



BAHIR DAR UNIVERSITY

COLLEGE OF AGRICULTURE AND ENVIRONMENTAL SCIENCES

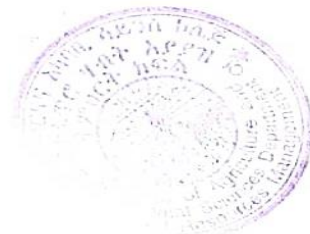
GRADUATE PROGRAM IN SOIL SCIENCE

**EFFECTS OF RHIZOBIUM STRAINS, LIME AND STARTER NITROGEN FERTILIZER
ON SOIL FERTILITY AND YIELD OF FABA BEAN (*VICIA FABA L.*) ON ACIDIC
SOILS OF NORTHWESTERN ETHIOPIA**

MSc Thesis

By

Tesema Minale Getahun



June 2025

Bahir Dar



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**A THESIS SUBMITTED
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF
MASTERS OF SCIENCE IN SOIL SCIENCE**

Major Advisor: Enyew Adgo (Prof.)

June 2025

Bahir Dar

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Declaration

This is to certify that the thesis entitled “**EFFECTS OF RHIZOBIUM STRAINS, LIME AND STARTER NITROGEN FERTILIZER ON SOIL FERTILITY AND YIELD OF FABA BEAN IN ACIDIC SOILS OF NORTHWESTERN ETHIOPIA**”, submitted in partial fulfillment of the requirements for the degree of Master of Soil science in Department of Natural resource management, Bahir Dar University, is a record of original work carried out by me and has never been submitted to this or any other institution to get any other degree or certificates. The assistance and help I received during the course of this investigation have been duly acknowledged.

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Graduate Program in Soil Science

Approval of Thesis for Defense

I hereby certify that I have supervised, read, and evaluated the thesis entitled: **“EFFECTS OF RHIZOBIA STRAINS, LIME AND STARTER NITROGEN ON SOIL FERTILITY AND YIELDS OF FABA BEAN IN ACIDIC SOILS OF NORTHWESTERN ETHIOPIA”** prepared by **Tesema Minale**, under my guidance. I recommend that the thesis be submitted for oral defense.

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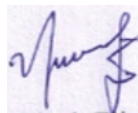
Graduate Program in Soil Science

Approval of Thesis for defense result

As members of the board of examiners of the Master of Sciences (MSc.) thesis open defense, we have read and evaluated this thesis prepared by Mr. Tesema Minale Entitled **“Effects of Rhizobial Strains, Lime and Starter Nitrogen Fertilizer on Soil Fertility and Yield of Faba bean on Acidic Soils of Northwestern Ethiopia”** We hereby certify that, the thesis is accepted for fulfilling the requirements for the award of the degree of Master of Science (M.Sc.) in Soil Science.

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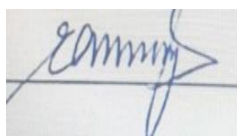
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LIST OF ACRONYMS AND ABBREVIATIONS

AGBY	Above ground dry biomass yield
ANOVA	Analysis of Variance
AV.P	Available Phosphorus
BD	Bulk Density
BNF	Biological Nitrogen Fixation
CIMMYT	International Maize and Wheat Improvement Center
CSA	Central Statistical Agency
CV	Coefficient of Variation
EIAR	Ethiopian Institute of Agricultural Research
ENN	Effective Nodule Number
ETB	Ethiopian Birr
FAO	Food and Agricultural Organization
GI	Gross Income
GY	Grain Yield
HI	Harvest Index
ISFM	Integrated Soil Fertility Management
Kg	Kilogram
LSD	Least Significant Difference
MRR	Marginal Rate of Return
NDW	Nodule Dry Weight
NFB	Net Financial Benefits
NN	Nodule Number
OC	Organic Carbon
pH	Power of Hydrogen
SAS	Statistical Analysis Software
SE	Standard Error
SY	Straw yield
T	Ton
TVC	Total Variable Cost

EFFECTS OF RHIZOBIA STRAINS, LIME AND STARTER NITROGEN ON SOIL FERTILITY AND YIELDS OF FABA BEAN (*Vicia faba* L.) ON ACIDIC SOILS OF NORTH WESTERN ETHIOPIA

ABSTRACT

Soil acidity and nutrient depletion are key constraints to agricultural productivity in Northwestern Ethiopia. Despite the recognized importance of integrated soil fertility management, limited research has been conducted in Northwestern Ethiopia on the combined effects of lime, Rhizobium inoculation, and starter nitrogen on soil properties and Faba bean productivity. A field experiment was conducted in Koga and Injebara using 18 treatment combinations: two Rhizobium strains (FB-37 and FB-1035, plus a control), three nitrogen rates (0, 10, and 20 kg N ha⁻¹), and two lime rates (0 and 2 t ha⁻¹), arranged in a randomized complete block design with three replications.

The results revealed that the integrated application of FB-1035, 2 t ha⁻¹ lime, and 10 kg N ha⁻¹ significantly improved soil pH (5.68 and 6.51), organic carbon (1.89% and 4.16%), and available phosphorus (15.53mgkg⁻¹ and 46.45mgkg⁻¹) at Koga and Injebara respectively. Exchangeable acidity (0.73 Cmolkg⁻¹) and aluminum contents (0.49Cmolkg⁻¹) were notably reduced at Koga by the combined application of FB-1035, 2 t ha⁻¹ and 10 kg ha⁻¹. Agronomic performance, including nodulation, plant height, and grain yield, were enhanced under integrated application. The highest yields 2.87 t ha⁻¹ at Koga and 3.39 t ha⁻¹ at Injebara were achieved using FB-1035, 2 t ha⁻¹ lime, and 10 kg N ha⁻¹, which also offered the highest economic return. Thus, integrating lime, effective Rhizobium strains, and low-rate nitrogen is recommended for improving productivity on acidic soils. Further research is needed to examine the residual effects of lime and strains across varying soil types.

Keywords: *Soil acidity, Biological nitrogen fixation, integrated soil fertility management, Soil properties*

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1. INTRODUCTION

Agriculture serves as the economic backbone of many countries, particularly in the developing world (FAO, 2014). In Ethiopia, the sector plays a dominant role in the national economy and is heavily dependent on soil resources. However, soil acidity, coupled with a decline in soil fertility, is a major factor limiting crop productivity, especially in the tropical and subtropical regions (Biru Yitaferu *et al.*, 2017). These conditions arise due to both natural and anthropogenic processes, which lead to increased concentrations of hydrogen ions (H^+) in the soil. Globally, acid soils account for approximately 40% of arable land and are predominantly found in South and North America, Asia, and Africa (Kisinyo, 2014).

In the Ethiopian highlands, soil acidity and nutrient depletion are major forms of soil degradation that threaten sustainable crop production. These issues are often associated with high rainfall intensities and traditional agricultural practices such as limited use of manure and removal of crop residues (Endalkachew Fekadu *et al.*, 2017). According to Ethio SIS (2016), around 43% of Ethiopia's agricultural land is affected by soil acidity, with approximately 28.1% classified as strongly acidic (pH 4.1–5.5) (ATA, 2014).

Declining soil fertility has also been stressed to be the fundamental impediment to agricultural development and the major reason for the slow growth in food production in Ethiopia. Continuous nutrient mining, minimal external input use, and soil erosion have led to severe nutrient depletion particularly nitrogen, phosphorus, and potassium in many parts of the country, including the highlands (Amare Hailelassie *et al.*, 2005; Tamene Lulseged *et al.*, 2017). Multiple studies estimate annual nutrient losses from smallholder farmland to be approximately about 122 kg N/ha/year, 13 kg P/ha/year and 82 kg K/ha/year (Hailu Hillette *et al.*, 2015). The degradation of soil organic matter and acidification further constrain the productive capacity of soils, particularly for smallholder farmers who depend on rainfed agriculture and have limited access to inputs (Roberts *et al.*, 2021). As a result, crop yields have stagnated or declined in many regions, undermining national food security efforts despite increased demand and population growth (FAO, 2022).

Faba bean (*Vicia faba* L.) is particularly vulnerable to soil acidity, which significantly affects its productivity and sustainability in Ethiopia (Getachew Agegnehu & Rezene,

2006). As one of the earliest domesticated food legumes, Faba bean is cultivated under both rain-fed and irrigated conditions across many parts of the world (Singh *et al.*, 2013). In Ethiopia, it is a major pulse crop grown primarily in the highlands at altitudes ranging from 1,800 to 3,000 meters above sea level, with annual rainfall between 700 and 1,000 mm (Jarso & Keneni, 2006). Faba bean performs best in soils with a pH of 6–7 and shows poor growth in strongly acidic soils (Jensen *et al.*, 2010). The crop is vital for its nutritional value and its role in enhancing soil fertility through nitrogen fixation, providing a key protein source for subsistence farmers who often cannot afford animal-based proteins (Asnakech Tekalign *et al.*, 2016). Globally, Faba bean can fix between 45 to 300 kg N ha⁻¹, with an estimated fixation of 69 kg N ha⁻¹ reported in Northern Ethiopia (Mesfin Tadele, 2020).

Despite its significance, the productivity of Faba bean in Ethiopia remains low, averaging 2.11 t ha⁻¹ (CSA, 2021/2022), compared to 3.47 and 3.83 t ha⁻¹ in Egypt and the United Kingdom, respectively (FAOSTAT, 2018). This productivity gap is attributed to a combination of biotic and abiotic stresses, particularly poor soil fertility and soil acidity in high rainfall areas (Mesfin Tadele, 2020).

Liming is a widely used practice to correct soil acidity by increasing pH, which in turn improves nutrient availability and soil fertility (Gupta *et al.*, 2020; Chen *et al.*, 2021). Applied as calcium carbonate or dolomitic lime, it neutralizes harmful hydrogen (H⁺) and aluminum (Al³⁺) ions that restrict root growth and nutrient uptake (Fageria *et al.*, 2019). This reaction not only reduces aluminum toxicity but also enhances the availability of essential nutrients like calcium, magnesium, potassium, and sodium, which are vital for plant functions such as enzyme activation, cell wall formation, and photosynthesis (Chen *et al.*, 2021; Wang *et al.*, 2023). Additionally, liming creates a more favorable environment for soil microbial communities, especially nitrogen-fixing bacteria like *Rhizobium*, which are inhibited by low pH. This supports improved biological nitrogen fixation in legumes such as Faba bean (Liu *et al.*, 2022). Increased microbial activity also promotes organic matter decomposition and nutrient cycling, contributing to higher soil organic carbon and overall soil health.

Bio-fertilizers also play a key role in enhancing soil fertility and plant productivity. These biological agents improve nitrogen fixation and soil nutrient content while being environmentally friendly and biodegradable (Esraa *et al.*, 2023). Bio-fertilizers can

enhance crop yields by 10–40% and increase levels of proteins, amino acids, and vitamins and nitrogen fixation (Shahwar *et al.*, 2023). However, symbiotically fixed nitrogen is often insufficient to meet the crop's full demand. Thus, the application of small amounts of “starter” nitrogen fertilizer is recommended to promote early seedling development and stimulate nitrogen fixation (Dereje Debocha *et al.*, 2021).

Integrated soil fertility management (ISFM) is defined by as “a set of soil fertility management practices that necessarily include the use of fertilizer, organic inputs, and improved germplasm combined with the knowledge on how to adapt these practices to local conditions, aiming at maximizing agronomic use efficiency of applied nutrients and improved crop productivity (Vanlauwe *et al.*, 2010). The soils of Northwestern Ethiopia are characterized by high acidity, low available nitrogen, and poor biological activity, all of which limit legume productivity, particularly Faba bean (Getachew Agegnehu *et al.*, 2017). The ISFM approach supports the use of rhizobia strains to enhance biological nitrogen fixation, lime to correct soil pH and reduce aluminum toxicity, and starter nitrogen to improve early plant growth, especially before nodulation becomes fully effective (Endalkachew Woldemeskel *et al.*, 2018; Wuletaw Tadesse *et al.*, 2022). These combined practices exemplify ISFM's emphasis on synergistic input use for maximum nutrient efficiency and yield response. As highlighted by HLPE (2020), ISFM also contributes to climate-smart and agro ecological goals by enhancing soil health and building long-term resilience. Over the past 15 years, research across sub-Saharan Africa has demonstrated ISFM's role in improving the productivity of smallholder systems while promoting sustainable resource use (Bekunda *et al.*, 2022).

Despite the importance of integrated soil fertility management, limited research has been conducted on the combined use of bio-fertilizers, lime, and inorganic nitrogen fertilizers for ameliorating acidic soils in Northwestern Ethiopia. Therefore, this study was initiated to evaluate the effects of integrated applications of rhizobium, lime, and nitrogen fertilizer on soil fertility and Faba bean productivity in the acidic soils of Northwestern Ethiopia.

1.1. Statement of the Problem

Soil acidity and poor fertility remain among the most critical constraints to agricultural productivity in Northwestern Ethiopia, particularly for leguminous crops such as Faba bean (*Vicia faba L.*). As a nitrogen-fixing crop, Faba bean is highly sensitive to soil acidity, which inhibits *Rhizobium* activity, restricts root growth, reduces nutrient availability, and significantly lowers yield (Getachew Agegnehu & Rezene, 2006; Du et al., 2024). Lime is widely recognized as an effective amendment to neutralize soil acidity and improve nutrient uptake. Similarly, inoculation with effective *Rhizobium* strains enhances biological nitrogen fixation, while starter nitrogen improves early plant vigor, especially before full nodulation (Endalkachew WoldeMeskel *et al.*, 2018; Wuletaw Tadesse *et al.*, 2022).

Several studies have evaluated these practices individually, demonstrating soil properties improvement and yield gains with lime in acidic soils (Getachew Agegnehu *et al.*, 2019), improved nodulation and nitrogen fixation with rhizobia inoculation (Endalikachew Wolde-Meskel *et al.*, 2018), and enhanced early growth from starter N applications (Almaz Gezahagn *et al.*, 2021). However, research combining lime, rhizobia inoculants, and starter nitrogen remains limited, especially under the specific soil and climatic conditions of Northwestern Ethiopia. Furthermore, the lack of locally adapted inoculants, limited fertilizer input use, and widespread soil acidification contribute to the underperformance of Faba bean in the region (Dereje Debocha *et al.*, 2021; Samirawiet Mebrhatu, 2024). While ISFM principles advocate for such combined interventions, evidence on how they function together under real field conditions in highland acidic soils is scarce, representing a significant knowledge gap.

This research addresses these gaps by investigating the individual and combined effects of lime, rhizobia strains, and starter nitrogen on soil properties and Faba bean productivity in acidic soils of Northwestern Ethiopia. The findings are expected to guide the development of integrated soil fertility management strategies tailored to smallholder conditions in the region.

1.2. Objectives

The general objective of this research was to evaluate the main and/or interaction effects of rhizobia strains, lime, and starter nitrogen fertilizer on selected soil properties, yields, and yield components of Faba bean in the acidic soils of Northwestern Ethiopia.

The following specific objectives are addressed:

- To assess the effects of lime, rhizobia inoculation, and starter nitrogen fertilizer- individually and in combination - on selected soil properties.
- To investigate the main and interaction effects of rhizobia strains, lime, and starter nitrogen fertilizer on nodulation parameters of Faba bean.
- To evaluate the impact of these treatments on the yield and yield components of Faba bean.

1.3. Research Questions

In light of the issues discussed above, this study was guided by the following research questions:

- Does the main or integrated application of rhizobia strains, lime, and starter nitrogen fertilizer significantly affect the yield of Faba bean?
- Can the sole or combined application of rhizobia strains, lime, and nitrogen fertilizer improve selected soil properties?
- Do these soil amendments significantly influence the nodulation parameters of Faba bean?

2. LITERATURE REVIEW

2.1 Soil Fertility Status in Northwestern Ethiopian

Soil fertility degradation is a major constraint to sustainable agricultural production in the Ethiopian highlands, where over 80% of the population depends on subsistence farming (Yibrah *et al.*, 2024). The region is characterized by intensive cultivation, steep topography, and limited soil fertility management, all of which contribute to rapid nutrient depletion and land degradation (Hurni *et al.*, 2015). In northwestern Ethiopia, soil fertility problems are especially severe due to high rainfall, steep slopes, and intensive land use without sufficient fallow periods or replenishment of nutrients. Over time, these factors contribute to nutrient mining, reduced productivity, and ultimately, food insecurity. Nutrient depletion, particularly of nitrogen (N), phosphorus (P), and potassium (K), is widespread. Studies show that Ethiopian highlands lose an estimated 122 kg N, 13 kg P, and 82 kg K per hectare annually, mainly through soil erosion, crop uptake without replenishment, and residue removal (Stoorvogel & Smaling, 1990; Tamene Lulseged *et al.*, 2017). These losses are among the highest in Sub-Saharan Africa and threaten the long-term productivity of the soil.

