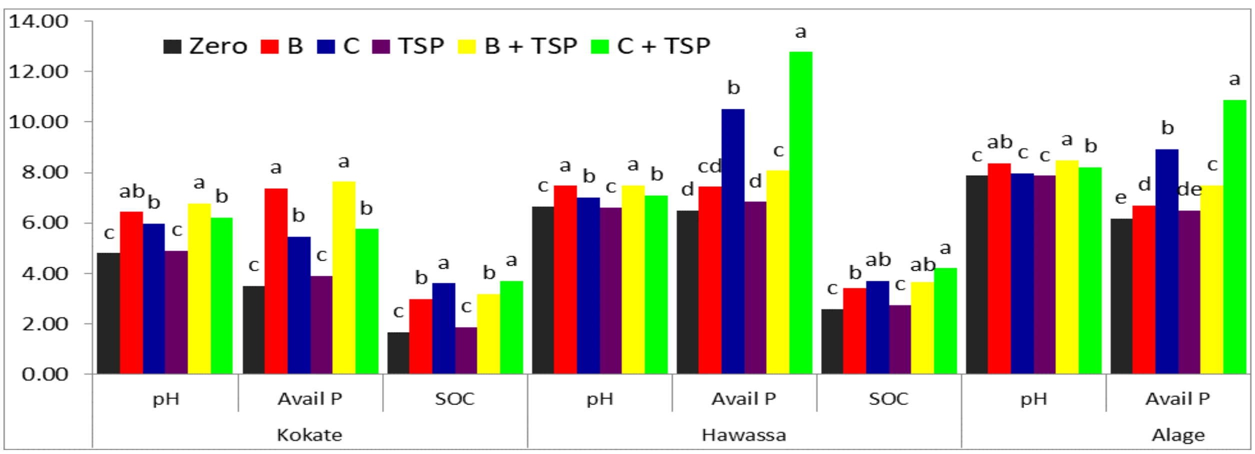

Figure 5.1. Influence of soil amendments on selected soil properties of the Kokate, Hawassa and Alage

5.3.2. Inorganic and organic fertilizer on yield and yield components of common bean

5.3.2.1. Number of pods per plant and number of seeds per pod

The interaction between inorganic and organic fertilizers on the number of pods per plant (NPP) and the number of seeds per pod (NSP) in common bean was not statistically significant in all sites (Table 5.1). However, the induvial effects of inorganic P and organic fertilizer had a significant impact on both traits. The lowest NPP and NSP were recorded in the control, while the highest values were obtained at 17, 11.6, and 14.2 kg P ha^{-1} in KK, HW, and AL, respectively (Table 5.2). The increase in NPP and NSP with higher P rates can be attributed to the vital role of phosphorus in reproductive growth, nutrient uptake, nodulation, and nitrogen fixation, all of which contribute to improved pod setting and seed formation (Rafat and Sharifi, 2015; Alemu et al., 2018; Bahru, 2019; Olika et al., 2024). The increase in NPP and NSP at higher P rates is due to the essential role of P in reproductive growth, nutrient absorption, nodulation, and nitrogen fixation. These factors collectively enhance pod setting and seed formation (Rafat and Sharifi, 2015; Alemu et al., 2018; Bahru, 2019; Olika et al., 2024). Similar results were reported by Alemayehu (2014), Tesfaye et al. (2015), Dereje et al. (2016), Amanuel et al. (2018), and Sigaye et al. (2020), indicating that increased P application significantly enhanced pod and seed numbers in common bean.

Table 5.1. Mean square values for yield and yield components of common beans at three sites

			Kokate				
Sources	DF	NPP	NSP	NN	HSW	GY	BY
Replication	2	13.58^{ns}	0.05^{ns}	76.44^{ns}	20.53^{ns}	0.07^{ns}	2.93^{ns}
P	2	107.79^{***}	5.19^{***}	12267.11^{***}	11.69^{ns}	2.60^{***}	17.25^{***}
OF	3	6.92^{ns}	2.09^{*}	1768.32^{*}	41.22^{*}	0.68^{*}	42.43^{*}
P*OF	6	7.54^{ns}	0.72^{ns}	304.19^{*}	42.77^{***}	0.05^{**}	1.20^{**}
Error	22	7.54	0.497	75.79	4.41	0.03	0.194
			Hawassa				
Sources	DF	NPP	NSP	NN	HSW	GY	BY
Replication	2	18.04^{ns}	0.23^{ns}	16.44^{ns}	0.08^{ns}	0.19^{ns}	0.03^{ns}
P	2	210.38^{***}	9.77^{***}	15702.78^{***}	3.00^{ns}	4.73^{***}	23.34^{***}
OF	3	74.06^{***}	1.85^{***}	7468.85^{***}	0.77^{ns}	1.71^{***}	9.28^{***}
P*OF	6	10.46^{ns}	0.38^{ns}	1099.41^{***}	5.74^{**}	0.31^{**}	1.25^{**}
Error	22	6.19	0.25	137.23	1.36	0.06	0.17
			Alage				
Sources	DF	NPP	NSP	NN	HSW	GY	BY
Replication	2	9.85^{ns}	0.09^{ns}	81.03^{ns}	18.86^{ns}	0.02^{ns}	0.01^{ns}
P	2	217.06^{***}	1.78^{***}	14650.11^{***}	16.36^{ns}	4.28^{***}	13.50^{***}
OF	3	94.65^{***}	0.39^{ns}	4748.56^{***}	67.06^{***}	1.83^{***}	7.52^{***}
P*OF	6	18.41^{ns}	0.18^{ns}	1016.56^{***}	28.51^{**}	0.21^{**}	0.84^{**}
Error	22	12.35	0.17	75.79	5.65	0.07	0.18

*Note: P, phosphorus fertilizer; OF, Organic fertilizers; NPP, Number of pods per plant; NSP, Number of seeds per pod; NN, Number of nodules; HSW, hundred seed weight; GY, Grain yield; BY, Biomass yield; ∗, ∗∗, ∗∗∗ and ns refer to $p < 0.05$, 0.01, 0.001, and not significant, respectively

The application of organic fertilizers and rhizobium inoculation (RI) significantly affected NPP and NSP in common bean across sites, except for NPP at KK and NSP at AL (Table 5.1). The highest values were obtained with 5 t ha^{-1} compost, followed by 500 g ha^{-1} RI at HW and AL, while at KK, the highest NSP was from 5 t ha^{-1} biochar (Table 5.2). Unfertilized plots consistently showed the lowest NPP and NSP. Previous studies by Santosa et al. (2017) and

Shanka et al. (2017) also reported increased pod numbers with compost application. This improvement is likely attributed to enhanced nutrient availability (N, P, and S), which supports seed development and grain filling (Tana and Woldesenbet, 2017). Other research studies also showed the positive response of common bean to organic fertilizers (Kassa et al., 2014; Turuko and Mohammed, 2014; Brady and Weil, 2016; Shekedir et al., 2022). The limited response of RI at KK may be the strains' due to poor adaptation acidic soil conditions (Chekanai et al., 2018; Chimdi et al., 2022), while its effectiveness at HW and AL is consistent with the finding of Woldekiros et al. (2018), who reported improved NPP and NSP in faba bean following rhizobia inoculation.