Soil erosion is a major driver of fertility decline in Northwestern Ethiopia. Estimates suggest topsoil loss in the Ethiopian highlands averages 42 t ha⁻¹ year⁻¹, and in some areas, can exceed 100 t ha⁻¹ year⁻¹ (FAO, 2021). This erosion not only removes the most fertile layer of soil but also leads to the loss of critical plant nutrients and organic matter. The Blue Nile Basin, for example, loses up to 14 kg N and 6.8 kg P per hectare annually due to erosion alone (Tamene Lulseged *et al.*, 2017). Soil organic carbon (SOC), a key indicator of soil health, is also declining. Continuous cultivation and low organic matter inputs have led to losses of up to 3 t C ha⁻¹ year⁻¹, reducing the soil's capacity to retain nutrients and water, and undermining soil structure (Gebremedhin Maheteme *et al.*, 2022). Loss of SOC further accelerates the decline in soil fertility and crop yields.

Acidic soils, which are prevalent in the high rainfall highland zones, pose additional challenges. About 43% of Ethiopia's cultivated land is affected by soil acidity, limiting nutrient availability and inhibiting biological nitrogen fixation in legume crops (EthioSIS, 2016). High concentrations of exchangeable aluminum and low pH levels reduce root growth and nutrient uptake efficiency.

Furthermore, the limited use of inputs such as lime, organic amendments, and rhizobia inoculants exacerbates soil nutrient depletion. Fertilizer application rates in the highlands remain far below crop demand, and the heavy reliance on urea and DAP without soil-specific recommendations results in nutrient imbalances (Muragea *et al.*, 2000). Also, the removal of crop residues for fuel and feed leads to further nutrient mining and organic matter loss (Zenebe Gebreegziabher, 2007).

Integrated Soil Fertility Management (ISFM) has been identified as a sustainable solution to address the complex soil fertility challenges in the highlands. ISFM involves the combined use of organic amendments, inorganic fertilizers, lime, and improved germplasm, tailored to local conditions. Research has shown that ISFM can improve nutrient availability, reduce acidity, and enhance crop productivity in degraded highland soils (Vanlauwe *et al.*, 2010; Getachew Agegnehu & Amede, 2017).

2.2. Overview of Faba Bean Production and its Significance in Ethiopia

Faba bean (*Vicia faba* L.) is one of the oldest cultivated legume crops and continues to be a globally important pulse (Dhull *et al.*, 2021). Major producing countries include China, Ethiopia, Egypt, and the United Kingdom. The crop is cultivated on approximately 2.1 million hectares worldwide, contributing to an estimated annual production of 4.4 million tons (Ren *et al.*, 2019; Alharbi *et al.*, 2020). Ethiopia ranks as the second-largest global producer after China (Rahman *et al.*, 2021; Bultie *et al.*, 2019).

In Ethiopia, Faba bean is the most significant pulse crop in terms of both area coverage and total production. It occupies around 492,271 hectares and yields approximately 1.04 million tons annually, with an average productivity of 2.1 tons per hectare (CSA, 2021/22). The crop is extensively grown in Oromia, Amhara, and the Southern Nations, Nationalities, and Peoples' Region (SNNPR) (Wondafrash Mulugeta, 2019), with the Amhara region alone accounting for about 180,246 hectares of national production area (CSA, 2021/22).

Faba bean is predominantly grown in the highlands of Ethiopia, at altitudes ranging from 1,800 to 3,000 meters above sea level. At elevations below 1,800 m, the crop is prone to drought and disease, while elevations above 3,000 m can result in chilling injuries that hinder yield potential (Amare Tadesse *et al.*, 2019). Optimal growth occurs in regions

receiving 700–900 mm of annual rainfall in mid-altitude zones (*woinedega*) and 800–1,100 mm in highland zones (*dega*). In areas with insufficient rainfall, supplemental irrigation can significantly enhance productivity (Kubure *et al.*, 2016).

The crop thrives in soils dominated by Nitisols and Vertisols and is cultivated both as a mono crop and in intercropping systems with cereals and legumes such as field peas. Faba bean performs best in soils with a pH of 6.0 to 7.0, whereas yields are significantly reduced in highly acidic soils with a pH below 5.0 (Jensen *et al.*, 2010; French & White, 2005).

Faba bean is highly valued for its nutritional content, particularly its high protein concentration of approximately 33%, making it an essential source of dietary protein in low-income countries (Asnakech Tekalign *et al.*, 2016). In Ethiopia, it plays a vital role in the diets of smallholder farmers who lack access to animal-based protein (Mesfin Tadesse *et al.*, 2019). Agronomically, Faba bean contributes to soil fertility through biological nitrogen fixation via symbiosis with *Rhizobium* bacteria. This process enhances nitrogen availability in the soil, reducing the need for synthetic fertilizers and promoting environmentally sustainable agriculture (Wondafrash Mulugeta *et al.*, 2019). Its inclusion in crop rotations also helps suppress pests, diseases, and weeds, contributing to improved soil health and system sustainability (Jensen *et al.*, 2010). Additionally, the crop is often used for green manure and as part of integrated farming systems. Economically, Faba bean serves as a crucial source of income for farmers and significantly contributes to Ethiopia's foreign exchange earnings through export (Tewodros Tesfaye *et al.*, 2015; Asnakech Tekalign *et al.*, 2016).

2.3. Constraints of Faba Bean Production

Despite the favorable agro ecology and the availability of high-yielding varieties, the productivity of Faba bean in Ethiopia remains significantly below its potential. National average yields are less than 2.11 t ha⁻¹ (CSA, 2021/2022). This low productivity is largely attributed to both biotic and abiotic stresses, with abiotic constraints being especially critical.

Among these, soil-related factors such as poor fertility and widespread soil acidity particularly in high rainfall areas are major limitations to Faba bean productivity

(Getahun Mitiku *et al.*, 2019; Endalikachew Fekadu *et al.*, 2019). Soil acidity, characterized by low pH levels, is considered one of the most pressing constraints. Other contributing factors include declining soil fertility, limited use of bio-fertilizers (inoculants), and insufficient application of starter nitrogen fertilizers (Gemechu Keneni *et al.*, 2016). Across Africa, poor soil fertility is a widespread issue affecting Faba bean cultivation. It is estimated that 75% of agricultural soils are deficient in phosphorus, 65% lack sufficient nitrogen, and approximately 20% are acidic. These conditions collectively lead to deficiencies in several essential nutrients required for optimal Faba bean production (Lunze, 2012).

2.4. Bio fertilizer and its Preparations

Bio-fertilizers are substances containing living microorganisms that, when applied to seeds, plant surfaces, or soil, colonize the rhizosphere or plant interior and enhance plant growth by improving the availability of essential nutrients (Vessey, 2003). Common bio-fertilizers include *Rhizobium*, *Azotobacter*, *Azospirillum*, Phosphate-Solubilizing Microorganisms (PSMs), Arbuscular Mycorrhiza (AM), Plant Growth Promoting Rhizobacteria (PGPR), Blue Green Algae (BGA), and *Azolla* (Varma *et al.*, 1999).

Preparation of rhizobium bio-fertilizer begins with the collection of root nodules from a single host plant, ensuring that samples from different plants are not mixed to maintain environmental consistency. The nodules are preserved using desiccated silica gel and stored at 4°C to prevent decomposition and microbial contamination. Prior to isolation, nodules are washed and surface-sterilized using 70% ethanol (30 seconds) followed by 3% sodium hypochlorite (3 minutes). They are then crushed in a 15% glycerol solution, and a small volume is streaked onto yeast extract mannitol agar (YMA) medium. Remaining suspensions are stored at -30°C for further use. Isolated colonies are authenticated by verifying their ability to form nodules on a test legume host.

Once authenticated, rhizobia are cultured in a liquid medium enriched with yeast extract or baker's yeast to achieve high microbial density. Strict sterilization of all equipment and media is essential due to rhizobia's limited competitiveness with other microorganisms. To facilitate handling and ensure longevity, rhizobia are incorporated into carrier materials. For seed inoculation, fine powdered carriers (10–40 µm), particularly peat, are used. For soil application, granular carriers (0.5–1.5 mm) such as peat, perlite, or charcoal

are preferred. These carriers support microbial viability and effectiveness during application. Rhizobia inoculants are sensitive to heat and sunlight, which can drastically reduce their effectiveness. They should be stored between 4°C and 26°C in shaded or refrigerated conditions. Seeds should be inoculated just before planting, in a cool and shaded location, and sown in moist soil immediately to protect the microbial integrity.

2.4.1 Role of bio-fertilizers in pulse production

Bio-fertilizers have emerged as an important component in sustainable agriculture, particularly in legume or pulse production systems. They offer an environmentally sound and economically viable alternative to chemical fertilizers by enhancing nutrient availability and promoting plant growth through biological means. Numerous studies have demonstrated the potential of bio-fertilizers in improving soil health and increasing crop productivity. According to Emami *et al.* (2019), bio-fertilizers contribute to agricultural productivity by fixing atmospheric nitrogen, solubilizing insoluble phosphates, synthesizing plant growth-promoting substances, and improving nodulation in leguminous crops. Yield increases attributed to bio-fertilizer application have ranged from 16% to 60%, underscoring their significance in pulse cultivation.

One of the most widely used bio-fertilizers in legume systems is *Rhizobium*, a genus of aerobic bacteria that establishes a symbiotic relationship with legumes. These bacteria infect the root system and form nodules wherein they convert atmospheric nitrogen into plant-usable ammonia. This biological nitrogen fixation (BNF) is a critical process in reducing the dependency on synthetic nitrogen inputs. Wanda *et al.* (2023) reported that nitrogen fixation by *Rhizobium* in legume crops can range between 40–250 kg N ha⁻¹ year⁻¹, contributing to yield enhancements of 10–30% in pulses.

In addition to nitrogen fixation, phosphate-solubilizing microorganisms (PSMs) also play a vital role in nutrient dynamics. Genera such as *Pseudomonas*, *Bacillus*, and *Aspergillus* are known for their ability to solubilize bound phosphates through the secretion of organic acids and other bioactive compounds. These organisms not only increase the availability of phosphorus in the soil but also enhance its uptake by plants, thereby improving overall growth and yield. Idriss *et al.* (2002) emphasized the role of microbial phytase activity in mineralizing phytate, a major form of organic phosphorus in soil, further contributing to plant phosphorus nutrition.

Another critical group of microorganisms in this context is arbuscular mycorrhizal fungi (AMF), specifically vesicular-arbuscular mycorrhizae (VAM). These fungi establish obligatory symbiotic associations with plant roots, extending their hyphal network beyond the root zone and thereby improving the plant's access to phosphorus and other immobile nutrients. Smith and Smith (1990) highlighted the ability of AMF to enhance nutrient absorption and improve plant resilience.

Plant Growth Promoting Rhizobacteria (PGPR) offer both direct and indirect benefits to plants. Directly, they stimulate plant development through the production of phytohormones such as auxins, gibberellins, and cytokinins. Indirectly, they act as biocontrol agents against soil-borne pathogens by synthesizing antimicrobial compounds; including antibiotics, ammonia, and hydrogen cyanide (HCN). The latter disrupts the respiratory processes of pathogenic fungi, inhibiting their growth (Martinez-Viveros *et al.*, 2010; Verma *et al.*, 2015). PGPRs also compete for space and nutrients with harmful microbes and can trigger systemic resistance in host plants.

Abiotic stress factors such as drought, salinity, and high temperature often limit pulse productivity. Certain PGPR strains are capable of producing exopolysaccharides (EPS), which enhance soil structure and water retention. These properties help mitigate the effects of environmental stressors on plant growth. Chenu and Roberson (1996) demonstrated the role of EPS-producing bacteria in improving stress tolerance in crops, highlighting their importance in climate-resilient agriculture.

Overall, the integration of bio-fertilizers into pulse production systems presents a promising strategy for enhancing crop yield, nutrient efficiency, and environmental sustainability. The synergistic effects of nitrogen fixation, phosphate solubilization, growth promotion, and stress alleviation underscore their potential as key components of sustainable legume farming practices.

2.5. Biological Nitrogen Fixation of Faba Bean

Nitrogen (N) is a crucial element in the production of both leguminous and non-leguminous crops and has constructive impacts on growth of legumes (Tairo and Ndakidemi, 2013). There is enormous reservoir of atmospheric nitrogen (78%) in the atmosphere. Unfortunately, it is not available for organism such as green plants in a

usable for (e.g. NO_3^- , NH_4^+) (Vitousek *et al.*, 2002). Biological nitrogen fixation, especially rhizobia-legumes symbiosis, plays a significant role in the conversion of atmospheric nitrogen to ammonia and increase the available form of nitrogen. Biological nitrogen fixation (BNF) is the process in which nitrogen gas (N_2) from the atmosphere convert into ammonia (NH_3) is incorporated into the tissue of legume plants, with the help of soil microorganisms. It is estimated that over 60% of the Earth's fixed nitrogen originates from biological nitrogen fixation. Biological nitrogen fixation can supply up to 300 kg N/ha per season in grain legumes or green manures, and in exceptional cases, up to 600 kg N/ha per year in tree legumes (Bohlool *et al.*, 1995). On a global scale, nodulated legumes (including pulses and oilseed legumes) contribute approximately 21.45 Tg (teragrams) of nitrogen annually to agricultural systems (Herridge *et al.*, 2008).

Symbiotic nitrogen fixation involving *Rhizobium* species and legumes represents a renewable and sustainable source of nitrogen for agriculture (Bohlool *et al.*, 1995). The success of pulse production depends on biological nitrogen fixation (BNF) attributes of rhizobium, and efficient nitrogen fixation occurs with development of root nodules which are induced by bacterial symbiont with host plant in a specific manner (Wanda *et al.*, 2023). Faba bean has a high nitrogen demand, and biological nitrogen fixation (BNF) plays a vital role in meeting this need. Among pulse crops, Faba bean is recognized for its high nitrogen fixation capacity, fulfilling up to 80% of its nitrogen requirement through this process. Globally, nitrogen fixation in Faba bean has been estimated to range between 45 and 300 kg N/ha (Smil, 1999). In Northwestern Ethiopia, Faba bean has been reported to fix approximately 69 kg N/ha annually due to its symbiotic relationship with rhizobium. Microorganism-mediated nitrogen fixation is a major source of nitrogen in the soil, contributing up to 75% of total nitrogen content (Subba Rao, 2001). Biological nitrogen fixation is important for smallholder farmers, as it provides a cost-effective alternative to synthetic nitrogen fertilizers and is less prone to losses via leaching and denitrification (Mhango *et al.*, 2017). Rhizobium-legume symbiosis, in particular, offers a promising strategy for improving soil fertility, reducing chemical fertilizer use, lowering production costs, and minimizing environmental pollution (Sameh, 2017).

2.6. Soil Acidity and Its Causes

Soil acidity refers to the dominance of hydrogen (H^+) and aluminum (Al^{3+}) ions relative to hydroxide (OH^-) and basic cations in the soil solution. More specifically, it is defined as a

soil condition in which the pH of the soil solution is less than 7, and in most practical contexts, soils with pH values below 6.6 are considered acidic (Brady, 2002).

In Ethiopia, soil acidity is a growing concern both in scope and severity, although it varies geographically. It has become a major constraint to agricultural productivity, particularly in highland regions dominated by Nitisols (Abdenna *et al.*, 2007; Gete Zelleke *et al.*, 2010). It is a serious threat to crop production in Ethiopia that strong soil acidity affects 28% of the entire country and 43% of the agricultural land mostly in the highlands of Oromiya, Amhara and Southern Nation Nationalities and Peoples region (Tegbaru Belay, 2015). Strongly acidic soils are typically found in regions with high rainfall and warm temperatures throughout the year, such as western and southwestern Ethiopia, parts of the central highlands, and northwestern areas. These soils are often associated with Oxisols, Nitisols, and Ferralsols. Moderately acidic soils (pH 5.5–6.5) are more widely distributed across the country (Lulseged Tamene *et al.*, 2017).

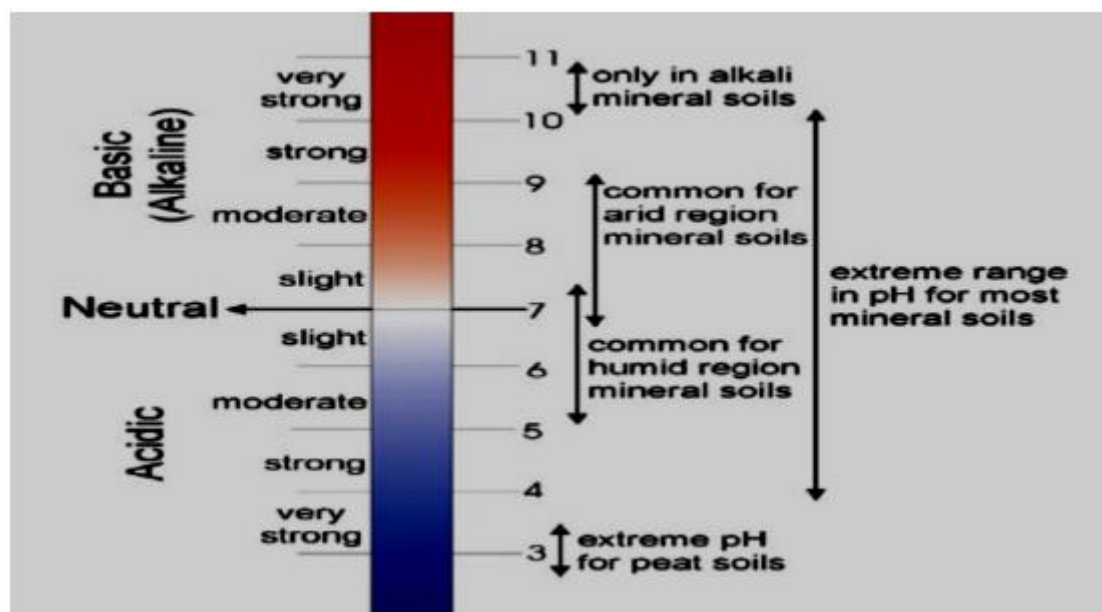


Figure 2.1. General soil pH ranges and reaction classes of soils

Source: Brady, 2002

High rainfall is a major factor contributing to soil acidification through the leaching of essential base-forming cations such as calcium (Ca), magnesium (Mg), sodium (Na), and potassium (K). These elements are displaced from the soil profile as water percolates downward, resulting in a net increase in soil acidity (Brady & Weil, 2016). The process is particularly significant in regions where annual precipitation exceeds evapotranspiration,

creating conditions favorable for leaching. In such environments, base cations on soil colloids are gradually replaced by hydrogen (H^+) ions, leading to a progressive decline in soil pH (Slattery & Hollier, 2002). Although the acidifying effect of rainfall occurs slowly over time, it can lead to profound soil acidification over long periods, with notable impacts observed over centuries (Jackson, 1967).

The mineral composition of parent rock influences the rate and extent of soil acidification. Acidic parent materials such as granite and rhyolite contribute to the formation of acidic soils, whereas basalt and limestone tend to neutralize acidity. Soils derived from quartz-rich rocks tend to be more acidic due to their low content of base-forming elements (Jackson, 1967). While organic matter improves soil structure, its decomposition releases hydrogen ions (H^+) into the soil. Carbon dioxide (CO_2) produced from decaying matter reacts with water to form weak carbonic acid, further lowering the soil pH (Kochian *et al.*, 2004; Slattery & Hollier, 2002). Organic acids produced during decomposition can also displace base cations, enhancing acidity. High-yielding crops absorb large amounts of essential base nutrients such as Ca, Mg, and K. When crop residues are removed from the field, the soil loses these basic cations, increasing its acidity (Upjohn *et al.*, 2005; Fageria & Baligar, 2008).

Nitrogenous fertilizers like urea contribute to soil acidity during the nitrification process. Ammonium (NH_4^+) is converted into nitrate (NO_3^-), releasing H^+ ions that lower soil pH (Bolan *et al.*, 1991; Fageria & Baligar, 2008). The chemical reaction is as follows:



The acidifying effect is compounded when nitrates leach out of the root zone, carrying away base cations like Ca^{2+} and Mg^{2+} . Long-term and frequent use of ammonium-based fertilizers, especially in systems with low organic matter input, can significantly increase soil acidity (Harter, 2007; Cai *et al.*, 2015).

2.6.1 Management of soil acidity

In order to feed the increasing population from existing natural resources, significant advances are required in the field of agricultural production. Increasing agricultural productivity from the existing arable land in an environmentally friendly manner; however, it's a big challenge for the global agricultural system (Robertson and Swinton,

2005). To improve production and productivity of crops in soil acidity problem areas, different strategies need to be implemented: appropriate soil management practices such as liming, use of soil acidity tolerant genotypes (fitting genotypes to environments) for sustainable production, returning crop residues to the soil and using organic fertilizers such as farmyard manure (FYM), compost (Getachew Agegnehu & Tilahun Amede, 2017; Lal, 2009; Kochian *et al.*, 2004, Ma *et al.*, 2001)

2.6.2 Managing soil acidity with lime

Liming is the most effective and widely practiced method for managing soil acidity. It involves applying calcium- and magnesium-rich materials, typically in the form of carbonates (CaCO_3 and MgCO_3) to neutralize excess acidity in soils (Edmeades *et al.*, 2003). Liming raises soil pH, increases base saturation, and improves the availability of Ca and Mg (Kisinyo *et al.*, 2012). Additionally, it reduces the fixation of P and Mo by inactivating reactive Al and Fe compounds. Liming also promotes root growth, particularly by enhancing the length and density of root hairs, thus improving P uptake efficiency (Bolan *et al.*, 2003). Liming acidic soils improves crop yields by elevating pH levels (Temesgen Desalegn *et al.*, 2016), enhancing nutrient availability (Geremew Taye *et al.*, 2020), reducing toxic soluble aluminum (Álvarez *et al.*, 2009), and stimulating beneficial microbial activity (Fageria & Baligar, 2008).

When lime such as CaCO_3 is applied to moist soil, the following reactions take place:

1. Lime dissolves slowly in moisture, releasing Ca^{2+} and OH^- ions.
2. Ca^{2+} replaces Al^{3+} and H^+ on soil colloids.
3. OH^- neutralizes Al^{3+} (forming $\text{Al}(\text{OH})_3$) and H^+ (forming H_2O).

These reactions eliminate toxic Al^{3+} and H^+ from the soil and result in an increase in soil pH—the most visible effect of liming. Furthermore, liming supplies calcium and, in the case of dolomite, magnesium, which are both vital plant nutrients (Hue, 2008).

The most commonly used liming agents include carbonates, oxides, and hydroxides of calcium (Ca) and/or magnesium (Mg) (Mullins *et al.*, 2009). Among these, calcium carbonate is the most widely used and cost-effective material for correcting soil acidity. Quicklime, or burnt lime, is produced by heating limestone to release carbon dioxide; while it is more reactive, it is caustic and unpleasant to handle, making it rarely used in

agriculture. Hydrated lime, created by adding water to lime, is mainly used in construction rather than farming due to its higher cost. Dolomitic limestone, composed of calcium and magnesium carbonates, is particularly suitable for soils deficient in both Ca and Mg.

The effectiveness of a liming material depends on several factors, including its neutralizing value (purity), particle size (fineness), calcium and magnesium content, and overall reactivity (Foth & Ellis, 1996; Snyder & Leep, 2007). The neutralizing value indicates the material's capacity to counteract soil acidity, with pure calcium carbonate rated at 100%. Materials such as calcium oxide or calcium hydroxide can exceed this value (Andrew *et al.*, 2018). Fineness is another critical factor. Finer particles provide greater surface area and react more quickly with the soil. Ideally, more than 60% of the lime should pass through a 0.3 mm sieve to ensure rapid effectiveness (Conyers *et al.*, 1995; Taye Belachew *et al.*, 2008).

2.7. Effects of Lime on Soil pH and Legume Growth

Application of lime at an appropriate rate brings several chemical and biological changes in the soils, which are beneficial or helpful in improving crop yields on acid soils (Fageria and Baligar, 2008). Plant growth improvement in acid soils is not due to addition of basic cations (Ca, Mg), but because of increasing pH reduces toxicity of phytotoxic levels of Al (Crawford *et al.*, 2008 and Awkes, 2009). Liming raises soil pH, base saturation, and Ca and Mg contents, and reduces aluminum concentration in acidic soils (Fageria and Stone, 2004). The acidic soils are naturally deficient in total and plant available phosphorus. This is because significant portions of applied P are immobilized due to precipitation of P as insoluble Al phosphate or chemisorption to Al oxide and clay minerals (Nurlaeny *et al.*, 1996). The liming of acidic soils results in the release of P for plant uptake; this effect is often referred to as “P spring effect” of lime (Bolan, 2003).

Soil microbiological properties can serve as soil quality indicators. Soil acidity restricts the activities of beneficial microorganisms, except fungi, which grow well over a wide range of soil pH (Brady and Weil, 2002). Liming acidic soils enhance the activities of beneficial microbes in the rhizosphere and hence improve root growth by the fixation of atmospheric nitrogen because neutral pH allows more optimal conditions for free-living N fixation (Stephen *et al.*, 2011). Soil properties such as organic matter content, clay type,

redox potential, and soil pH are considered the major factors that determine the bioavailability of heavy metals in soil (Treder and Cieslinski, 2005). Hence, liming certainly helps in reducing availability of heavy metals to crop plants.

Soil acidity is also responsible for low nutrient use efficiency by crop plants. Liming acid soil make the soil environment better for leguminous plants and associated microorganisms as well as increase concentration of essential nutrients by raising its pH and precipitating exchangeable aluminum (Kisinyo *et al.*, 2012). Most legumes prefer pH > 5.0 at least in a depth of 20cm and layers below 5cm adversely affect root growth, nodulation, plant vigour and N-fixation potential of acid-sensitive pulses (Burns *et al.*, 2017). Different researchers reported about reclamation of acidic soil by lime application is an effective and dominant practice through raising soil pH and reducing acidity-related constraints to improve crop yields (Achal Chimeri *et al.*, 2012; Osundwa *et al.*, 2013; Asmare Melese, 2014).

2.8. Nitrogen and its Role in Legume Growth

Nitrogen (N) is a crucial element in the production of both leguminous and non-leguminous crops and has constructive impacts on growth of legumes (Tairo and Ndakidemi, 2013). It is part of the enzymes associated with chlorophyll synthesis which reflect relative crop N status present in plants. It is also a major part of the chlorophyll molecules and plays a necessary role in photosynthesis and also is a major component of several vitamins (Sara *et al.*, 2013). Legume crops require little or no nitrogen fertilizer. However symbiotically fixed N₂ is inadequate for realizing maximum seed yield, and that an application of small amounts of “starter” fertilizer N is needed to establish seedlings and promote early dinitrogen fixation (Sogut *et al.*, 2013). Although legumes have the capacity to fix atmospheric nitrogen through biological nitrogen fixation (BNF), they also utilize nitrogen in mineral forms such as nitrate (NO₃⁻) and ammonium (NH₄⁺). In legume agriculture, this mineral nitrogen may originate from fertilizer applications (Liu *et al.*, 2018).

Mostly N₂-fixation by legumes began 14 days after planting, thus a small amount of nitrogen fertilizer at planting might be beneficial to early vegetative growth. Starter nitrogen fertilizer can supply nitrogen until biological N₂-fixation begins by the root nodule (Touchton, Rickerl, 1986). Starter nitrogen in the starter may also help plants

overcome early season N deficiency due to the slow release of nitrogen from organic matter during cold, springtime conditions. Also, it has been shown that some N in the ammonium form common in starter fertilizers will enhance P uptake from the starter and from the soil.

2.9. Integrated Soil Fertility Management (ISFM)

Integrated Soil Fertility Management (ISFM) is a systems-based strategy that integrates organic and inorganic nutrient sources with improved crop and soil management practices to enhance nutrient use efficiency, soil fertility, and crop productivity (Vanlauwe *et al.*, 2010). In Ethiopia, where soil acidity, nutrient depletion, and low organic matter are widespread ISFM offers a practical framework for improving smallholder agricultural systems. It is particularly relevant in managing the highly weathered and acidic soils of the Northwestern highlands, where conventional input use alone often fails to restore soil productivity. Lime (calcium carbonate or dolomitic lime) is central to acid soil management within ISFM. Liming neutralizes exchangeable acidity, raises pH, reduces toxic aluminum (Al^{3+}) and manganese (Mn^{2+}), and improves phosphorus (P) availability. In acidic soils ($\text{pH} < 5.5$), aluminum toxicity is a key barrier to root elongation and nutrient uptake, particularly for legumes like Faba bean that rely on extensive root systems and biological nitrogen fixation (BNF) (Fageria *et al.*, 2019). By correcting soil pH, lime enhances rhizobia survival and effectiveness, enabling more efficient symbiotic nitrogen fixation (Du *et al.*, 2024).

Organic inputs such as compost, farmyard manures (FYM), crop residues, and biochar play a dual role in ISFM: improving soil structure and nutrient dynamics while also contributing to acid soil remediation. Lal (2009) estimates that incorporating 1 metric ton of crop residues can return 20–60 kg of macro- and micronutrients to the soil. These amendments increase soil organic carbon (SOC), enhance microbial activity, and improve aggregate stability and water retention. In acidic soils, organic matter contributes to aluminum detoxification in two ways: (1) by increasing pH through decomposition and the release of basic cations (Ca^{2+} , Mg^{2+} , K^{+}), and (2) by forming stable organo-Al complexes that render toxic aluminum non-reactive (Getachew Agegnehu & Amede, 2017). FYM and compost also release organic acids during decomposition, which can chelate Al and Fe, thereby reducing P fixation and enhancing phosphorus use efficiency.

In low-fertility acid soils, even legumes benefit from modest starter N to support early growth before effective nodulation occurs. Starter N has been shown to enhance root biomass and early canopy development, facilitating better photosynthesis and carbon allocation for nodulation (Almaz Gezahagn *et al.*, 2020). However, high N rates can suppress nodulation, underscoring the need for balance.

Effective rhizobia inoculation is another ISFM component especially vital for legumes. In acidic soils, native rhizobia populations are often ineffective or absent. Inoculation with acid-tolerant strains, combined with lime and organic matter, has been shown to enhance nodulation, BNF, and yield in Faba bean (Endalikachew Wolde-Meskel *et al.*, 2018; Wuletaw Tadesse *et al.*, 2022). However, few studies have simultaneously evaluated the synergistic effects of these three inputs lime, inoculants, and starter N under real field conditions in Northwestern Ethiopia.

3. MATERIALS AND METHODS

3.1 Description of the Study Area

The experiment was conducted during the 2022/2023 cropping season in Injebara and Koga, Amhara National Regional State (ANRS), Northwest Ethiopia. Both locations are prominent Faba bean production areas within the region.

Banja is located approximately 122 kilometers Southwest of Bahir Dar and about 465 kilometers Northwest of Addis Ababa. It lies between $10^{\circ}57'17''$ and $11^{\circ}03'05''$ N latitude and between $36^{\circ}39'09''$ and $36^{\circ}48'25''$ E longitude, with altitude ranging from 1,700 to 3,000 meters above sea level. North Mecha is situated about 38 kilometers Southwest of Bahir Dar and approximately 525 kilometers northwest of Addis Ababa. It is geographically positioned between $11^{\circ}23'39''$ and $11^{\circ}26'02''$ N latitude and between $37^{\circ}08'49''$ and $37^{\circ}10'29''$ E longitude, with an average altitude of 1,953 meters above sea level.