Table 5.2. Main effects of inorganic and organic fertilizer on yield component of common beans parameters

Treatments (kg ha^{-1})	NPP			NSP		
	KK	HW	AL	KK	HW	AL
Control	8.48^{b}	16.14^{c}	12.67^{b}	3.28^{c}	4.16^{b}	3.82^{b}
50% P	9.68^{b}	21.65^{b}	19.38^{a}	3.97^{b}	5.30^{a}	4.65^{a}
100% P	14.17^{a}	24.36^{a}	20.55^{a}	4.59^{a}	5.45^{a}	4.92^{a}
No organic fertilizer (control)	9.70	17.38^{c}	13.29^{b}	3.30^{c}	4.30^{b}	4.38
5 t ha^{-1} BC	11.80	19.89^{b}	16.722^{ab}	4.40^{a}	4.67^{b}	4.42
5 t ha^{-1} Com	11.00	24.24^{a}	20.33^{a}	4.22^{ab}	5.29^{a}	4.79
500 g ha^{-1} RI	10.60	21.36^{b}	19.78^{ab}	3.87^{bc}	5.16^{a}	4.71
CV%	15.27	11.25	20.05	17.86	8.61	9.06

*Note: RI, *Rhizobium* inoculation; 50% P, 50% of the site recommended P kg ha^{-1}; 100% P, 100% of the site recommended P kg ha^{-1}. Means within a column followed by the same letter (s) are not significantly different at $p \leq 0.001$.

5.3.2.2. Inorganic and organic fertilizers on number of nodules and hundred seed weight

The interaction between inorganic and organic fertilizers significantly ($p \leq 0.001$) affected NN and HSW at all sites (Table 5.3). The highest NN and HSW were obtained from the integrated application of 11.6 and 14.2 kg P ha^{-1} with 5 t ha^{-1} Com at HW and AL, while the lowest values were from 5 t ha^{-1} BC and control treatment. At KK, maximum NN and HSW were recorded with 17 kg P ha^{-1} + 5 t ha^{-1} BC, whereas RI treatment gave the lowest values in this site. This in turn may have accelerated metabolic processes, resulting in improved photosynthesis and efficient photosynthetic translocation from the sink to the source, resulting in higher seed weight. In this study, the effects of the integrated treatments on the NN and HSW varied across different soils. These results agree with Tadesse et al. (2022) and Habibi et al. (2025), who reported improved NN and HSW with integrated TSP and compost. Similar findings were also observed in peanuts, lentils, faba beans, and soybeans under integrated organic and inorganic fertilizer management (Argaw, 2016; Assefa et al., 2017; Fatima et al., 2018; Fekadu et al., 2019). As a result, the increase in NN and HSW could be attributed to improved soil rhizobia conditions because of increased P and other micronutrient contents of the soil. The improvements may be due to enhanced nutrient release, better root development, and favorable rhizobia activity that increase nodulation and seed filling (Zengeni, 2006; Shanka et al., 2017; Zahida et al., 2016). Similarly, other studies have shown that RI considerably affects the nodule dry weight of soybean together with starter N and common bean (Argaw, 2016; Tarekegn and Kibret, 2017). The variation in responses across sites could be attributed to soil pH differences, which influence the effectiveness of specific integrated treatments.

Table 5.3. Interaction effects of inorganic and organic fertilizer on nodule number and hundred seed weight of common bean

Treatments		NN			HSW		
PF rate	OF	KK	HW	AL	KK	HW	AL
0	0	31.67^{e}	35.00^{f}	33.67^{e}	27.67^{c}	35.00^{d}	27.67^{d}
0	5 t ha^{-1} BC	56.33^{d}	37.00^{f}	35.00^{e}	35.00^{bc}	36.33^{bcd}	31.33^{cd}
0	5 t ha^{-1} Com	45.00^{de}	98.00^{cd}	46.33^{de}	34.67^{bc}	36.67^{bcd}	34.67^{bc}
0	500 g ha^{-1} RI	35.33^{e}	55.33^{f}	55.67 ^{cd}	31.33^{c}	37.33^{bcd}	35.67^{b}
50%	0	57.00^{d}	112.67^{c}	92.00^{c}	35.00^{bc}	36.33^{bcd}	37.33^{ab}
50%	5 t ha^{-1} BC	64.33^{cd}	86.33^{de}	63.67^{c}	37.67^{ab}	36.33^{bcd}	35.00^{bc}
50%	5 t ha^{-1} Com	60.33^{d}	135.67^{b}	126.67^{a}	37.33^{ab}	37.33^{bcd}	37.00^{ab}
50%	500 g ha^{-1} RI	46.67^{de}	94.00^{cde}	97.00^{b}	35.67^{b}	35.33^{d}	38.33^{ab}
100%	0	95.00^{b}	158.00^{a}	132.67^{a}	38.00^{ab}	38.00^{bc}	38.67^{ab}
100%	5 t ha^{-1} BC	119.00^{a}	75.67^{e}	69.00^{c}	40.33^{a}	35.67^{cd}	37.67^{ab}
100%	5 t ha^{-1} Com	98.00^{b}	166.67^{a}	135.75^{a}	38.67^{ab}	41.00^{a}	40.33^{a}
100%	500 g ha^{-1} RI	81.67^{bc}	133.00^{b}	128.33^{a}	38.33^{ab}	38.67^{b}	38.00^{ab}
CV%		12.13	12.13	10.32	5.86	6.61	3.40

*Note: PF, inorganic phosphorus fertilizer; OF, Organic fertilizers; B, biochar; C, compost; NN, Number of nodules; HSW, hundred seed weight

5.3.2.3. Inorganic and organic fertilizers on grain yield and biomass yield

The interaction between inorganic and organic fertilizers significantly ($p < 0.01$) influenced grain yield (GY) and biomass yield (BY) across all sites (Table 5.4). At HW and AL, the highest GY and BY were obtained with 100% P combined with 5 t ha^{-1} Com, whereas at KK, maximum yields were obtained with 100% P + 5 t ha^{-1} BC. Compared with sole inorganic fertilizer, combining 50% P with BC or Com increased GY by 26–33% and BY by 12–28% across sites (Table 5.4; Figures 5.2 and 5.3). Further increasing P from 50% to 100% with organic fertilizer enhanced GY by 18–24% and BY by 10–23% over sole P. The results indicate that integrated TSP with Com or BC generally provided the highest yields, but soil type influenced the most effective combination: Com with inorganic P fertilizer performed best in neutral to moderately alkaline soils (HW and AL), whereas BC with inorganic P fertilizer was superior in the strongly acidic soil at KK.