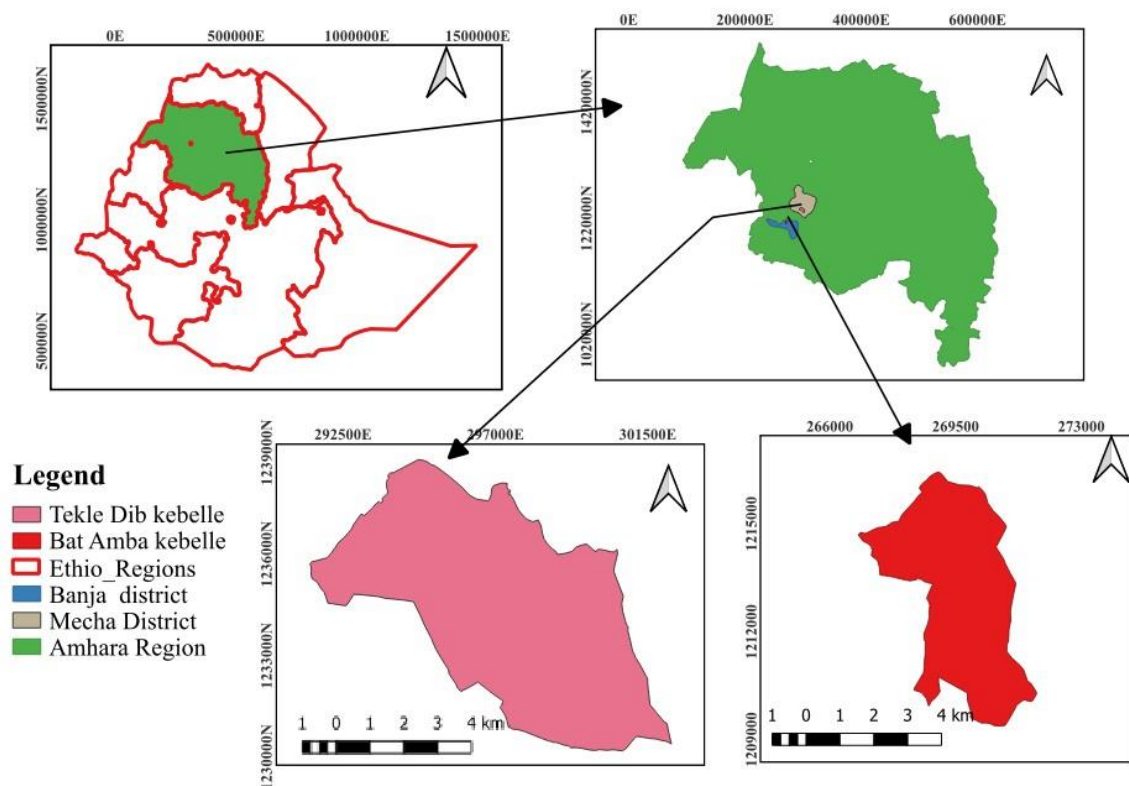


Fig3.1. Map showing the study sites

3.1.1 Climate and agro ecology

According to a land use survey (Awi Zone, 2017), the agro ecology of Banja district is primarily classified as Dega (high altitude, 80%) and Woyena-Dega (mid-altitude, 20%). In contrast, North Mecha encompasses a mix of Dega, Weyna-Dega, and Kolla agro ecological zones. The two study sites receive an annual average rainfall of approximately 1,603.3 mm, with elevations ranging from 1,972 to 2,161 meters above sea level (MWAO, 2019).

The main rainy season in both districts spans from mid-May to mid-September, with peak rainfall occurring between June and August (see Figure 3.2). In 2022, the recorded monthly minimum and maximum temperatures in Banja were 9.4°C and 26°C, respectively. For North Mecha, the mean monthly minimum and maximum temperatures during the same year were 10.8°C and 27.9°C, respectively (Figure 3.2).

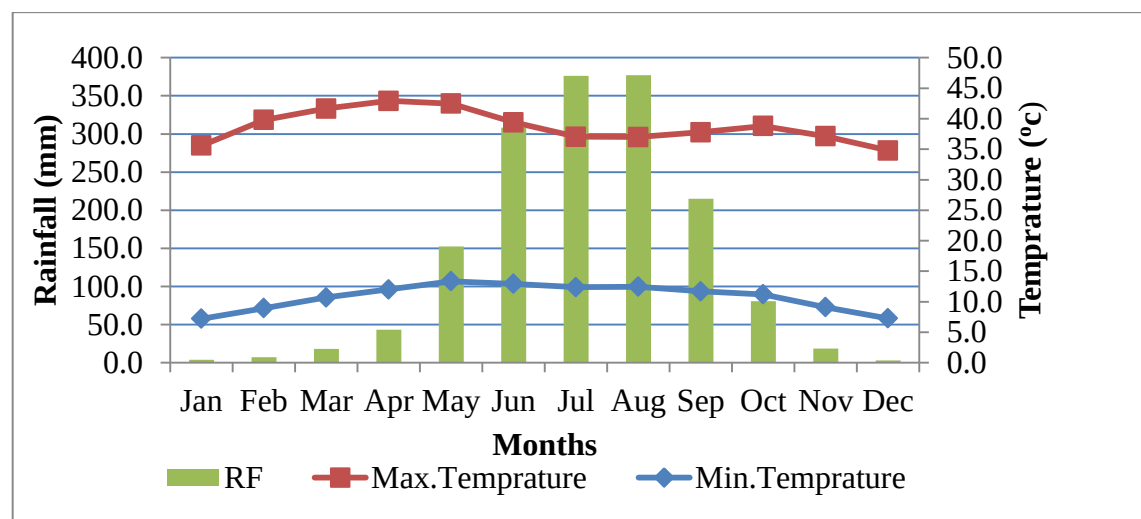


Fig 3.1. Mean monthly rainfall (RF), mean monthly maximum and minimum temperatures of the study areas from 2019-2022

(Source: National Metrological Agency, Bahir Dar Branch).

3.1.2 Geology, soils and topography

The geology of the study area in both Banja and North Mecha districts, as in much of the Amhara region, is primarily derived from basaltic parent materials. These formations resulted from structural processes such as faulting and uplifting during the Tertiary period and were subsequently modified by external processes including recent volcanic activity, denudation, and sedimentation during the Quaternary period (FAO, 1998).

The topography of Banja district is characterized by a mix of terrain, with approximately 45% of the land being level and the remaining 55% consisting of hilly or mountainous areas. In contrast, North Mecha is primarily composed of gently sloping terrain (0–5%) and is predominantly flat, with 70% of the land categorized as level. The district also includes 13% undulated terrain, 8% mountainous areas, and 4% valley landscapes.

In terms of soil types, Banja district is dominated by highly weathered and leached Acrisols, which exhibit red to brown coloration and strong acidity (pH 4.81), along with high levels of exchangeable acidity (Yihenew Gebresilassie, 2002). Acrisols, as defined by the IUSS Working Group WRB (2022), are clay-rich soils typically associated with humid tropical climates. In the USDA Soil Taxonomy, they correspond to the Humult, Udult, and Ustult suborders of Ultisols, and in some cases, to Oxisols with a kandic horizon or to certain Alfisols (Soil Survey Staff, 2014). Due to their low fertility and high aluminum toxicity, Acrisols present limitations for agriculture and are often better suited for forestry, low-intensity grazing, or conservation purposes (Chesworth & Ward, 2001).

The dominant soil type in North Mecha district is Nitisols, which are deep, well-drained, and clay-rich tropical soils with favorable physical properties (FAO, 2001). The subsoil (B horizon) of these profiles exhibits Cambic features and a dominance of clay content, indicative of intense weathering. The structure is typically weakly developed with a medium sub-angular blocky form. There is a noticeable increase in clay content from the surface horizon to the subsoil, attributed to clay illuviation and the deposition associated with gentle slope gradients. These properties qualify the soil as Cambisols. Due to base saturation levels below 50%, the soils are further classified as dystic Cambic-Nitisols (Mulunesh Addis, 2021), and the pH levels indicate strong acidity (Asmamaw Desale *et al.*, 2021).

3.1.3 Farming system

Agricultural activities in North Mecha district include both rain-fed and irrigated farming systems. The Koga dam serves as a major water source for irrigation practices. During the main cropping season, farmers grow field crops such as maize (*Zea mays*), finger millet (*Eleusine coracana*), bread wheat (*Triticum aestivum*), and teff (*Eragrostis tef*). In the irrigation season, commonly cultivated crops include bread wheat, potato (*Solanum*

tuberosum), onion (*Allium cepa*), tomato (*Solanum lycopersicum*), and cabbage (*Brassica oleracea*) (Melkamu Alemayehu *et al.*, 2018).

In the Banja district, rain-fed agriculture predominates, supplemented by small-scale irrigation. Major field crops include wheat, maize, teff, faba bean (*Vicia faba*), and barley (*Hordeum vulgare*). Horticultural crops such as onion, tomato, potato, cabbage, and pepper (*Capsicum* spp.) are also grown under irrigated conditions.

Both districts follow a mixed farming system that integrates crop production with livestock rearing. This system is largely subsistence-based and relies heavily on rainfall. Productivity has been declining in recent years due to constraints such as declining soil fertility, land scarcity, and crop damage from pests and diseases. Agricultural operations including ploughing, harvesting, and threshing are mainly carried out using human and animal labor.

3.2 Experimental Materials

The Faba bean (*Vicia faba* L.) variety ‘Welki’ was used as the test crop in this experiment. This variety was released by the Holeta Agricultural Research Center in 2008 and is recognized for its high yield potential. It is recommended for cultivation at altitudes ranging from 1,900 to 2,800 meters above sea level and requires annual rainfall between 700 and 1,000 mm. Carrier-based *Rhizobium* inoculants were used for seed-inoculated treatments. The indigenous isolates FB-37 and FB-1035 were obtained from Holeta Agricultural Research Center. These isolates were originally sourced from Faba bean rhizospheres in Ethiopia and selected based on their symbiotic efficiency and compatibility with local agro ecological conditions. The strains are prepared by the Soil Microbiology Laboratory at Holeta Agricultural Research Center. These strains were applied at a rate of 500 g/ha.

Agricultural lime (CaCO_3) was supplied by the Banja District Agricultural Office and was applied only in lime-treated plots. Lime was applied as calcium carbonate (CaCO_3) at a rate of 2 t/ha, as recommended by the Adet Agricultural Research Center for legume production in acidic soils of the study areas. Nitrogen fertilizer in the form of urea [$\text{CO}(\text{NH}_2)_2$] was used exclusively in nitrogen-treated plots. Starter nitrogen fertilizer was applied in the form of urea (46–0–0) at three different rates: 0, 10, and 20 kg N/ha.

Phosphorus was supplied to all treatments using triple superphosphate (TSP) [$\text{Ca}(\text{H}_2\text{PO}_4)_2$]. Triple superphosphate (TSP) was used as a phosphorus source at a uniform rate of 46 kg P_2O_5 /ha across all plots. The Faba bean variety ‘Welki’ was used as the test crop and sown at the recommended seed rate of 150 kg/ha.

3.3 Experimental Treatments, Design and Methods

The experiment followed a factorial treatment structure with three factors:

- Rhizobium inoculation: No inoculant, FB-37, and FB-1035
- Starter nitrogen rate: 0, 10, and 20 kg N/ha
- Lime rate: 0 and 2 t/ha

These treatment combinations were arranged in a randomized complete block design (RCBD) with three replications. Each plot measured 8.4 m² (2.8 m × 3 m), with 1 m spacing between replications and 0.5 m between plots. Within plots, rows and plants were spaced at 0.4 m and 0.1 m, respectively. Ridges were constructed between plots to minimize nutrient leaching and the movement of *Rhizobium* strains across plots.

The experimental field was prepared using conventional farmer practices. Lime was uniformly broadcast by hand and incorporated into the soil two months prior to planting in lime-treated plots. *Rhizobium* inoculants were applied at 500 g/ha. To improve adherence, the inoculants were mixed with sugar and water to form a thick slurry, which was then coated onto the Faba bean seeds. Inoculation was conducted in the shade to protect microbial viability, and the treated seeds were air-dried for 30 minutes. To prevent cross-contamination, non-inoculated seeds were sown first. Urea and TSP were applied in rows at planting, alongside the Faba bean seeds. Seeds were immediately covered with soil after sowing to prevent cell death due to sun exposure.

3.4 Treatment Combination and Field Layout

Two Faba bean rhizobia strains were combined with two rates of lime and three rates of nitrogen fertilizer and hence there were 18 treatments in each replication.

Table 3.1. Treatment combination and their description

Treatment	Treatment combination	Description
T1	$R_0 + L_0 + N_0$	Without any input application(control)
T2	$R_0 + L_0 + N_1$	10 kg/ha Starter nitrogen
T3	$R_0 + L_0 + N_2$	20 kg/ha Starter nitrogen
T4	$R_0 + L_1 + N_0$	2 t/ha lime
T5	$R_0 + L_1 + N_1$	2 t/ha lime + 10 kg/ha Starter nitrogen
T6	$R_0 + L_1 + N_2$	2 t/ha lime + 20 kg/ha Starter nitrogen
T7	$R_1 + L_0 + N_0$	Rhizobia strain FB-37
T8	$R_1 + L_0 + N_1$	Rhizobia strain FB-37 + 10kg/ha Starter nitrogen
T9	$R_1 + L_0 + N_2$	Rhizobia strain FB-37 + 20kg/ha Starter nitrogen
T10	$R_1 + L_1 + N_0$	Rhizobia strain FB-37 + 2t/ha lime
T11	$R_1 + L_1 + N_1$	Rhizobia strain FB-37+2 t/ha lime+10kg/ha starter nitrogen
T12	$R_1 + L_1 + N_2$	Rhizobia strain FB-37+2 t/ha lime+20 kg /ha starter nitrogen
T13	$R_2 + L_0 + N_0$	Rhizobia strain FB-1035
T14	$R_2 + L_0 + N_1$	Rhizobia strain FB-1035 + 10kg/ha starter nitrogen
T15	$R_2 + L_0 + N_2$	Rhizobia strain FB-1035 + 20 kg /ha starter nitrogen
T16	$R_2 + L_1 + N_0$	Rhizobia strain FB-1035 + 2t/ha of lime
T17	$R_2 + L_1 + N_1$	Rhizobia strainFB-1035+2t/ha lime+10kg/ha starter nitrogen
T18	$R_2 + L_1 + N_2$	Rhizobia strain FB-1035+2t/halime+20kg/ha starter nitrogen



Fig3.3. Field performance of Faba bean at Koga

3.5 Data Collected

3.5.1 Soil physico-chemical properties

Prior to treatment application, surface soil samples at a depth of 0–20 cm were randomly collected using a soil auger from five representative points within each experimental plot at both sites to ensure a composite and representative sample. In addition, a representative undisturbed core soil sample was collected at each site using a core sampler to determine soil bulk density.

Similarly, composite soil samples were collected after harvest from each treatment plot (0–20 cm depth) to evaluate treatment effects on bulk density, soil pH, available phosphorus, organic carbon, exchangeable acidity, and exchangeable aluminum (Al^{3+}). For bulk density determination, undisturbed core samples were taken using a sharp-edged steel cylinder manually driven into the soil.

All soil samples were transported to the Soil and Plant Laboratory of Assosa agricultural research for analysis. Samples were air-dried, ground with a mortar and pestle, and passed through a 2 mm sieve for the determination of soil texture, bulk density, pH, exchangeable acidity, exchangeable Al, and available phosphorus. For organic carbon analysis, samples were further sieved through a 0.5 mm mesh.

Soil texture was determined using the Bouyoucos hydrometer method (Bouyoucos, 1951). The proportions of sand, silt, and clay were used to classify soil texture based on the USDA textural triangle. Bulk density was determined using the core sampling method, with soil samples oven-dried at 105°C for 24 hours (Blake & Hartge, 1986). Soil pH was measured potentiometrically in a 1:2.5 soil-to-water suspension using a digital pH meter (Van Reeuwijk, 2002).

Organic carbon was analyzed following the Walkley-Black rapid dichromate oxidation method (Walkley & Black, 1934). Available phosphorus was extracted using the sodium bicarbonate (NaHCO_3) method as outlined by Olsen et al. (1954). Exchangeable acidity was determined by saturating the soil with 1M KCl solution and titrating with 0.02M NaOH (Rowell, 1994). Exchangeable aluminum was quantified using 1M KCl and NaF extracts followed by titration with 0.02M HCl.

3.5.2 Agronomic data collection

Agronomic data, including phenological, growth, nodulation, and yield-related parameters, were collected throughout the growing season. Days to 90% flowering were recorded by observing each plot daily and noting the number of days from sowing until 90% of the plants exhibited visible flowering. Similarly, days to maturity were determined by counting the days from sowing to the date when 90% of the plants in a plot reached physiological maturity. Plant height was measured in centimeters from the soil surface to the apex of the shoot on ten randomly selected and tagged plants within each

plot, and the average height was calculated. The number of pods per plant was determined by counting all pods on the same ten randomly selected plants, and the mean was taken. The number of seeds per pod was recorded by counting the seeds from each pod of the selected plants, and the average was used for analysis. The number of grains per plant was then estimated by multiplying the average number of pods per plant by the average number of seeds per pod. Above-ground dry biomass yield was measured by harvesting all plants from the net plot area (excluding border rows), sun-drying them, and weighing the biomass, which was then converted to kilograms per hectare. Grain yield was recorded after threshing and cleaning the harvested grains from each plot and was similarly converted to yield per hectare. Straw yield was calculated as the difference between total biomass yield and grain yield. Finally, harvest index was computed as the ratio of grain yield to total above-ground biomass yield, expressed as a percentage.

$$\text{Harvest index (\%)} = \frac{\text{Grain yield} \times 100}{\text{Biomass yield}}$$

3.5.3 Nodulation data

Nodulation data were collected by excavating the roots of five randomly selected plants from the border rows of each plot during the mid-flowering stage of Faba bean. Destructive sampling was performed by carefully digging around the roots using a hoe and a spade to a depth of approximately 20 cm, the typical rooting depth of Faba bean. The radius of excavation extended about 12 cm outward from the central stem to ensure the entire root system was collected. The excavated roots were gently washed using a washing bottle to remove adhering soil. Nodules from both the crown region and lateral roots were detached and collected in labeled plastic bags for counting and analysis.

The total number of nodules per plant was determined by counting all nodules formed on both the crown and lateral roots. To assess the number of effective nodules, each nodule was sliced and examined visually; those exhibiting a pink interior were considered effective, indicating active nitrogen fixation. The number of effective nodules per plant was averaged for the five plants in each plot. The number of non-effective nodules was calculated by subtracting the effective nodule count from the total nodule number. For nodule dry weight determination, all nodules from the five sampled plants were collected, oven-dried at 70°C for 48 hours to a constant weight, and then weighed. The average dry

weight was expressed in milligrams per plant (Yoseph Tarekegn & Serawit Shanko, 2017).

3.6 Economic Analysis

Economic feasibility was evaluated using the partial budget analysis method described by the International Maize and Wheat Improvement Center (CIMMYT, 1988). Input costs (e.g., nitrogen fertilizer, lime, and rhizobium inoculants) were valued using local market prices in Ethiopian Birr (ETB) per kilogram. Fixed and common management costs were assumed to be equal across all treatments and thus were excluded from the analysis. To reflect real farming conditions, the average grain yield was reduced by 10% to account for the difference between experimental results and expected farm yields.

Adjusted grain yield (AjGY): Was the average yield adjusted downward by a 10% to reflect the difference between the experimental yield and yield of farmers.

$$\text{AjGY} = \text{GY} - (\text{GY} \times 0.1)$$

Adjusted straw yield (AjSY): Was the average straw yield adjusted downward by a 10% to reflect the difference between the experimental yield and yield of farmers.

$$\text{AjSY} = \text{SY} - (\text{SY} \times 0.1)$$

Gross field benefit (GFB): Computed by adding price of grain and straw yield from each treatment that farmers receive for the crop when they sell it as adjusted grain and straw yield.

$$\text{GFB} = \text{AjGY} + \text{AjSY}$$

Total variable cost (TVC): The prices of lime, starter N fertilizer and rhizobia strains were determined through market survey in the growing season.

Net benefit (NB): was calculated by subtracting the total costs from gross field benefits for each treatment.

$$\text{NB} = \text{GFB} - \text{TVC}$$

Marginal rate return (MRR): It measures of increasing in return by increasing input. The marginal rate of return (MRR) was calculated by dividing the net benefit by the total variable cost.

$$\text{MRR (\%)} = \frac{\text{Change NFB (NFBb - NFBa)}}{\text{Change TVC (TVCb - TVCa)}}$$

Where NFBa = NFB with the immediate lower TVC, NFBb = NFB with the next higher TVC, TVCa = the immediate lower TVC, TVCb = the next highest TVC and Change in NFB and TVC also referred to marginal benefits and costs, respectively. For a treatment to be considered economically feasible, an MRR of at least 100% is required. When multiple treatments met this threshold, the one with the highest net income was identified as the most profitable.

3.7 Statistical Analysis

All collected data were subjected to analysis of variance (ANOVA) using SAS version 9.4 (SAS Institute, 2014). Before performing ANOVA, data from each location were assessed for homogeneity of variance using Levene's test and for normality using the Shapiro-Wilk test, to ensure the assumptions of ANOVA were met. When the ANOVA results indicated significant differences among treatments, Duncan's Multiple Range Test (DMRT) was used for mean separation at the 5% probability level. Additionally, correlation analyses were performed to assess relationships among soil properties, yield, and yield components.

4. RESULT AND DISCUSSION

4.1. Soil Physico-chemical Properties of the Experimental Plots

Based on the pre-planting soil analysis, the soil texture at the Koga site was classified as clay, containing 52% clay, 12% silt, and 36% sand. In contrast, the Injebara site had a clay loam texture with 28% clay, 32% silt, and 40% sand, as determined using the USDA soil textural triangle (Hengl *et al.*, 2021) (Table 4.1). The variation in soil texture between the two sites is attributed to differences in parent material composition, topography, in-situ weathering, and clay translocation through eluviation processes (Geetha & Naidu, 2013). Over time, pedogenic processes such as erosion, deposition, and weathering modify the texture of soil horizons (Brady & Weil, 2002). Since soil texture is an inherent property, it is less influenced by management but plays a significant role in nutrient availability, organic matter content, water retention, and air circulation.

The bulk density of the soil was found to be 1.31 g/cm³ at Koga and 1.23 g/cm³ at Injebara (Table 4.1). According to the classification by Blake and Hartge (1986), the bulk density at Koga exceeds the ideal range for clay soils, indicating potential compaction and reduced suitability for optimal plant growth. Soil aeration and organic matter additions can help alleviate compaction. The soil pH values were 4.78 and 5.44 for Koga and Injebara, respectively. This indicates that the Koga site was acidic, while the Injebara site was slightly acidic according to the soil pH rating scale by Landon (2014). Such acidic conditions especially at Koga can limit nutrient availability and microbial activity and lime may be needed, particularly in legume cultivation where nodulation and nitrogen fixation are sensitive to low pH.

In terms of organic carbon content, the values were 1.41% at Koga and 3.94% at Injebara (Table 4.1). Based on the classification by (Hazleton & Murphy, 2023), the organic carbon level in Koga falls in the moderate range, while Injebara's value is considered high. The organic carbon at Koga was sufficient for most crops, but adding organic amendments can still improve soil properties. The higher organic carbon at Injebara indicates better soil structure, water-holding capacity, and biological activity, all of which are favorable for sustainable crop production. The total available phosphorus (P) content in the experimental plots was 7.06 mg/kg at Koga and 30.92 mg/kg at Injebara (Table 4.1). According to Olsen method; FAO land suitability frameworks (FAO, 2021),

available phosphorus levels in soil are classified as very low (<5 mg/kg), low (5–10 mg/kg), and medium (10 – 20 mg/kg), high (20 – 40 mg/kg) and very high (> 40 mg/kg). Based on this classification, the soil at Koga exhibited a lower level of available P, while the soil at Injebara had a high P content. Given the lower phosphorus status at Koga, liming is advisable to exploit the so-called "P-spring effect" a phenomenon in which liming enhances phosphorus availability by neutralizing soil acidity and promoting better root access to immobile P (Bolan *et al.*, 2003). This strategy is particularly effective in acid-prone soils where P is often fixed by aluminum and iron oxides. Phosphorus fertilization is also necessary due to low Av. P levels at Koga.

The exchangeable acidity (sum of Al^{3+} and H^{+} ions) was 2.25cmolc/kg at Koga and 1.04 cmolc/kg at Injebara. Likewise, exchangeable aluminum concentrations were 1.77 and 0.72 cmolc/kg, respectively (Table 4.1). Based on Laekemariam (2021) rating Koga had a moderate and Injebara had a lower rate of exchangeable acidity. This indicates Koga site may require lime or organic matter amendments to adjust pH and reduce acidity. Whereas Laekemariam (2021) rating on exchangeable aluminum indicates there is moderate and lower aluminum toxicity at the Koga and Injebara site respectively. Under such acidic conditions, crop growth is significantly constrained due to aluminum toxicity, reduced phosphorus availability, and inhibited microbial activity such as organic matter decomposition and nitrogen fixation (Fageria & Baligar, 2008; Kisinyo *et al.*, 2014). Hence, ameliorative practices, particularly the application of lime are essential to improve the soil chemical environment and enhance crop productivity, especially at Koga.

Table 4.1 Soil characteristics of the experimental sites before treatment application

Parameters	Koga	Injebara	Rating	Reference
Sand (%)	36	40	-	USDA (Hengl et al., 2021)
Silt (%)	12	32	-	
Clay (%)	52	28	-	
Textural class	Clay	Clay Loam		
pH (1:2.5)	4.78	5.44	Acidic & Slightly acidic	Landon (2014)
Av. P (mg/kg)	7.06	30.92	Low & high	Olsen (FAO, 2021)
OC (%)	1.41	3.94	Moderate & high	Hazleton&Murphy,2023
Ex. A (Cmol/kg)	2.25	1.04	Moderate	Laekemariam (2021)
Ex. Al^{3+} (Cmol/kg)	1.77	0.72	Moderate & low	Laekemariam (2021)
B.D(g/cm ³)	1.31	1.23	High & moderate	Blake & Hartge (1986).

pH= Power of Hydrogen, Av P= Available Phosphorus, ex Ac= Exchangeable Acidity, ex Al= Exchangeable Aluminum, OC= Organic Carbon, OM= organic Matter, BD= Bulk density

4.2. Main Effects of Soil Amendments on Soil Properties and Plant Parameters

4.2.1. Main effects of soil amendments on soil properties

Bulk Density

Bulk density was significantly influenced ($p < 0.05$) by the application of lime alone but did not significantly affected by sole application rhizobium strains or starter nitrogen at both the Koga and Injebara sites (Appendix Tables 1 & 2).

The lowest bulk density values were observed with the application of 2 t/ha of lime (1.22 g/cm³) at Koga and (1.17 g/cm³) at Injebara. In contrast, the highest bulk density values (1.25 and 1.19 g/cm³, respectively) were recorded in the control plots (Table 4.2a and 4.2b). Lime application significantly influenced bulk density because lime improves soil structure by reducing soil acidity. It promotes flocculation (aggregation) of soil particles, particularly in acidic soils, which leads to better pore space and lower bulk density. Therefore, they had little to no effect on bulk density in the short term at either site. This finding align with previous studies by Frank *et al.* (2021), Asmamaw Desale *et al.* (2022) and Birtukan Amare *et al.* (2022), who reported that lime application reduced soil bulk density in the highlands of Ethiopia. The impact of lime on soil physical properties, particularly bulk density, can be explained by its role in promoting soil aggregation and reducing soil compaction. In contrast, rhizobium strains and starter nitrogen primarily influence biological and nutritional aspects of the soil rather than its physical structure. This is consistent with the findings of Makgato *et al.* (2020) and Sadiq *et al.* (2023), who also concluded that rhizobium inoculation and nitrogen fertilizers have limited effects on soil physical properties like bulk density.

Soil pH

Soil pH was highly significantly affected ($p < 0.05$) by the application of lime and starter nitrogen at both the Koga and Injebara sites, while the effect of rhizobium inoculation was not significant at Koga (Appendix Tables 1 & 2).

Lime application at 2 t/ha increased soil pH by 11.9% at Koga and 7.8% at Injebara compared to un limed plots (Tables 4.2a and 4.2b). Lime (commonly calcium carbonate) neutralizes soil acidity by reacting with hydrogen ions in the soil solution, thus increasing the pH (Rakkar *et al.*, 2024). This aligns with the findings of Kebede Dinkecha (2017)

and Sopha *et al.* (2022), who noted that soil pH improved linearly with increasing lime application.

Starter nitrogen application had a pH-depressing effect. At Koga, soil pH decreased by 1.37% with 20 kg N/ha compared to the control (Table 4.2a). Similarly, at Injebara, the application of 20 kg N/ha decreased soil pH by 0.34% (Table 4.2b). The observed linear decrease in soil pH with nitrogen fertilization may be due to the nitrification and nitrate leaching dynamics in the soil. Nitrogen fertilizers, especially ammonium-based fertilizers like urea or ammonium nitrate, are known to induce acidification at higher rates. These results are consistent with Molin *et al.* (2020) and Birtukan Amare *et al.* (2022), who found that nitrogen fertilizer application, particularly in the form of urea or ammonium-based fertilizers, leads to a decrease in soil pH over time. Similarly, Daba *et al.* (2021) observed that nitrogen fertilizers consistently lower soil pH.

Rhizobium inoculation increased soil pH by 3.5% (FB-1035) and 4.7% (FB-37) at Injebara, but had no significant effect at Koga (Tables 4.2a and 4.2b). This finding corresponds with Bambara *et al.* (2010), who reported increased soil pH following rhizobium inoculation due to improved organic matter decomposition and nutrient cycling. This lack of significant effect at Koga may be due to higher acidity at the site, which could impede microbial activity (Table 4.1). This result supported by Wang *et al.* (2024) reported that rhizobium inoculation alone does not significantly alter soil pH, as its main function is fixing atmospheric nitrogen in symbiosis with legumes.

Available Phosphorus (P)

Available phosphorus (P) was highly significantly ($p < 0.0001$) affected by lime, starter nitrogen (N), and rhizobium strain at Koga, though rhizobium had no significant effect at Injebara (Appendix Tables 1 & 2).

Lime application alone increased available P by 53% at Koga and 15.38% at Injebara compared to un limed plots (Tables 4.2a and 4.2b). The increase in available P following lime application is attributed to the ability of lime to increase soil pH, which enhances the release of phosphate that is fixed by Al and Fe ions into the soil solution, thereby increasing phosphorus availability. This finding is consistent with Birtukan Amare *et al.* (2022), who reported an increase in available P following lime application. Similarly,

Adane Buni (2014) noted that lime applications significantly increased available phosphorus.

Starter nitrogen at 10 kg/ha produced the highest available P at both Koga (11.35 mg/kg) and Injebara (36.95 mg/kg), while increasing the nitrogen rate to 20 kg/ha reduced available P to 10.3 mg/kg and 34.1 mg/kg at Koga and Injebara, respectively (Tables 4.2a and 4.2b). This reduction is likely due to acidification-induced phosphorus fixation. This pattern aligns with findings by Habtamu Admas *et al.* (2015) and Yang *et al.* (2024).

Rhizobium inoculation with FB-1035 resulted in the highest available phosphorus (11.4 mg/kg), followed by FB-37 (10.75 mg/kg), while un inoculated plots recorded the lowest (9.55 mg/kg) at Koga (Table 4.2a). This increase is likely due to the activity of soil microorganisms involved in organic matter mineralization and plant residue decomposition. Similarly, Almaz *et al.* (2022) and Gezahagn Goshu (2023) found that rhizobium inoculation increased available phosphorus. However, contrary evidence was reported by Abiyot Abeje *et al.* (2022), who found no significant effect. The lack of significant effect at Injebara from rhizobium inoculation could be because the soils were not as phosphorus-limited, and the pH was not a major constraint to phosphorus availability. This finding is supported by Yamamoto *et al.* (2023), who reported that rhizobium alone did not significantly increase available phosphorus or phosphorus use efficiency (PUE) in soils where pH was not a limiting factor.

Organic carbon (OC)

Soil organic carbon (OC) was highly significantly affected ($p < 0.05$) by lime and starter nitrogen at Koga, and by lime, rhizobium, and nitrogen at Injebara (Appendix Tables 1 & 2). Lime alone increased organic carbon by 10.97% at Koga and 4.31% at Injebara (Tables 4.2a and 4.2b). This increase in OC is likely due to the effects of lime in increasing soil pH, which reduces stress on soil microbes, enhances microbial activity, and increases soil organic carbon and organic matter. This agrees with Abdissa Bekele *et al.* (2018), who observed a significant improvement in organic carbon after lime application. However, Abiyot Abeje *et al.* (2022) found that lime application had no effect on organic carbon.

At Injebara, rhizobium strains FB-37 and FB-1035 increased OC by 4.02% and 3.98%, respectively, compared with un inoculated plots (Tables 4.2a and 4.2b). This may be due

to the bio-fertilizers enhancing stable organic fractions and reducing decomposition, which is crucial for increasing soil OC sequestration. Zhao *et al.* (2022) also reported that rhizobium inoculation improved soil OC. At Koga, rhizobium inoculation did not significantly affect soil OC, likely because the soil conditions were not conducive to the stabilization of additional organic matter. This is supported by Shamem *et al.* (2022), who found that rhizobium inoculants improve plant growth and nitrogen fixation but do not consistently increase soil organic carbon unless combined with other soil amendments or microbial partners.