Table 5.4. Interaction effects of inorganic and organic fertilizer on grain yield and biomass yield

Treatments		GY, t ha^{-1}			BY, t ha^{-1}		
P levels, kg ha^{-1}	OF	KK	HW	AL	KK	HW	AL
0	0	0.91^{f}	1.03^{f}	1.31^{d}	1.36^{d}	2.34^{e}	2.40^{e}
0	5 t ha^{-1} BC	1.54^{e}	1.05^{f}	1.42^{d}	3.72^{c}	2.44^{e}	2.54^{e}
0	5 t ha^{-1} Com	1.55^{de}	1.55^{ef}	1.75^{cd}	3.35^{c}	4.60^{c}	3.73^{d}
0	500 g ha^{-1} RI	1.15^{f}	1.35^{fg}	1.51^{d}	1.97^{d}	2.99^{de}	3.58^{d}
50%	0	1.64^{e}	1.84^{cd}	2.13^{c}	3.57^{c}	4.72^{c}	5.02^{c}
50%	5 t ha^{-1} BC	2.10^{bc}	1.31^{ef}	1.62^{d}	4.58^{b}	3.48^{d}	3.59^{d}
50%	5 t ha^{-1} Com	2.03^{cd}	2.45^{b}	2.68^{b}	4.45^{b}	5.30^{bc}	6.03^{b}
50%	500 g ha^{-1} RI	1.59^{e}	2.12^{bc}	2.61^{b}	4.49^{b}	4.62^{c}	6.02^{b}
100%	0	2.14^{bc}	2.55^{b}	2.81^{b}	5.01^{b}	4.97^{c}	6.32^{ab}
100%	5 t ha^{-1} BC	2.53^{a}	1.53^{de}	1.77^{cd}	5.74^{a}	3.57^{d}	3.61^{d}
100%	5 t ha^{-1} Com	2.33^{ab}	3.15^{a}	3.45^{a}	5.85^{a}	6.11^{a}	6.96^{a}
100%	500 g ha^{-1} RI	1.77^{de}	2.50^{b}	2.94^{b}	4.52^{b}	6.00^{ab}	5.92^{b}
CV%		9.36	12.84	11.71	10.26	9.86	8.80

Integrated soil fertility management and appropriate crop management practices at the Kokate, Hawassa, and Alage sites led to improved crop growth and increased GY and BY, taking into account the specific soil conditions at each site. Previous studies have shown that the integrated application of compost and mineral fertilizers (Agegnehu et al., 2016; Ejigu et al., 2021) or mineral NPK with organic amendments like chicken manure (Alhrout et al., 2016) can result in higher GY in common bean and maize. Other similar studies reported that the integrated organic and inorganic fertilizers generally improved yield and yield components compared with sole applications (Baghdadi et al., 2018; Ahmadi et al., 2021), with maximum GY also observed under TSP + BC treatments (Melaku et al., 2020; Ye et al., 2020). These benefits may be attributed to improved soil quality, nutrient availability, root development, and nutrient use efficiency (Agegnehu et al., 2016; Zhang et al., 2020; ; Zhang et al., 2021). The synergistic effects of combined fertilizers can also enhance photosynthetic activity, microbial activity, and biomass growth, leading to higher GY (Backer et al., 2018; Geleta and Bekele, 2022; Liu et al., 2022). Similar effects were reported for chickpea, where inoculation with TSP increased GY by improving nutrient availability and soil physical properties (Assefa et al., 2017).

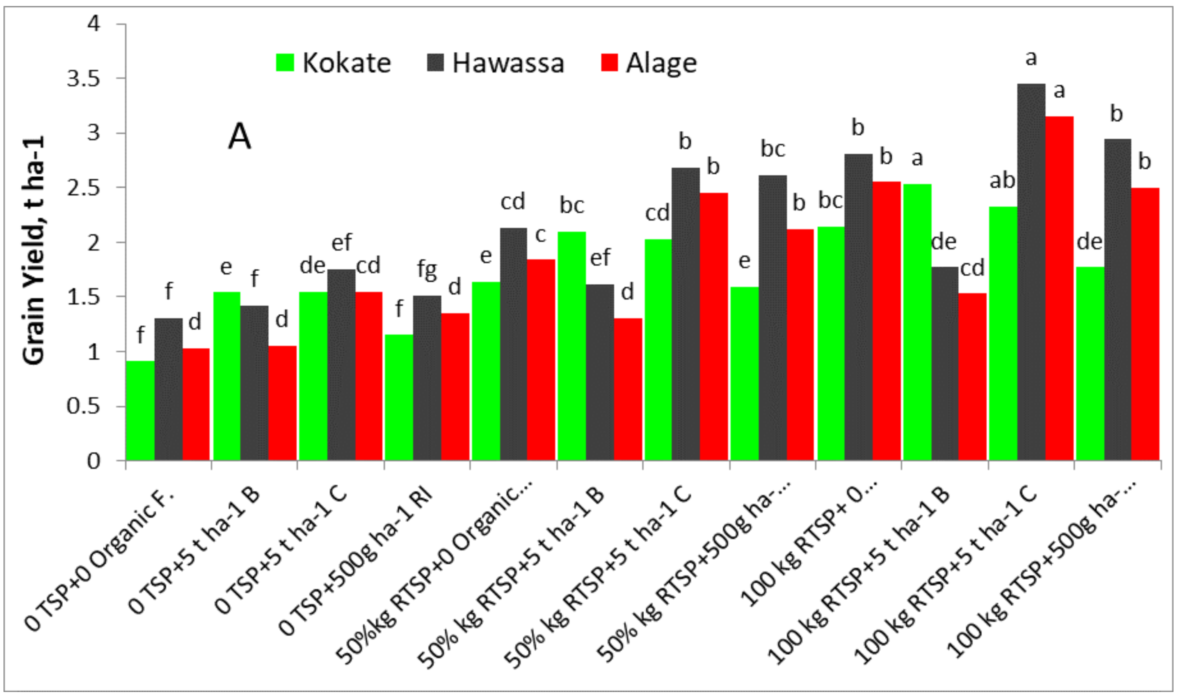

Figure 5.2. Interaction effects of inorganic and organic fertilizer on Grain yield

The increase in BY from integrated organic and inorganic fertilizers is attributed to improved leaf area index and branch number, which enhance light interception and photosynthesis (Geleta and Bekele, 2022). Studies have shown significant BY increases in legumes with integrated applications of blended mineral fertilizers (NPSB or NPK) and organic amendments such as compost or poultry manure (Alhrout et al., 2016; Demissie et al., 2017; Gyamfi, 2017; Obsa, 2017; Tadesse et al., 2022). Biochar (BC) also stimulates plant growth and improves fertilizer use efficiency when combined with inorganic fertilizers, likely due to enhanced phosphorus availability in shoots (Lehmann et al., 2003; Schulz and Glaser, 2012; Alburquerque et al., 2013).