Starter N fertilizer application at 10 and 20 kg/ha increased soil OC by 4.73% and 2.3% at Koga, and by 5.1% and 2.56% at Injebara, respectively, compared with the control (Table 4.2). The increase in soil OC with higher nitrogen rates is attributed to greater carbon sequestration in plant biomass, which is later returned to the soil as crop residue. This result is consistent with Lawrence *et al.* (2016) and Chai *et al.* (2019), who reported that nitrogen fertilization improves soil organic carbon. Similarly, Esther *et al.* (2016), Yang *et al.* (2022) and Yang *et al.* (2024) observed increased soil OC and dissolved organic carbon in different ecosystems following nitrogen fertilization.

Exchangeable acidity and aluminum

Exchangeable acidity and Al^{3+} were highly significantly ($p < 0.05$) affected by the sole application of lime and starter N fertilizer, but not significantly ($p < 0.05$) affected by rhizobium strains alone at both sites (Appendix Tables 1 & 2).

Lime application alone reduced exchangeable acidity by 59.3% at Koga and 30.3% at Injebara compared with un limed plots, while exchangeable aluminum was reduced by 60% and 51.9%, respectively (Table 4.2). The reduction in acidity and aluminum is likely due to lime's ability to raise soil pH and reduce acidity by displacing H^+ , Fe^{2+} , Al^{3+} , and Mn^{4+} ions from the soil adsorption sites. These results are consistent with Achalu Chimdi *et al.* (2012), Kebede Dinkecha *et al.* (2017), Kryževičius *et al.* (2019), Getachew Alemu *et al.* (2017), Mathew *et al.* (2022) and Abdi Bizuayehu (2024). Application of 20 kg/ha N increased exchangeable acidity by 30.89% at Koga and 13.8% at Injebara compared with the control. Similarly, 10 kg/ha N raised acidity by 1.97% and 2.7%, respectively (Tables 4.2a and 4.2b). This result indicates that higher mineral nitrogen fertilization significantly lowers soil pH, which increases acidity by enhancing the availability of H^+ ,

Fe²⁺, Al³⁺, and Mn⁴⁺ ions. These findings align with Daba *et al.* (2021) and Zhang *et al.* (2024), who reported that nitrogen fertilization leads to nitrification and nitrate leaching, releasing protons (H⁺) into the soil.

The non-significant effects of rhizobium strains on exchangeable acidity and aluminum may be due to the primary influence of rhizobium on nitrogen fixation and plant growth, rather than directly affecting soil pH or aluminum levels. This is supported by Shi *et al.* (2022), who found that rhizobium inoculation had little impact on exchangeable acidity or Al³⁺. In contrast, Zhang *et al.* (2018) and Macias *et al.* (2020) reported that rhizobium can produce organic acids, such as lactic, oxalic, and citric acids, which stimulate soil enzymatic activity and alter microbial community structure. However, these effects are often short-lived as the acids are rapidly metabolized by soil microorganisms.

Table 4.2a Main effects of rhizobia strains, lime and starter nitrogen fertilizer on selected soil properties at Koga site

Treatments	BD (g/cm ³)	pH (1; 2.5 H ₂ O)	Av.P (mgkg ⁻¹)	OC (%)	ex A (Cmolckg ⁻¹)	ex Al (Cmolckg ⁻¹)
R ₀	1.23 ^a	5.14 ^a	9.55 ^c	1.72 ^a	1.45 ^a	1.03 ^a
R ₁	1.24 ^a	5.15 ^a	10.75 ^b	1.41 ^a	1.72 ^a	1.07 ^a
R ₂	1.24 ^a	5.19 ^a	11.40 ^a	1.74 ^a	1.32 ^a	0.92 ^a
L ₀	1.25 ^a	4.87 ^b	8.35 ^b	1.64 ^b	1.99 ^a	1.44 ^a
L ₁	1.22 ^b	5.45 ^a	12.78 ^a	1.82 ^a	0.86 ^b	0.57 ^b
N ₀	1.24 ^a	5.15 ^b	10.04 ^b	1.69 ^b	1.23 ^c	0.87 ^b
N ₁	1.23 ^a	5.25 ^a	11.35 ^a	1.76 ^a	1.35 ^b	0.92 ^b
N ₂	1.24 ^a	5.08 ^b	10.31 ^b	1.73 ^a	1.61 ^a	1.23 ^a

R₀ = no rhizobia, R₁= FB-37, R₂=FB-1035, L₀= 0 t/ha lime, L₁= 2 t/ha lime, N₀= 0kg/ha N, N₁= 10kg/ha N and N₂ = 20kg/ha N, pH= Power of Hydrogen, Av P= Available Phosphorus, ex A= Exchangeable Acidity, ex Al= Exchangeable Aluminum, OC= Organic Carbon, OM= organic Matter and BD= Bulk density. Means followed by the same letter in a column are not significantly different at p ≤ 0.05.

Table 4.2b Main effects of rhizobia strains, lime and starter nitrogen fertilizer on selected soil properties at Injebara site

	BD (g/cm ³)	pH (1;2.5 H ₂ O)	Av.P (mgkg ⁻¹)	OC (%)	ex A (Cmolckg ⁻¹)	ex Al (Cmolckg ⁻¹)
R ₀	1.18 ^a	5.73 ^c	34.51 ^b	4.06 ^a	0.40 ^a	0.12 ^a
R ₁	1.18 ^a	6.00 ^a	35.39 ^{ba}	4.02 ^{ba}	0.37 ^a	0.11 ^a
R ₂	1.18 ^a	5.93 ^b	36.34 ^a	3.98 ^{ba}	0.37 ^a	0.11 ^a
L ₀	1.19 ^a	5.67 ^b	32.88 ^b	3.94 ^b	0.43 ^a	0.15 ^a
L ₁	1.17 ^b	6.1 ^a	37.94 ^a	4.11 ^a	0.33 ^b	0.07 ^b
N ₀	1.18 ^a	5.81 ^b	35.19 ^b	3.92 ^c	0.36 ^b	0.09 ^b
N ₁	1.17 ^a	6.02 ^a	36.95 ^a	4.10 ^a	0.37 ^b	0.10 ^b
N ₂	1.19 ^a	5.83 ^b	34.1 ^b	4.04 ^b	0.41 ^a	0.14 ^a

R₀ = no rhizobia, R₁= FB-37, R₂=FB-1035, L₀ = 0 t/ha lime, L₁ = 2 t/ha lime, N₀= 0kg/ha N, N₁= 10kg/ha N and N₂ = 20kg/ha N, pH= Power of Hydrogen, Av P= Available Phosphorus, ex A= Exchangeable Acidity, ex Al= Exchangeable Aluminum, OC= Organic Carbon, OM= organic Matter and BD= Bulk density. Means followed by the same letter in a column are not significantly different at $p \leq 0.05$.

4.2.2. Main effects of soil amendments on nodulation and yield Parameters

Nodule Number

The total number of nodules was highly significantly affected ($p < 0.05$) by the individual application of rhizobia strains, lime, and starter nitrogen at the Koga site (Appendix Table 4). At the Injebara location, the nodule number was also significantly influenced ($p < 0.05$) by these sole treatments (Appendix Table 4).

Specifically, lime application alone improved the nodule count by 61.3% at Koga and 10.9% at Injebara compared to the untreated plots (Figure 4.1). This improvement in nodule count may be due to the liming-induced enhancement of the soil environment, which reduces acidity and increases pH conditions favorable for rhizobia activity and nodule formation. The lower response observed at Injebara could be due to its relatively less acidic soil and a more abundant native rhizobia population compared to Koga.

Seed inoculation with rhizobia isolates FB-1035 and FB-37 increased the number of nodules per plant by 233.9% and 197.3%, respectively, at Koga, and by 11.2% and 1.8%, respectively, at Injebara, compared to the control at each site (Figure 4.1). The higher

response at Koga likely due to the native rhizobia was insufficient in number or ineffective, and thus inoculation significantly boosted nodulation. Similar findings were reported by Argaw Anteneh and Abere Mnalku (2017) and by Demissie Alemayehu *et al.* (2022) in southern Ethiopia, who also noted increased nodule formation following inoculation. Masresha Abitew *et al.* (2012) likewise observed increased nodule numbers in soybean due to *Bradyrhizobium japonicum* inoculation.

Application of starter nitrogen alone increased nodule number, but the effect was not consistent with increasing nitrogen levels (Figure 4.1). At Koga, applying 10 kg ha⁻¹ of nitrogen increased nodule number by 30.64% compared with the control, while 20 kg ha⁻¹ reduced it by approximately 7.5%, compared to the 10 kg/ha N. Similarly, at Injebara, 10 kg ha⁻¹ of nitrogen improved nodule number by 13.6% compared with the control, whereas 20 kg ha⁻¹ led to a reduction of about 10.3% of nodule number compared with 10 kg/ha N (Figure 4.1). This suggests that a high dose of nitrogen may inhibit rhizobia infection by reducing root hair and secondary root development, which are essential for effective nodulation. This finding aligns with Dereje Geleta and Getachew Bekele (2022), who reported decreased nodulation in Faba bean with increased starter nitrogen rates. Similarly, Abera Tolera *et al.* (2018) reported that elevated soil nitrogen levels suppressed nodulation and biological nitrogen fixation in field pea. Majid *et al.* (2018) also found that increasing nitrogen from 25 to 50 kg/ha diminished the effectiveness of rhizobia inoculation in soybean.

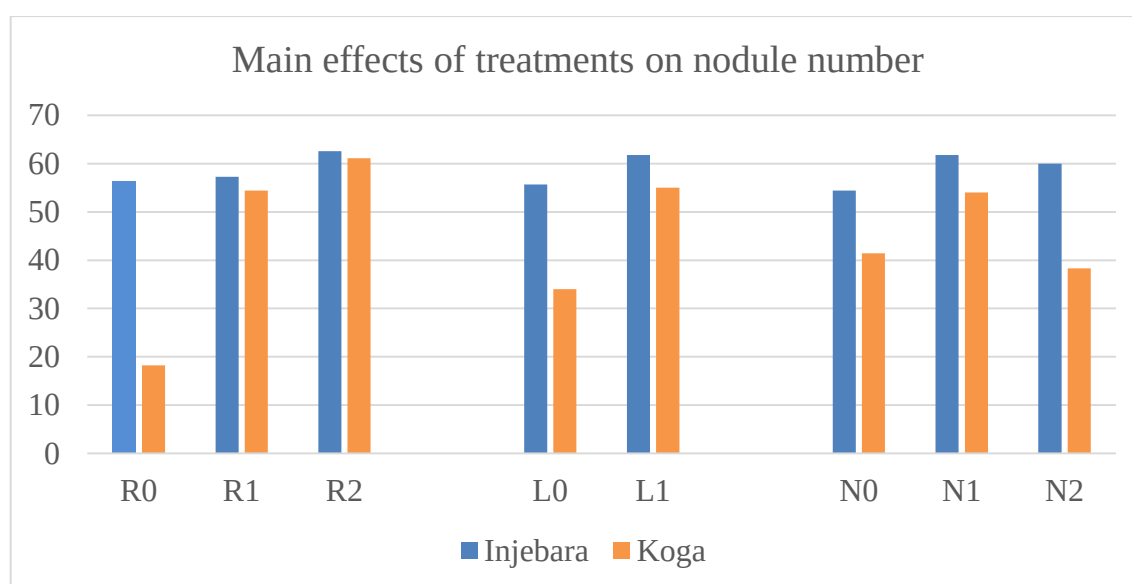


Figure 4.1 Main effects of lime, rhizobia strain and starter nitrogen on nodule number

Number of pods per plant (PNP)

The number of pods per plant was highly significantly ($p < 0.05$) affected by the individual application of lime, rhizobia strains, and starter nitrogen fertilizer at both Koga and Injebara locations (Appendix Table 5).

The sole application of lime increased number of pod per plant (PNP) by 132.14% and 37.28% at Koga and Injebara, respectively, compared to the untreated plots (Figure 4.2). This improvement may be due to lime's ability to neutralize soil acidity, reduce toxic levels of aluminum (Al), iron (Fe), and manganese (Mn), and enhance the physiological, chemical, and biological properties of the soil. This result aligns with the finding of Mekonnen Asrat *et al.* (2020), who observed similar improvements in pods numbers following lime application. Likewise, Workneh Bekere (2013) reported significant increases in pods number per plant when lime and *Bradyrhizobium* inoculation were applied either separately or together.

Inoculating Faba bean seeds with rhizobia strain FB-1035 significantly increased PNP by 126.2% at Koga and 52.4% at Injebara, while inoculation with strain FB-37 led to improvements of 84.08% and 40.89% at the respective sites compared with the uninoculated plots (Figure 4.2). These enhancements are likely due to improved nitrogen availability from biological nitrogen fixation, which also enhances macro- and micronutrient uptake. The increased availability of nitrogen may also promote plant height and vigor, contributing to a higher pod count. These findings are consistent with those reported by Samuel Adissie *et al.* (2021), who demonstrated that rhizobia inoculation significantly increased pod numbers in Faba bean. Similarly, Woldekiros Bezabih *et al.* (2018) and Paulos Ketema *et al.* (2022) found that rhizobia inoculation significantly influenced pod development.

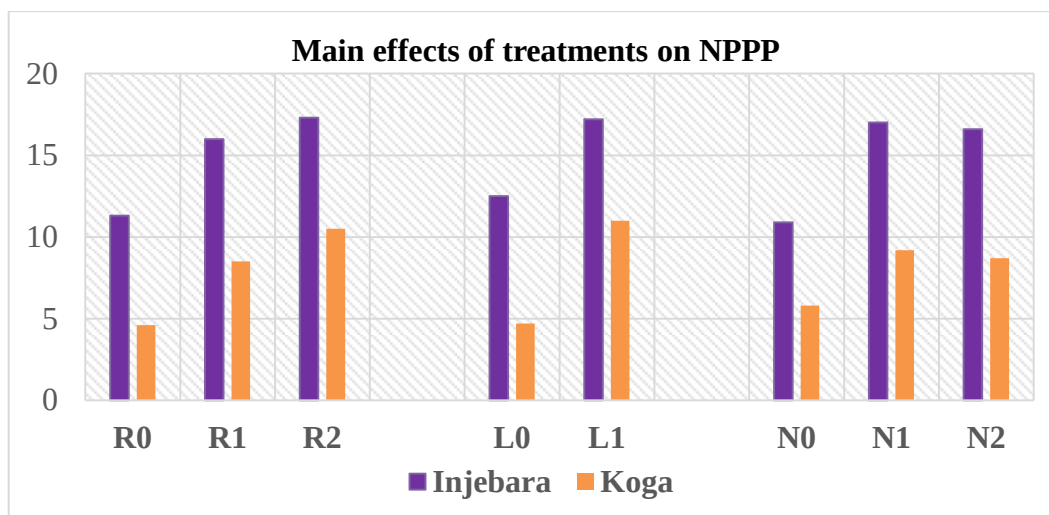


Figure 4.2. Main effects of treatments on number of pod per plant

Number of seeds per plant (NSPP)

The number of seeds per plant (NSPP) was significantly ($p < 0.05$) affected by the individual application of lime, rhizobium strains, and starter nitrogen at both locations (Appendix Table 5).

Lime application alone markedly increased NSPP by 137.2% at Koga and by 25% at Injebara compared to the control (Figure 4.3). This improvement may be due to the role of lime in enhancing phosphorus availability in acidic soils, which is vital for grain formation and development. This finding is consistent with Ayalew Melese (2022), who reported that lime application improved the number of seeds per plant in Faba bean. Similarly, Dereje Geleta and Getachew Bekele (2022) highlighted the positive impact of lime on NSPP.

Inoculating seeds with rhizobium strains also significantly increased the number of seeds per plant (NSPP). Strain FB-1035 increased NSPP by 136.5% at Koga and 54.7% at Injebara, while strain FB-37 enhanced NSPP by 98% and 45.1%, respectively, compared to the control (Figure 4.3). This improvement is likely due to enhanced biological nitrogen fixation, which improves plant nutrition and supports better grain development. This finding is consistent with those of Allito *et al.* (2020) and Samuel Adissie *et al.* (2021), who reported that rhizobium strains enhance nitrogen fixation and nutrient uptake in Faba bean, resulting in a higher number of seeds per plant.

However, in contrast to these results, Dejene Dessalegn (2018) reported that rhizobium inoculation did not significantly affect the number of seeds per pod or per plant.

Starter nitrogen fertilizer application at 10 and 20 kg ha⁻¹ increased NSPP by 55.9% and 46.3% at Koga, while at Injebara; the increases were 63% and 55.4%, respectively (Figure 4.3). This suggests that early nitrogen availability is beneficial for nodulation and seed formation. This result aligns with Wendesen Melak *et al.* (2019), who found that inorganic nitrogen is essential for legume development during the “nitrogen hunger period.” However, applying 20 kg ha⁻¹ of nitrogen reduced NSPP by 6.93% compared to 10 kg ha⁻¹ at Koga (Figure 4.3). This may be due to high nitrogen levels suppressing nodulation and biological nitrogen fixation, leading to limited nitrogen supply during seed filling. A similar trend was observed by Cheema and Ahmad (2000) and Xia *et al.* (2017), who reported a seed number reduction of 12–46% under high nitrogen rates.

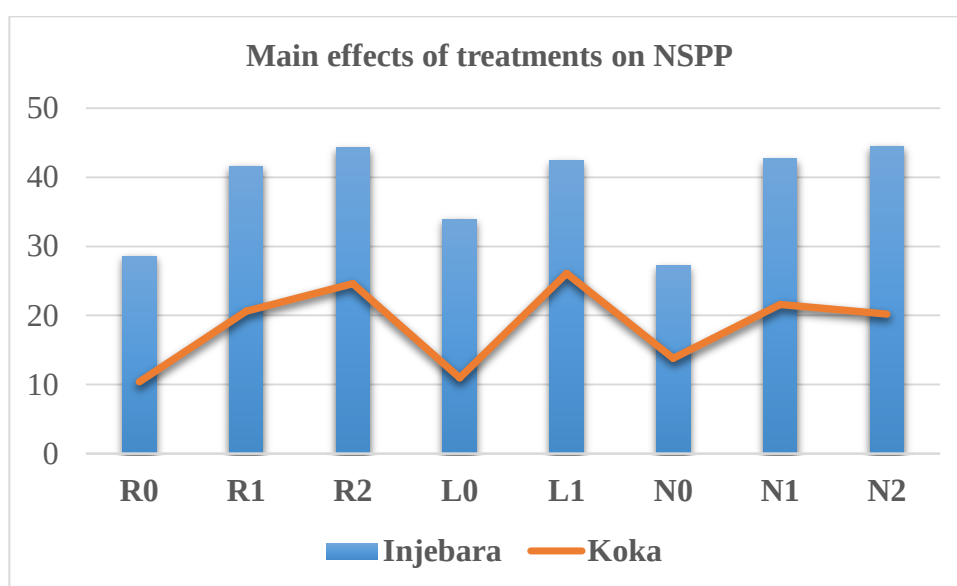


Figure 4.3 Main effects of treatments on number of seed per plant.

Above ground biomass yield

Aboveground biomass yield (AGBY) was highly significantly ($p < 0.01$) influenced by the individual applications of lime, starter nitrogen, and rhizobium strains at both study locations, with the exception of rhizobium application alone at Injebara, where the effect was not statistically significant (Appendix Table 6).

Among the sole treatments, the application of lime at 2 t ha⁻¹ had the strongest impact on biomass production, surpassing the effects of both starter nitrogen and rhizobium inoculation. Lime application increased AGBY by 52% at Koga and 20.55% at Injebara compared to the control (Figure 4.4). This significant increase is likely due to lime's role in ameliorating soil acidity and enhancing the availability of key nutrients, particularly phosphorus, which is essential for legume growth in acidic soils. This result highlights the critical role of lime in improving Faba bean productivity in strongly acidic environments. This finding is consistent with those of Melsew Ayalew (2019), Dereje Geleta *et al.* (2022), and Tsige Bekalu *et al.* (2023), who reported that lime application increased both biomass and grain yields in Faba bean.

Starter nitrogen application also showed notable positive effects on aboveground biomass yield. At Koga, application rates of 10 and 20 kg N ha⁻¹ increased biomass by 23.5% and 32.9%, respectively, compared to the unfertilized control (Figure 4.4). At Injebara, the corresponding increases were 12.2% and 11.5%. The observed increase in biomass may be attributed to nitrogen's stimulatory effect on meristematic activity and cell division, leading to enhanced vegetative growth. This result is in line with the findings of Lawlor (2002) and Dereje Dobocho and Debela Bekele (2021), who emphasized the importance of nitrogen in cell proliferation and biomass accumulation in Faba bean. Similarly, Annadurai *et al.* (2009) and Mesfin Tadele *et al.* (2020) reported that nitrogen application significantly enhanced vegetative growth, biomass yield, and tissue nitrogen content in Faba bean.

Regarding rhizobium inoculation, the highest AGBY values at Koga were recorded for strains FB-1035 and FB-37, which produced 4,221.6 kg ha⁻¹ and 4,004.2 kg ha⁻¹, respectively. By contrast, the un inoculated control plot yielded only 3,284.5 kg ha⁻¹ (Figure 4.4). This result suggests that rhizobium inoculation positively influenced biomass production, likely due to enhanced biological nitrogen fixation. This observation is supported by Pastor *et al.* (2021), Ajayi *et al.* (2024), and Duan *et al.* (2024), who reported that inoculating legumes with effective rhizobia strains significantly increases plant growth and total biomass compared to un inoculated controls. However, the effect at Injebara was not statistically significant, possibly due to the presence of sufficient indigenous rhizobia populations already capable of forming effective symbioses with the host plant.

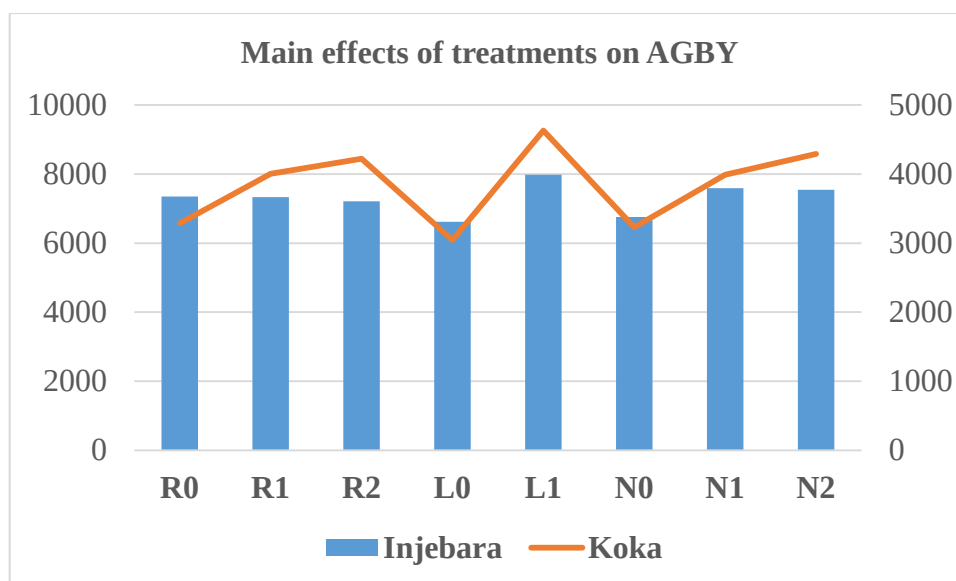


Figure 4.4 Main effects of treatments on aboveground biological yield

Grain yield (GY)

Grain yield was highly significantly affected ($p < 0.0001$) by the individual applications of lime, rhizobium strains, and starter nitrogen at both locations (Appendix Table 6).

Among the sole treatments, lime application alone significantly improved grain yield. As lime rates increased from 0 to 2 t ha⁻¹, grain yield increased by 101.4% at Koga and 43.8% at Injebara compared to the control (Figure 4.5). This substantial increase is likely attributed to lime's ability to neutralize soil acidity and enhance the availability of essential nutrients, particularly phosphorus, which is often limited in acidic soils. These findings are consistent with those of Abebe Zerihun and Abera Tolera (2014), Melsew Ayalew (2019), and Tsige Bekalu *et al.* (2023), who reported that liming significantly improves Faba bean productivity.

Rhizobium inoculation alone also significantly increased grain yield over the uninoculated control. At Koga, inoculation with strains FB-1035 and FB-37 resulted in yield increases of 68.8% and 50.1%, respectively (Figure 4.5). At Injebara, inoculation similarly led to significant yield improvements; however, the difference between the two strains was not statistically significant. The greater effectiveness of rhizobium inoculation at Koga may be due to the limited presence of indigenous rhizobia, whereas Injebara, with its history of continuous Faba bean cultivation, likely hosts an established native rhizobia population capable of effective nitrogen fixation.

This observation aligns with the findings of Abera Tolera and Abebe Zerihun (2018), Allito (2021), and Alemayehu Demissie and Dechassa Nigussie (2022), who noted that the benefits of inoculation are more pronounced in areas with low indigenous rhizobia populations and diminish in regions with a long history of legume cultivation.

Starter nitrogen application also significantly influenced grain yield at both sites. At Koga, yields increased by 43% and 30.4% with the application of 10 and 20 kg N ha⁻¹, respectively (Figure 4.5). At Injebara, the same rates led to increases of 33.9% and 36.4% over the control. These results underscore the important role of nitrogen in early crop development, particularly before effective nodulation and nitrogen fixation begin. Supporting this, Mesfin Tadele *et al.* (2020) and Dereje Dobocha and Debela Bekele (2021) observed that small “starter” nitrogen doses (up to 20–27 kg N ha⁻¹) can enhance both yield and biological nitrogen fixation. However, excessive nitrogen rates may suppress nodulation and reduce the crop’s nitrogen-fixing ability. Similarly, Getachew Yilma *et al.* (2022) reported improved soybean yields with starter nitrogen, while Zhang *et al.* (2017) found that excessive nitrogen application can negatively impact root and nodule development, ultimately limiting nitrogen fixation and reducing long-term productivity.

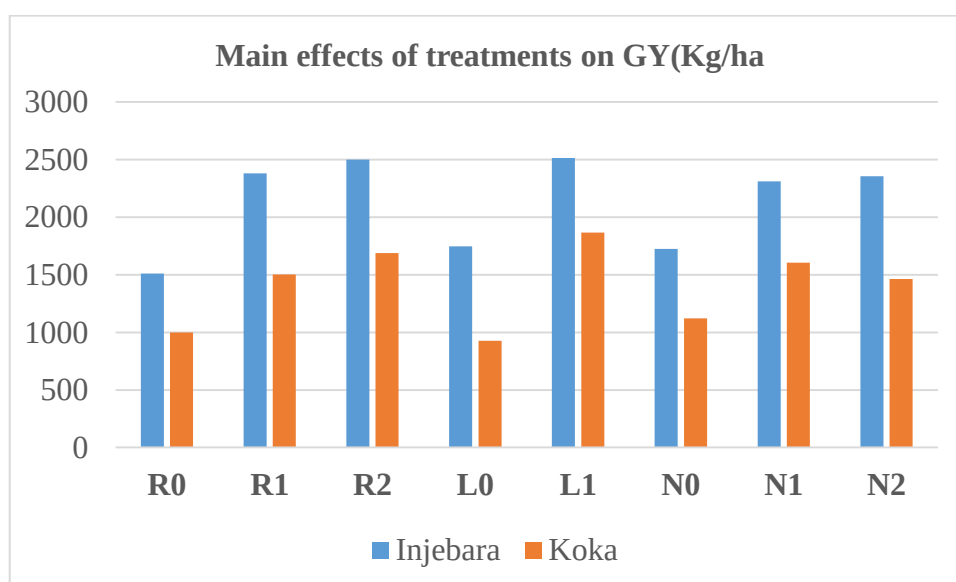


Figure 4.5 Main effects of treatments on grain yield

4.3. Interaction Effects of Soil Amendments on Selected Soil Properties

4.3.1. Soil pH

Soil pH was significantly ($p \leq 0.05$) affected by the interaction of lime with starter nitrogen, rhizobia strains with starter nitrogen, and the three-way interaction of rhizobia strains, lime, and starter nitrogen fertilizer at Koga (Appendix Table 1). However, the interaction between lime and rhizobia strain was not significantly ($p < 0.05$) related to soil pH. At the Injebara location, all two- and three-way interactions involving lime, rhizobia strains, and starter nitrogen significantly ($p \leq 0.05$) affected soil pH (Appendix Table 2).

The three way combined applications creates a more balanced soil chemical and biological environment, reducing net acid production while increasing nutrient cycling efficiency, leading to a greater overall increase in soil pH than when treatments are applied alone or in pairs. The highest soil pH values, 5.68 and 6.51, were recorded from treatments receiving FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ N at Koga and Injebara, respectively (Tables 4.3a and 4.3b). The lowest pH values, 4.79 and 5.56, were observed in the control treatments at Koga and Injebara, respectively (Tables 4.3a and 4.3b).

The improvement in soil pH from the integrated application of lime, rhizobia strains, and starter nitrogen could be attributed to the role of lime in neutralizing soil acidity. This increase in pH creates a more favorable environment for microbial activity, leading to enhanced nutrient release. Starter nitrogen supports initial plant and microbial activity, but lime buffers its acidifying effects. This indicates a synergistic effect of lime, nitrogen fertilizers, and rhizobia strains in improving soil pH. This finding is consistent with those of Moreira and Fageria (2010), Buni (2014) and Hanafiah *et al.* (2022), who reported increases in soil pH with integrated soil fertility management.

4.3.2. Available phosphorus (mg/kg)

Available phosphorus was highly significantly ($p \leq 0.05$) affected by all two- and three-way interaction effects involving rhizobia strains, lime, and starter nitrogen at both locations, except for the interaction between starter nitrogen and rhizobia strains, which did not significantly ($p < 0.05$) influence available phosphorus at Injebara (Appendix Tables 1 and 2).

This finding showed that the interaction of lime, rhizobia strains and starter nitrogen fertilizer was superiorly improved available phosphorus compared from the two way interaction, sole application and from the control (Table 4.3a and 4.3b). Thus, the highest available phosphorus values, 15.5 mg/kg and 45.5 mg/kg, were recorded from treatments with FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ N at Koga and Injebara, respectively (Tables 4.3a and 4.3b). The lowest available phosphorus values, 7.2 mg/kg and 32 mg/kg, were observed in the control plots at Koga and Injebara, respectively (Tables 4.3a and 4.3b).

The enhancement of available phosphorus due to the combined application of lime, rhizobia strains, and a moderate dose of starter nitrogen fertilizer can be attributed to the synergistic effects of these inputs on soil chemistry and microbial activity. Lime raises soil pH, which reduces phosphorus fixation by aluminum and iron oxides in acidic soils, thereby increasing the pool of available phosphorus. Rhizobia strains enhance root development and biological nitrogen fixation, which in turn stimulate root exudation and microbial processes that help mobilize phosphorus from organic and inorganic sources. The moderate application of starter nitrogen supports early plant growth and improves rhizobia establishment without fully suppressing biological nitrogen fixation. Together, these factors create a more favorable soil environment that promotes phosphorus availability far beyond what each input could achieve alone. This result is in agreement with the findings of Razafintsalama *et al.* (2022) Abiyot Abeje *et al.* (2022), who reported increased available phosphorus with the combined use of bio fertilizers, inorganic fertilizers, and lime, and Mesfin Kassa *et al.* (2014), who observed a similar increase with the application of fresh cattle manure, bio fertilizers, inorganic fertilizers, and lime. Wanjiru (2018) also found that soil available phosphorus increased after the application of lime combined with manure and chemical fertilizers.

4.3.3. Organic carbon (%)

Soil organic carbon (OC) was significantly ($p \leq 0.05$) affected by the interaction of lime with rhizobia strains and by the three-way interaction of lime, rhizobia strains, and starter nitrogen at both locations (Appendix Tables 1 & 2). However, the interaction between lime with starter nitrogen at Koga and rhizobia strains with starter nitrogen at both locations did not significantly ($p < 0.05$) affect OC (Appendix Tables 1 & 2).

This study emphasized the superior effects of the interaction between lime and starter nitrogen at the Injebara location (Table 4.3b). The highest OC value of 4.3% was observed in soil treated with 2 t ha^{-1} lime + 10 kg ha^{-1} N at Injebara (Table 4.3b). Conversely, the combined application of lime, starter nitrogen, and rhizobia strains resulted in the highest OC value of 1.89% at Koga (Table 4.3a), while the lowest OC values of 1.57% and 3.78% were recorded in the control treatments at Koga and Injebara, respectively (Tables 4.3a and 4.3b).