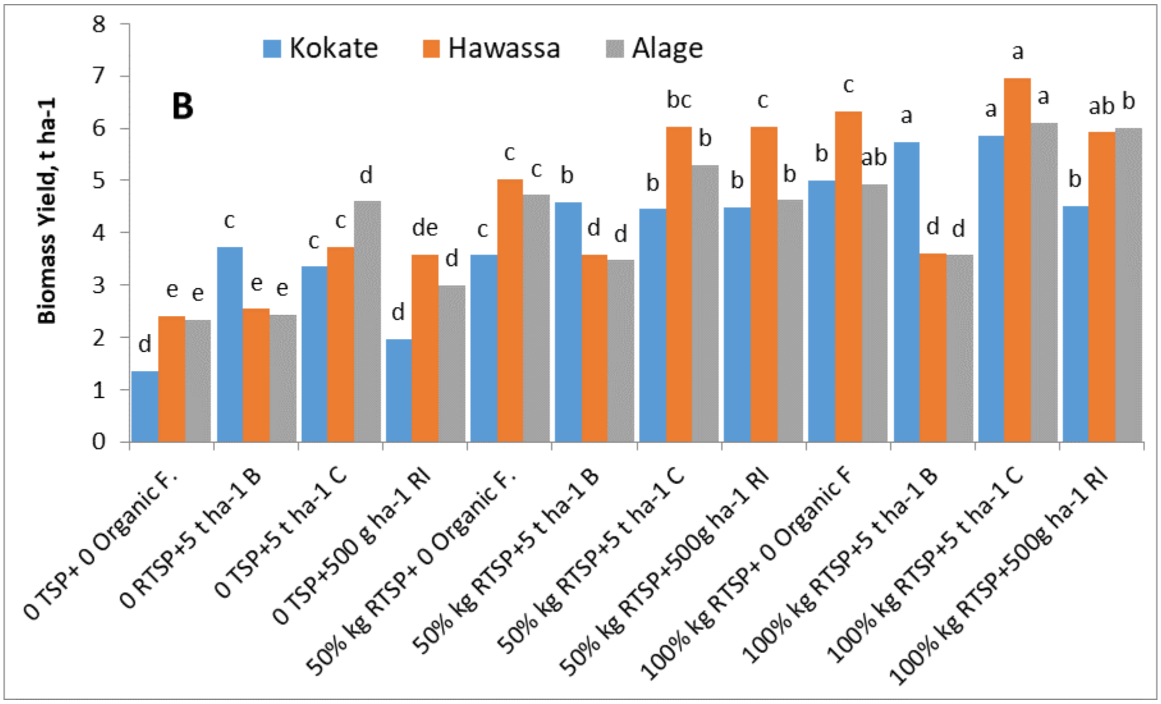

Figure 5.3. Interaction effects of inorganic and organic fertilizer on biomass yield

5.3.3. Partial budget analysis

The partial budget analysis showed that the highest net benefits of 69,460 and 63,250-birr ha^{-1} was obtained from the integrated application of 5.8 and 7.1 kg P ha^{-1} with 5 t ha^{-1} Com in HW and AL, respectively. This was followed by net benefits of 65,223 and 61,570-birr ha^{-1} from 11.6 and 14.2 kg P ha^{-1} with 5 t ha^{-1} Com, respectively, in HW and AL. On the other hand, the lowest net benefits of 36,840 and 26,850-birr ha^{-1} were obtained from the addition of 5 t ha^{-1} BC in HW and AL sites. However, the highest net benefit of 53,583-birr ha^{-1} was obtained from the integrated application of 17 kg P ha^{-1} with 5 t ha^{-1} BC, followed by 17 kg P ha^{-1} and 5 t ha^{-1} Com

(51,545-birr ha^{-1}) in the KK site. On the other hand, the lowest net benefit (30,550-birr ha^{-1}) was obtained from the addition of RI at the KK site. The highest net benefit in response to the integrated application of inorganic and organic fertilizers depended on the nature of the organic fertilizer and soil type. This was due to the differential effect of organic fertilizers on the soil type, which leads to varied effects on the increment of common bean grain yields.

5.4.Conclusions

The low soil fertility of the study sites was improved by integrating biochar or compost with inorganic P fertilizer. These applications significantly enhanced soil pH, SOC, and avail P compared to sole fertilizer and control treatments. Similarly, the integrated application also resulted in improved grain yield, biomass yield, and other yield component parameters compared with sole fertilizers and the control treatment. The integrated fertilizer application increased grain yield by 26%–33% compared to sole P fertilizer and by 105%–138% compared to the control. The yield improvements of PF + Com was superior in the neutral to moderately alkaline soils of Hawassa and Alage, while PF + BC was more effective in the acidic soils of Kokate. The use of BC alone in Hawassa and Alage sites did not perform well in nearly neutral or moderately alkaline soils, but it was comparable to the integrated use of Com and superior to sole Com in the acidic soils of Kokate site. These differences may be due to variations soil type and acid levels at the different sites. Partial budget analysis confirmed the economic feasibility, with maximum net benefits from PF + Com at Hawassa and Alage, and from PF + BC at Kokate. Therefore, smallholder farmers in southern Ethiopia can enhance common bean productivity and profitability by combining compost with PF in neutral/alkaline soils and biochar with PF in acidic soils. Further research is needed to optimize integration levels and assess long-term effects across different soil types.

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CHAPTER SIX

6. SUMMARY, CONCLUSION, AND RECOMMENDATIONS

6.1. Summary and Conclusion

A comprehensive understanding of ISFM is essential for effectively addressing challenges related to soil fertility and crop productivity. However, research remains limited on the combined effects of inorganic and organic fertilizers on soil properties, phosphorus characteristics, and common bean yield. Consequently, this study was undertaken to: (i) characterize and classify the soils within the study sites, (ii) investigate phosphorus sorption characteristics and impact of ISFM on its characteristics, (iii) assess the native rhizobia population, and (iv) evaluate the effects of inorganic and organic fertilizers on soil properties and common bean yield in different soil types. To fulfill the objectives of the dissertation, comprehensive studies were carried out in three experimental sites: Kokate, Hawassa, and Alage located in southern Ethiopia. These sites were deliberately chosen to represent variations in soil pH and the common bean production systems.

The soils at the experimental sites were initially characterized and classified through detailed soil profile descriptions. Three profiles, one from each site, were excavated and examined *in situ*, with comprehensive assessments of their morphological, physical, and chemical attributes. The findings revealed considerable variability in these properties both within individual horizons and across the different profiles. This heterogeneity is likely attributable to differences in parent material and climatic conditions.

All three profiles were very deep (>200 cm) with well-developed granular to sub-angular blocky structures. The surface soils of Kokate were clay, Hawassa soils were loam, and Alage soils were silt clay loam. Bulk density in the surface horizons was 1.23 g/cm^3 in Kokate, 1.10 g/cm^3 in Hawassa and 1.20 g/cm^3 in Alage. The higher value in Kokate and the lower value in Hawassa were mainly influenced by differences in soil organic carbon and parent material. In all profiles, surface horizons had lower bulk density than subsurface layers, which can be attributed to higher SOC content, active root systems, and reduced compaction.

Soil pH and EC vary with sites and with soil horizons. Surface soil pH ranged from very strongly acidic (4.6) in Kokate to neutral (6.8) in Hawassa and moderately alkaline (7.9) in Alage. A consistent trend of increasing soil pH with depth was observed in all soil profiles, likely due to the downward leaching of exchangeable bases. Electrical conductivity values in the surface horizons 0.08 dS/m in Kokate, 0.21 dS/m in Hawassa and 1.20 dS/m in Alage, its value ranged from 0.08 dS/m in Kokate to 1.20 dS/m in Alage, indicating that salinity is not a concern in these soils.

The SOC and TN content in the surface horizons were 1.65 and 0.14% in Kokate, 2.58 and 0.23% in Hawassa, and 2.15 and 0.20% in Alage, all falling within the medium range. A strong positive correlation between SOC and TN suggests that organic matter is the primary source of N. The observed decline in SOC and TN with depth may be due to nutrient removal through crop harvesting and continuous cultivation with limited inputs. The avail P values in surface horizon were 3.4 mg/kg in Kokate, 6.5 mg/kg in Hawassa, and 6.0 mg/kg in Alage. The overall avail P (1.3–6.5 mg/kg) was very low to low, suggesting potential P deficiencies across the study sites, likely due to fixation, leaching, and suboptimal fertilizer management.

The CEC, exchangeable bases, base saturation and micronutrient concentration varied between horizons and sites. The CEC values in the surface horizon were 25.7 cmol (+) kg^{-1} in Kokate, 28.0 cmol (+) kg^{-1} in Hawassa, and 27.0 cmol (+) kg^{-1} in Alage. Overall, the CEC (15.5–33.6 cmol(+) kg^{-1}) was medium to high, with higher values in the surface horizons. These values show favorable capacity for retention. Exchangeable base cations Ca, Mg, K, and Na ranged from 3.5 to 12.9, 1.2 to 5.7, 0.4 to 3.5, and 0.38 to 5.90 cmol (+) kg^{-1}, respectively, the Kokate, Hawassa, and Alage profiles in southern Ethiopia**.** Exchangeable bases followed the order **Ca >** Mg > K > Na, except Na dominated in the moderately alkaline Alage soils. Base saturation in the surface horizon was <50% in Kokate but >50% in Hawassa and Alage, indicating higher leaching losses due to higher rainfall conditions of Kokate. Micronutrient availability decreased with depth. Kokate soils were rich in micronutrients, whereas Hawassa and Alage soils were deficient, based on established critical thresholds, suggesting the need for micronutrient-enriched fertilizer applications in the latter sites.

Based on WRB classification, the soils were classified as: Luvisols (Kokate), Cambisols (Hawassa), and Fluvisols (Alage), indicating differences in epipedons and subsurface horizons.

Laboratory and incubation experiments were conducted to assess P sorption characteristics and amendments under different soil types. Both the Langmuir and Freundlich models adequately described the sorption data from Luvisols, Cambisols, and Fluvisols, with the Freundlich model providing the well fitted. According to this model, sorption capacity (Kf) ranged from 43–81, bonding energy (n) ranged from 0.49–0.71, and phosphorus buffering capacity (PBCf) ranged from 64–128 mL kg^{-1}. The EPRf was ranged from 63–87 mg kg^{-1}, indicating substantial variation in all soil types.

The blanket phosphorus fertilizer recommendations are ineffective, as soil types differ in their P demand. Clay content, soil pH, avail P, and SOC were the major determinants of P sorption behavior. Specifically, Luvisols (Kokate) had the highest P sorption and EPR, then Cambisols (Hawassa) and Fluvisols (Alage). This means Luvisols require higher P fertilizer rates to achieve balanced soil P availability. The commonly applied P rate of 20 kg P ha^{-1} by farmers in the study areas is substantially lower than the EPR values, which range from 69 to 107 kg P ha^{-1}.

Under the Freundlich model, the application of organic amendments, either alone or in combination with inorganic P fertilizers, significantly reduced Kf, n, PBCf, and EPRf values, thereby increasing P release into the soil solution. Integrating biochar or compost with inorganic P fertilizers could improve P availability, with benefits varying by soil type. This shows the capacity of ISFM to enhance phosphorus availability and reduce P fixation. The combination of biochar and inorganic P fertilizer was most effective in acidic soils in Kokate, while the combination of compost and inorganic P fertilizer was most effective in neutral soil in Hawassa and moderately alkaline soils in Alage.

To evaluate the abundance of rhizobia populations and their association with soil properties and cropping history in all the study sites, both laboratory and lath house experiments were conducted in 2021 and 2022. The experiment consists native rhizobia, commercial rhizobium inoculants, and inorganic N fertilizer treatments, arranged in a completely randomized design. Native rhizobia populations varied by different site: Hawassa and Alage soils contained high bacterial counts per gram of soil, whereas Kokate soils contained low rhizobia populations, due to poor nutrient availability and low soil pH.

Common bean nodulation responded positively to inoculation in sites with substantial native rhizobia populations (Hawassa), where commercial strains successfully outcompeted native populations. The combined used of Rhizobium inoculation and inorganic N fertilizer significantly improved common bean yield components. These results emphasize the importance of selecting appropriate rhizobium strains to enhance symbiotic efficiency. However, under harsh environmental soil conditions like Kokate soils, the application of commercial strains may be ineffective in improving common bean yield component, even in soils with low native rhizobia populations. The commercial inoculation was found to be ineffective in the high rhizobia soils of Alage. This could be due to the lower competitiveness of the commercial inoculation compared to the native rhizobia present in the soils.

A two-year field experiment conducted from 2021 to 2022 evaluated the combined effects of inorganic and organic fertilizers on soil properties and common bean yield. Integrated use of inorganic and organic fertilizers significantly improved soil properties and common bean productivity, with combined applications providing the highest yield. From an economic perspective, the most effective fertilization strategies involved combining inorganic P with organic amendments: specifically**,** 17 kg ha^{-1} P with 5 t ha^{-1} biochar for Kokate soil, and 5.8 and 7.1 kg ha^{-1} P with 5 t ha^{-1} compost for Hawassa and Alage soils, respectively. These combinations were identified as optimal for improving both soil fertility and common bean yield, underscoring their potential for wider implementation in sustainable agricultural systems.

6.2.Recommendations

Based on the above findings, here are some recommendations for improving soil fertility and crop yield in research sites.

- The soils examined have diverse properties, indicating that there is no one-size-fits-all solution for all soil types. Therefore, we recommend the implementation of specific soil management practices for soil types to improve nutrient levels and maximize agricultural productivity.

- A uniform or "blanket" P recommendation will not be effective. Recommendations on P application rates should be based on the specific soil type to improve crop yields. Moreover, organic inputs like biochar and compost are recommended to correct P limitations in acidic and alkaline soils. Further research is recommended to better understand the long-term effects and mechanisms of P-fertilizer in these soils.
- To correct problems associated with P limitation and low availability in acidic and alkaline soils, organic inputs like biochar and compost can be utilized as supplementary amendments. Further research is needed to assess the effect of biochar derived from high pyrolysis processes on alkaline soils.
- The soils in the study sites especially Hawassa and Alage have sufficient native rhizobia populations for common bean production. The study found that common bean nodulation and yield improved with inoculation, suggesting that commercial rhizobium strains are either more competitive than the native ones or operating synergistically. This makes inoculation with suitable rhizobium strains a good strategy to improve crop performance. However, it requires further investigation into the effectiveness of the native rhizobia and the interaction of native rhizobia and commercial inoculants.
- A combined approach using both inorganic and organic fertilizers is recommended over the common practice of using sole inorganic P fertilizers. A specific, economically beneficial fertilizer combination is recommended for different soil types. Farmers are encouraged to use these integrated applications to promote sustainable agricultural production. The optimal rates are:

- Kokate (acidic Luvisols): 17 kg ha^{-1}P + 5 t ha^{-1} biochar
- Hawassa (neutral Cambisols): 5.8 kg ha^{-1} P + 5 t ha^{-1} compost
- Alage (alkaline Fluvisols): 7.1 kg ha^{-1} P + 5 t ha^{-1} compost

- While this study provides valuable short-term results, we recommend further research to assess the long-term effects of the integrated fertilizer applications both on soils and crops.

7. APPENDICES

Appendix Table 7. 1. Profile description sheet

Profile ID:	Kokate
Date of examination:	15 December 2021
Surveyor	Rameto Wabela, Bishri Mohammed and Haile Hasana
Coordinates:	06º49'17.6``N and 37º44'56.2``E
Elevation:	2143 m a.s.l
Major landform:	Sloping
Physiographic position:	Upper
Slope	≥ 5%
Crop	Vegetable and Maize
Human influence	Fertilizing application
Moisture condition	Moist
Drainage	Well drained
Ground water table	at time profile description not observed up to 200^{+} cm
Parent materials	Baslt
Erosion	evidence of erosion
Rock outcrops/stoniness	No evidence of rock out crops
Present land use	Crop agriculture
Depth to bedrock	Not observed up to 200^{+} cm depth
Local soil name	Zobita
Soil type (WRB)	Luvisols

Horizon designation	**Horizon boundaries**	**Description of horizon**
Ap	0-21 cm	Reddish black (2.5YR2.5/1, moist) to red (2.5YR4/8, dry) clay; weak, fine to coarse granular structure; hard, friable, sticky and plastic; many fine to coarse roots; common other insect activity; diffuse smooth boundary.
AB	21-45 cm	Very dusky red (2.5YR2.5/2, moist) to red (2.5YR4/8, dry) clay; moderate, medium, angular blocky structure; slightly hard, firm, sticky, plastic; few fine roots; few other insect activities; gradual and smooth boundary.
Bt1	45-85 cm	Dusky red (10R3/3, moist) to red (10R4/6, dry) clay; moderate, medium, sub angular blocky structure; slightly hard, firm, very sticky, very plastic; very few very fine roots; gradual and smooth boundary.
Bt2	85-150 cm	Dusky red (10R3/3, moist), red (10R5/6, dry) clay; weak medium sub-angular blocky structure; slightly hard, friable, very

		sticky, very plastic; non-roots; gradual and smooth boundary.
Bt3	150-200^{+}	Dusky red (10R3/4, moist), weak red (10R4/4, dry) clay; weak fine sub-angular blocky structure; slightly hard, friable, very sticky, very plastic; non-roots.

Profile ID:	Hawassa
Date of examination:	17 December 2021
Surveyor	Rameto Wabela, Bishri Mohammed and Haile Hasana
Coordinates:	07^{o}03'53.8``N and 38$^{o}$28'59.2``E
Elevation:	1694 m a.s.l
Major landform:	Nearly flat
Physiographic position:	Bottom
Slope	2%
Crop	Maize and common bean
Human influence	Fertilizer application
Moisture condition	Dry
Drainage	Poor drained
Ground water table	at time profile description not observed up to 200^{+} cm
Parent materials	Alluvium
Erosion	Evidence of erosion
Rock outcrops/stoniness	No evidence of rock out crops
Present land use	Crop agriculture
Depth to bedrock	Not observed up to 200^{+} cm depth
Local soil name	Bula

Soil type (WRB) Cambisols

Horizon designation	Horizon boundaries	Description of horizon
A	0-27 cm	Very dark brown (10YR2/2, moist) to dark brown (10YR3/3, dry) loam; weak, fine to coarse granular structure; slightly hard, friable, sticky and plastic; many mediums to coarse roots; common other insect activity; diffuse smooth boundary.
Bw1	27-50 cm	Dark brown (10YR3/3, moist) to brown (10YR4/3, dry) clay loam; weak, medium, sub angular blocky structure; hard, very friable, sticky, plastic; very fine roots; common other insect activity; gradual and smooth boundary.
Bw2	50-90 cm	Dark brown (10YR3/3, moist) to dark yellowish brown (10R4/4, dry) clay loam; weak, medium, sub angular blocky structure; hard, firm, sticky, plastic; very few very fine roots; gradual and smooth boundary.
Bw3	90-110 cm	Dark grayish brown (10YR4/2, moist), brown (10R5/3, dry) clay loam; weak, medium, sub angular blocky structure; slightly hard, friable, sticky, plastic; very few very fine roots; clear and smooth boundary.
BC	110-150	Light brownish gray (10YR6/2, moist), pale brown (10YR6/3, dry) clay loam; weak, medium, sub angular blocky structure; hard, firm, slightly sticky, slightly plastic; non-roots; gradual and smooth boundary.

C	150-200^{+}	Light brownish gray (10YR6/2, moist), light yellowish brown (10YR6/4, dry) loam; weak, medium, single grain structure; hard, firm, non-sticky, non-plastic; non- roots.

Profile ID:	Alage
Date of examination:	16 December 2021
Surveyor	Rameto Wabela, Bishri Mohammed and Haile Hasana
Coordinates:	7°35`30``N and 38°24`59``E
Elevation:	1585 m a.s.l
Major landform:	Flat
Physiographic position:	Bottom
Slope	1%
Crop	Maize and common bean
Human influence	Fertilizer application
Moisture condition	Dry
Drainage	Poor drained
Ground water table	at time profile description not observed up to 200^{+} cm
Parent materials	Lacustrine deposits
Erosion	Evidence of erosion
Rock outcrops/stoniness	No evidence of rock out crops
Present land use	Crop agriculture
Depth to bedrock	Not observed up to 200^{+} cm depth
Local soil name	Boji
Soil type (WRB)	Fluvisols

Horizon designation	Horizon boundaries	Description of horizon
Ap	0-35 cm	Dark brown (7.5YR3/2, moist) to dark brown (7.5YR3/3, dry) silt clay loam; weak, fine, granular structure; slightly hard, friable, sticky and plastic; many fine to coarse roots; common other insect activity; clear smooth boundary.
BC	35-70 cm	Dark brown (7.5YR3/4, moist) to brown (7.5YR5/4, dry) silt loam; weak, fine to coarse, sub angular blocky structure; hard, very firm, slightly sticky, slightly plastic; very few fine roots; few other insect activities; abrupt and wave boundary.
C	70-80 cm	Light brown (7.5YR6/3, moist) to dark light brown (7.5YR6/4, dry) loamy sand; strong, medium, single grain structure; hard, very firm, non-sticky, non-plastic; non-roots; abrupt and wave boundary.
2B1	80-105 cm	Brown (7.5YR4/4, moist), strong brown (7.5YR5/6, dry) loam; weak, fine, sub angular blocky structure; slightly hard, friable, sticky, plastic; very few very fine roots; clear and smooth boundary.
2B2	105-130	Strong brown (7.5YR4/6, moist), strong brown (7.5YR5/8, dry) silt loam; weak, fine, sub angular blocky structure; slightly hard, friable, sticky, plastic; very few very fine roots; abrupt and smooth boundary.
2C	130-160	Light brown (7.5YR6/4, moist), pinkish gray (7.5YR7/2, dry)

		sandy loam; strong, medium, single grain structure; hard, very firm, non-sticky, non-plastic; non-roots; abrupt and smooth boundary.
3B	160-200$^+$	Brown (7.5YR4/4, moist), strong brown (7.5YR5/6, dry) silt loam; weak, very friable, sub angular blocky structure; slightly hard, very friable, slightly sticky, slightly plastic; non-roots.

Appendix Table 7. 2. Surface soil physico-chemical properties prior treatment application (0-20 cm)

Soil properties	Kokate				Hawassa				Alage			
	S1	S2	S3	Mean	S1	S2	S3	Mean	S1	S2	S3	Mean
Physical properties												
Sand (%)	18	17	13	16	41	45	40	42	19	15	20	18
Silt (%)	27	24	33	28	36	37	35	36	45	44	49	46
Clay (%)	53	57	58	56	23	24	19	22	38	35	34	36
Silt: clay ratio	0.51	0.42	0.57	0.5	1.57	1.54	1.84	1.64	1.18	1.26	1.44	1.29
Bd g cm^{-3}	1.27	1.22	1.26	1.25	1.1	0.9	1.1	1.0	0.99	1.2	1.21	1.13
Chemical properties												
pH (H_2O)	4.79	4.87	4.74	4.8	6.6	6.65	6.67	6.6	7.92	7.73	7.95	7.9
EC (ds/m)	0.07	0.09	0.07	0.08	0.22	0.19	0.23	0.21	1.3	1.3	1.1	1.23
SOC (%)	1.57	1.87	1.56	1.7	2.4	2.8	2.7	2.6	2.35	1.95	2.10	2.1
Total nitrogen (%)	0.14	0.17	0.17	0.16	0.21	0.24	0.21	0.22	0.21	0.17	0.18	0.19
C: N	11.21	11.0	9.18	10.42	11.43	11.67	12.9	11.8	11.19	11.47	11.67	11
Available P (mg kg^{-1})	3.56	3.61	3.35	3.5	6.3	6.4	6.7	6.5	6.25	6.19	6.19	6.2
Ca (cmolc kg^{-1})	7.2	8.5	7.87	7.9	8.9	9.5	9.6	9.3	14.5	13.9	14.5	14.3
Mg (cmolc kg^{-1})	2.7	3.2	2.8	2.9	3.9	4.1	4.5	4.2	5.6	5.0	5.3	5.3
K (cmolc kg^{-1})	0.37	0.41	0.39	0.39	1.5	1.8	1.9	1.7	2.5	1.7	2.3	2.2
Na (cmolc kg^{-1})	0.39	0.41	0.35	0.38	0.71	0.68	0.67	0.69	1.2	1.3	1.1	1.2
CEC (cmolc kg^{-1})	24	28	25	26	26	29	30	28	29	25	25	27
Fe (mg kg^{-1})	19.92	21	20.9	20.6	2.2	2.1	2.5	2.3	1.4	1.2	1.2	1.3
Mn (mg kg^{-1})	16.9	19.5	16.5	17.6	2.3	2.7	2.6	2.5	1.7	1.4	1.3	1.5
Cu (mg kg^{-1})	0.31	0.35	0.34	0.33	0.42	0.43	0.49	0.45	0.18	0.16	0.18	0.17
Zn (mg kg^{-1})	2.1	2.3	1.9	2.1	0.31	0.33	0.29	0.31	0.28	0.27	0.21	0.25

Appendix Table 7. 3. Number of common bean native rhizobial population from the soil collection areas

Kokate Nodulation						Hawassa Nodulation					Alage Nodulation				
Dilution	Replication				Number of Nodulated Units	Replication				Number of Nodulated Units	Replication				Number of Nodulated Units
	I	II	III	IV		I	II	III	IV		I	II	III	IV	
10^{-1}	+	-	+	+	3	+	+	+	+	4	+	+	+	+	4
10^{-2}	+	+	-	+	3	+	+	+	+	4	+	+	+	+	4
10^{-3}	+	-	-	-	1	+	+	+	+	4	+	+	+	+	4
10^{-4}	-	-	-	-	0	+	+	+	+	4	-	+	+	+	3
10^{-5}	-	-	-	-	0	+	+	-	+	3	-	+	+	+	3
10^{-6}	-	-	-	-	0	-	+	-	-	2	-	+	-	+	2
10^{-7}	-	-	-	-	0	-	-	+	-	2	+	-	-	-	1
10^{-8}	-	-	-	-	0	-	-	+	-	1	-	-	-	-	0
10^{-9}	-	-	-	-	0	-	-	-	-	0	-	-	-	-	0
10^{-10}	-	-	-	-	0	-	-	-	-	0	-	-	-	-	0
Total					7					24					21

Appendix Table 7. 4. Published articles

Tropical and Subtropical Agroecosystems 27 (2024): Art. No. 148 Wabela et al., 2024

CHARACTERIZATION AND CLASSIFICATION OF SOILS FOR SELECTED SITES IN SOUTHERN ETHIOPIA †

[CARACTERIZACIÓN Y CLASIFICACIÓN DE SUELOS PARA SITIOS SELECCIONADOS EN EL SUR DE ETIOPÍA]

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SUMMARY

Background: Soils in southern Ethiopia are under intensive cultivation, and low soil fertility is a major problem. However, very little is known about soil types and their inherent nature to support specific decisions on soil managements. **Objective:** To characterize and classify soils for three selected agricultural sites in southern Ethiopia. **Methodology:** The field morphological description and laboratory analysis were carried out to characterize, and classify the soils of Kokate, Hawassa, and Alage in southern Ethiopia. A representative soil profile (2 m x 2 m x 2 m) was open at each site, for soil profile description. For each profile, soil samples were collected for each of the genetic horizons identified, and the samples were analyzed for their soil physicochemical properties. **Results:** The results showed that the surfaces of Kokate, Hawassa, and Alage were strongly acidic, neutral, and moderately alkaline, respectively. The surface soil of Kokate had clay texture, a high content of micronutrients, cation exchange capacity and moderate base saturation, low soil organic carbon, and available phosphorus. The surface soil of Hawassa had loam texture, high base saturation, cation exchange capacity, and low levels of soil organic carbon, available phosphorus, and micronutrients. The surface soil of Alage had silt clay loam texture, high base saturation, cation exchange capacity, sodium content, and low soil organic carbon content, available phosphorus, and micronutrients. Based on WRB, the soils of Kokate, Hawassa, and Alage were classified as Vertic Luvisols with an argic diagnostic subsurface horizon, Haplic Cambisols with a cambic diagnostic subsurface horizon, and Calcaric Fluvisols with fluvic diagnostic material, respectively. **Implications:** The differences may suggest that site-specific soil fertility management is desired, and the results may provide basic information to design soil management options to improve land productivity. **Conclusions:** The present study showed three soil types and revealed their low nutrient content and different soil pH.

Key words: Soil horizons; soil characterization; soil classification; soil profile; soil properties; soil types.

RESUMEN

Antecedentes: Los suelos del sur de Etiopía están bajo cultivo intensivo y la baja fertilidad del suelo es un problema importante. Sin embargo, se sabe muy poco sobre los tipos de suelo y su naturaleza inherente para respaldar decisiones específicas sobre el manejo del suelo. **Objetivo**: Caracterizar y clasificar suelos de tres sitios agrícolas seleccionados en el sur de Etiopía. **Metodología:** Se realizó la descripción morfológica de campo y análisis de laboratorio para caracterizar y clasificar los suelos de Kokate, Hawassa y Alage en el sur de Etiopía. Se abrió un perfil de suelo representativo (2 m x 2 m x 2 m) en cada sitio, para la descripción del perfil del suelo. Para cada perfil, se recolectaron muestras de suelo para cada uno de los horizontes genéticos identificados y se analizaron las muestras para determinar sus propiedades fisicoquímicas del suelo. **Resultados**: Según el estudio, las superficies de Kokate, Hawassa y Alage eran fuertemente ácidas, neutras y moderadamente alcalinas, respectivamente. El suelo superficial de Kokate tenía textura arcillosa, alto contenido de micronutrientes, capacidad de intercambio catiónico y saturación de bases moderada, bajo carbono orgánico del suelo y fósforo disponible. El suelo superficial de Hawassa tenía textura franca, alta saturación de bases, capacidad de intercambio catiónico y bajos niveles. del carbono orgánico del suelo, fósforo

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RESEARCH ARTICLE

Effects of Integrated Soil Fertility Management on Soil Properties and Phosphorus Sorption Characteristics at Three Soil Types in Southern Ethiopia

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ABSTRACT

Background

Low phosphorus availability in Ethiopian soil, mostly due to P sorption, is limiting agricultural crop productivity. Thus, effective phosphorus management is critical to addressing soil nutrient shortages.

Aim

This study evaluated the effect of integrated soil fertility management (ISFM) on soil properties and phosphorus sorption characteristics at three soil types in Southern Ethiopia.

Methods

Phosphorus sorption was determined by batch equilibrium methods, using the Langmuir and Freundlich models. Treatments included control, phosphorus fertilizer, biochar, compost, biochar with phosphorus fertilizer, and compost with phosphorus fertilizer.

Results

Results showed that the combined fertilizer application improved soil properties over the phosphorus fertilizer application. The application of biochar with phosphorus fertilizer to soil produced more available phosphorus in the acidic Luvisols, whereas the highest available phosphorus was obtained from the application of compost with phosphorus fertilizer in the Cambisols and Fluvisols, respectively. The phosphorus sorption data best fitted the Freundlich (R^2 = 0.82–0.98) models with all soil types. The application of ISFM decreased the Freundlich parameter values in all the studied soils compared to the addition of inorganic P. Luvisols require more phosphorus fertilizer to maintain optimal soil phosphorus concentration for crop growth compared to Cambisols and Fluvisols.

Conclusion

The ISFM showed potential to improve soil available phosphorus in the smallholder farming system of Southern Ethiopia. This could be attributed to the release of phosphorus through the mineralization of organic matter and phosphorus desorption from Fe and Al oxides in acidic, and Ca in alkaline soils.

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Research article

Effects of integrated fertilizer application on selected soil properties and yield attributes of common bean (*Phaseolus vulgaris* L.) on different soil types

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ABSTRACT

In Ethiopia, common bean (*Phaseolus vulgaris* L.) productivity remains low because of low soil fertility. However, both plant production and soil fertility benefit from integrated application of fertilizers. Thus, this study investigates the effect of integrated application of inorganic, organic and biofertilizers on selected soil properties and yield components of common bean. A field experiment was conducted at three sites in southern Ethiopia, under two consecutive cropping season (2021 and 2022). The experiment was conducted using a randomized complete block design (RCBD) with three replications. The treatments included three levels of inorganic fertilizer (Triple Superphosphate, TSP), applied at 0, 42.5, and 85 kg TSP ha^{-1} for Kokate; 0, 29, and 58 kg TSP ha^{-1} for Hawassa; and 0, 35.5, and 71 kg TSP ha^{-1} for Alage, tailored to the specific conditions of each site. Additionally, the experiment incorporated three levels of organic inputs 0, 5 t biochar ha^{-1}, and 5 t compost ha^{-1} as well as Rhizobium inoculation (HB-429) applied at 500 g ha^{-1}. These treatments were designed to assess the combined effects of inorganic, organic and biofertilizers on soil health and crop performance. Results showed that the integrated application of inorganic, and organic fertilizers significantly ($p \leq 0.05$) improved soil pH, soil organic carbon, and available P compared with the sole fertilizer application plots. Similarly, the integrated use of inorganic, organic and biofertilizers increased nodule numbers, seed weight, grain yield, and biomass yield. We also found that 23 and 24 % higher grain yield were achieved with integrated applications of TSP fertilizer with compost on Hawassa and Alage sites than sole inorganic fertilizer application. On the other hand, the integrated application of TSP fertilizer with biochar increased by 18 % grain yield on Kokate over the sole application of inorganic fertilizer. The highest economic benefit of 69,460 and 63,250 ETB was obtained from the integrated application of TSP fertilizer with compost at Hawassa and Alage sites, respectively. The highest economic benefit for the Kokate site was 53,583 ETB at TSP fertilizer with biochar application. Overall, the study confirms that site-specific integrated soil fertility management appears to be a prerequisite for sustainable and profitable common bean production over sole fertilizer application in southern Ethiopia.

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