The significant increase in soil organic carbon observed with the lime and rhizobia interaction, and especially with the three-way combination of lime, rhizobia strains, and starter nitrogen, can be attributed to enhanced soil biological activity and increased organic matter input. Lime improves pH, creating favorable conditions for rhizobia and soil microbes, while rhizobia enhance nitrogen fixation and root biomass (Dereje Geleta *et al.*, 2022). The addition of moderate starter nitrogen supports early plant growth without inhibiting rhizobia effectiveness (Samirawt Mebrahtu *et al.*, 2024). In contrast, interactions that excluded lime or relied solely on rhizobia and nitrogen were not significant, likely due to the suppressive effect of soil acidity on microbial processes and the reduced contribution of biological nitrogen fixation under those conditions. This finding aligns with the research of Abdissa Bekele *et al.* (2018) and Li *et al.* (2017) indicated that soil OC increased after the application of lime, organic chemical fertilizers, and bio fertilizers. Furthermore, Liao *et al.* (2022) and Abiyot Abeje *et al.* (2022), who reported that the integrated use of organic manure, inorganic fertilizers, bio fertilizers, and lime is a promising approach for preserving soil OC. Similarly, Gezahagn Goshu (2023) found that soil organic carbon content increased significantly in plots that received a combination of farmyard manure (FYM), rhizobium inoculation, and chemical fertilizer.

4.3.4. Exchangeable acidity and aluminum

At the Koga site, exchangeable acidity and exchangeable aluminum were highly significantly affected ($p < 0.05$) by the interaction of lime with starter nitrogen, lime with rhizobia strains, and the three-way interaction among lime, rhizobia strains, and starter nitrogen (Appendix Table 1). However, these interactions had no statistically significant effect ($p > 0.05$) at the Injebara site (Appendix Table 2).

The highest exchangeable acidity (2.46 cmol kg⁻¹) and aluminum (1.68 cmol kg⁻¹) values were recorded in the treatment that received 20 kg ha⁻¹ nitrogen without lime and rhizobia at Koga location. In contrast, the lowest values 0.49 cmol kg⁻¹ for acidity and 0.37 cmol kg⁻¹ for aluminum were observed under the treatment with 2 t ha⁻¹ lime at Koga (Table 4.3a). This marked reduction in exchangeable acidity and aluminum highlights the ameliorating role of lime, even in the absence of rhizobia and nitrogen. Lime increases soil pH and displace toxic cations such as H⁺, Al³⁺, Fe²⁺, and Mn⁴⁺ from soil exchange sites, thereby reducing their harmful effects (Osundwa *et al.*, 2013). In contrast, the lack of significant effects at Injebara is likely due to its relatively higher initial soil pH and lower levels of exchangeable acidity and aluminum, which limited the potential impact of lime and associated treatments. These findings are consistent with those of Abdissa Bekele *et al.* (2018), who demonstrated that integrating lime with organic and inorganic fertilizers reduces acidity and aluminum toxicity. Getachew Alemu *et al.* (2017) also reported reductions in exchangeable acidity to as low as 0.1 cmol kg⁻¹ with increased lime rates combined with bio fertilizers. Additional support comes from studies by Birhanu Agumas *et al.* (2016), Temesgen Desalegn *et al.* (2016a), Desalegn Temesgen *et al.* (2017), and Kebede Dinkecha (2017), who found that lime applications significantly lower exchangeable acidity and aluminum concentrations when combined with bio fertilizer use.

Table 4.3a. Interaction effects of rhizobia strains, lime and starter nitrogen fertilizer on selected soil properties at Koga

Treatment	pH(1:2.5 H ₂ O)	av. P (mgkg ⁻¹)	OC (%)	ex. A (Cmolkg ⁻¹)	ex. Al ³⁺ (Cmolkg ⁻¹)	B.D(g/c m ³)
R ₀ + L ₀ + N ₀	4.79 ^e	7.93 ^d	1.57 ⁱ	1.98 ^{bc}	1.49 ^{bac}	1.27 ^{ba}
R ₀ + L ₀ + N ₁	4.93 ^e	8.46 ^d	1.74 ^{tde}	2.25 ^{ba}	1.62 ^{ba}	1.23 ^{bdac}
R ₀ + L ₀ + N ₂	4.86 ^e	7.99 ^d	1.71 ^{tge}	2.46 ^a	1.68 ^a	1.22 ^{bdc}
R ₀ + L ₁ + N ₀	5.62 ^{ba}	11.43 ^c	1.75 ^{tde}	0.49 ^h	0.37 ^{fe}	1.17 ^d
R ₀ + L ₁ + N ₁	5.36 ^{dc}	11.08 ^c	1.82 ^{bdac}	0.49 ^h	0.42 ^{fe}	1.24 ^{bac}
R ₀ + L ₁ + N ₂	5.29 ^d	10.95 ^c	1.76 ^{dec}	0.94 ^{fe}	0.64 ^{fe}	1.27 ^{ba}
R ₁ + L ₀ + N ₀	4.81 ^e	8.08 ^d	1.6 ^{ih}	1.69 ^d	1.31 ^{dc}	1.25 ^{ba}
R ₁ + L ₀ + N ₁	4.94 ^e	8.52 ^d	1.66 ^{fhg}	1.85 ^{dc}	1.38 ^{bdac}	1.24 ^{bac}
R ₁ + L ₀ + N ₂	4.87 ^e	8.04 ^d	1.58 ^{ih}	1.82 ^{dc}	1.53 ^{bac}	1.25 ^{ba}
R ₁ + L ₁ + N ₀	5.35 ^{dc}	11.44 ^c	1.81 ^{bdec}	0.65 ^{gh}	0.35 ^f	1.25 ^{bac}
R ₁ + L ₁ + N ₁	5.67 ^{ba}	15.14 ^a	1.86 ^{ba}	0.81 ^{fg}	0.48 ^{fe}	1.24 ^{bac}
R ₁ + L ₁ + N ₂	5.31 ^d	13.23 ^b	1.84 ^{bac}	1.69 ^d	1.37 ^{bdac}	1.24 ^{bac}
R ₂ + L ₀ + N ₀	4.82 ^e	8.09 ^d	1.65 ^{ihg}	1.68 ^d	1.33 ^{bdc}	1.29 ^a

R ₂ + L ₀ + N ₁	4.96 ^e	8.5 ^d	1.62 ^{ihg}	1.85 ^{dc}	1.13 ^d	1.26 ^{ba}
R ₂ + L ₀ + N ₂	4.89 ^e	8.09 ^d	1.65 ^{ihg}	1.91 ^{dc}	1.53 ^{bac}	1.26 ^{ba}
R ₂ + L ₁ + N ₀	5.49 ^{bc}	11.45 ^c	1.78 ^{bdec}	0.62 ^{gh}	0.41 ^{fe}	1.25 ^{bac}
R ₂ + L ₁ + N ₁	5.68 ^a	15.53 ^a	1.89 ^a	0.73 ^{fgh}	0.49 ^{fe}	1.19 ^{dc}
R ₂ + L ₁ + N ₂	5.3 ^d	14.36 ^{ba}	1.86 ^{ba}	1.09 ^e	0.67 ^e	1.23 ^{bdac}
LSD(0.05)	0.19	1.53	0.08	0.27	0.31	0.07
CV (%)	2.16	8.82	2.93	11.55	18.3	3.2
MSE	0.11	0.92	0.05	0.16	0.18	0.039

R₀ = no rhizobia, R₁= FB-37, R₂=FB-1035, L₀ = 0 t/ha lime, L₁ = 2 t/ha lime, N₀= 0kg/ha N, N₁= 10kg/ha N and N₂ = 20kg/ha N, LSD= List significant difference, CV= Coefficient of variation, SE= standard error, pH= Power of Hydrogen, av P= Available Phosphorus, ex A= Exchangeable Acidity, ex Al³⁺= Exchangeable Aluminum, OC= Organic Carbon, BD= Bulk density. Means along the column with the same letter are not significantly different at 5% level of significance.

Table 4.3 b. Interaction effects of Rhizobia Strains, Lime and Starter Nitrogen Fertilizer on Selected Soil Properties at Injebara Site.

Treatment	pH(1:2.5 H ₂ O)	av. P (mgkg ⁻¹)	OC (%)	ex. A (Cmolkg ⁻¹)	ex. Al ³⁺ (Cmolkg ⁻¹)	B.D (g/cm ³)
R ₀ + L ₀ + N ₀	5.56 ^k	33.34 ^{gith}	3.78 ⁱ	0.42 ^a	0.16 ^a	1.22 ^a
R ₀ + L ₀ + N ₁	5.67 ^{jki}	31.65 ^{ijh}	3.99 ^{egf}	0.45 ^a	0.16 ^a	1.15 ^{bc}
R ₀ + L ₀ + N ₂	5.63 ^{jk}	29.27 ^j	3.95 ^{hgf}	0.48 ^a	0.19 ^a	1.17 ^{bac}
R ₀ + L ₁ + N ₀	5.81 ^{gh}	38.56 ^{cb}	4.16 ^{bac}	0.31 ^a	0.04 ^a	1.15 ^c
R ₀ + L ₁ + N ₁	5.96 ^{ef}	35.05 ^{gcfdeh}	4.28 ^a	0.33 ^a	0.06 ^a	1.18 ^{bac}
R ₀ + L ₁ + N ₂	5.74 ^{jhi}	34.53 ^{gifdeh}	4.23 ^{ba}	0.39 ^a	0.11 ^a	1.21 ^{ba}
R ₁ + L ₀ + N ₀	5.65 ^{jki}	34.03 ^{gifeh}	3.94 ^{hgf}	0.41 ^a	0.12 ^a	1.21 ^{ba}
R ₁ + L ₀ + N ₁	5.86 ^{gf}	32.76 ^{gijh}	4.02 ^{edf}	0.44 ^a	0.15 ^a	1.20 ^{bac}
R ₁ + L ₀ + N ₂	5.66 ^{jki}	31.02 ^{ij}	3.98 ^{hgf}	0.47 ^a	0.19 ^a	1.20 ^{bac}
R ₁ + L ₁ + N ₀	6.2 ^c	37.57 ^{cde}	3.89 ^{hgi}	0.31 ^a	0.06 ^a	1.15 ^{bc}
R ₁ + L ₁ + N ₁	6.39 ^b	41.74 ^b	4.21 ^{bac}	0.33 ^a	0.06 ^a	1.16 ^{bc}
R ₁ + L ₁ + N ₂	6.25 ^c	35.59 ^{gcfde}	4.13 ^{bdc}	0.38 ^a	0.1 ^a	1.16 ^{bc}
R ₂ + L ₀ + N ₀	5.62 ^k	34.78 ^{gfdeh}	3.92 ^{hgf}	0.39 ^a	0.12 ^a	1.21 ^{ba}
R ₂ + L ₀ + N ₁	5.76 ^{ghi}	33.04 ^{gith}	3.98 ^{hgf}	0.44 ^a	0.15 ^a	1.19 ^{bac}
R ₂ + L ₀ + N ₂	5.65 ^{jki}	32.44 ^{gijh}	3.9 ^{hg}	0.45 ^a	0.18 ^a	1.20 ^{bac}
R ₂ + L ₁ + N ₀	6.08 ^d	37.88 ^{cd}	3.87 ^{hi}	0.29 ^a	0.07 ^a	1.15 ^c
R ₂ + L ₁ + N ₁	6.51 ^a	46.45 ^a	4.16 ^{bc}	0.32 ^a	0.06 ^a	1.16 ^{bac}
R ₂ + L ₁ + N ₂	6.05 ^{ed}	36.45 ^{cfde}	4.1 ^{edc}	0.38 ^a	0.1 ^a	1.20 ^{bac}
LSD(0.05)	0.13	3.711	0.12	0.06	0.05	0.06
CV (%)	1.2	6.33	1.76	9.19	26.29	3.05
MSE	0.07	2.24	0.07	0.04	0.03	0.04

R₀ = no rhizobia, R₁= FB-37, R₂=FB-1035, L₀ = 0 t/ha lime, L₁ = 2 t/ha lime, N₀= 0kg/ha N, N₁= 10kg/ha N and N₂ = 20kg/ha N, pH= Power of Hydrogen, av P= Available Phosphorus, ex Ac= Exchangeable Acidity, ex Al³⁺= Exchangeable Aluminum, OC= Organic Carbon, BD= Bulk density. Means along the column with the same letter are not significantly different at 5% level of significance.

4.4. Interaction Effects of Soil Amendments on Growth Parameters of Faba Bean



Figure 4.6 Photo taken during visual observation of 90% flowering at Injebar

4.4.1. Days to 90% flowering

The days to 90% flowering were not significantly ($p < 0.05$) affected by the interaction effects whether two-way or three-way among lime, rhizobium strains, and starter nitrogen at either experimental site (Appendix Table 3). This lack of significant interaction implies that this phenological trait is primarily regulated by genetic and environmental factors, rather than by soil amendments (Samuel et al., 2017; Ohm, 2025). Although rhizobium strains and starter nitrogen likely enhanced soil fertility and overall plant vigor, they did not substantially alter the timing of flowering. This suggests that the treatments contributed to better growth conditions without modifying the crop's inherent flowering schedule.

Despite the non-significant interactions, the longest durations to 90% flowering were observed under the application of FB-1035 + 2 t/ha lime + 10 kg/ha N and FB-1035 + 2 t/ha lime, with values of 48.6 days at Koga and 58.6 days at Injebara, respectively (Table 4.4). Conversely, the shortest flowering times 42.3 days at Koga and 54.0 and 55.3 days at Injebara were recorded in the control and with the application of 10 kg/ha nitrogen alone, respectively (Table 4.4). This finding aligns with those of Bekalu Abebe *et al.* (2023) and Samrawit Mebrhatu *et al.* (2024), who reported that improved soil pH and nutrient status through lime, rhizobium inoculation, and fertilization can create favorable conditions for plant development. While these conditions may promote more uniform and potentially earlier flowering, such outcomes may not always be directly reflected in statistically significant differences.

4.4.2. Days to 90% Maturity

Days to 90% maturity were significantly influenced ($p < 0.05$) by all interaction effects of soil amendments at both experimental sites, except for the combination of rhizobia strains with starter nitrogen at Injebara (Appendix Table 3). The significant interactions, particularly those involving lime with both rhizobia and starter nitrogen, suggest that these treatments effectively altered the crop's maturity timeline. This effect is likely due to improved soil pH, enhanced nutrient availability, and optimized biological nitrogen fixation, which collectively promote more vigorous plant growth and extended developmental phases.

At the Koga site, the longest maturity period (119 days) was recorded under the combined application of rhizobia strain FB-1035 + 2 t ha⁻¹ lime + 20 kg ha⁻¹ nitrogen. Similarly, the longest maturity period at Injebara (153 days) was observed with the same treatment and was statistically comparable to the treatment with FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ nitrogen. In contrast, the shortest maturity periods were 105 days at Koga (observed in the control plot) and 141 days at Injebara under the sole application of lime, which was statistically similar to the application of FB-1035 alone (Table 4.4).

The observed delay in maturity under combined treatments can be attributed to the improvement in soil pH by lime, which enhances the availability of essential nutrients such as phosphorus, calcium, and molybdenum. These nutrients, along with increased nitrogen availability from rhizobia inoculation and starter nitrogen, likely promoted prolonged vegetative growth. A higher nitrogen supply is known to extend the vegetative phase of legumes, consequently delaying flowering and maturity. This result is consistent with the findings of Getnetu Getenesh *et al.* (2021), who reported delayed maturity in Faba bean due to the combined use of rhizobia inoculation and chemical fertilizers. Similarly, Assefa Habtamu *et al.* (2017) observed delayed maturity in common bean with the application of lime, rhizobia inoculants, and nitrogen fertilizers.

Conversely, studies by Sen *et al.* (2021) and Athul *et al.* (2022) reported that the combined use of lime, rhizobia, and starter nitrogen could lead to earlier and more synchronized crop maturity. According to these studies, the treatments enhanced root nodulation, nutrient uptake, and early vigor, thereby accelerating developmental processes. The contrasting findings may be due to differences in agro ecological

conditions, crop genotype, and native soil fertility, emphasizing the importance of context-specific management.

4.4.3. Plant height

Plant height was significantly influenced ($p < 0.05$) by the three-way interaction among lime, rhizobia strains, and starter nitrogen at both experimental locations (Appendix Table 3). In contrast, at the Koga site, the two-way interaction between starter nitrogen and rhizobia strains did not significantly affect plant height. Similarly, none of the two-way interactions (lime $\times$ rhizobia, lime $\times$ nitrogen, or rhizobia $\times$ nitrogen) at the Injebara site showed a statistically significant effect ($p < 0.05$) on this parameter (Appendix Table 3). This suggests that while individual or dual combinations of these treatments might improve plant vigor to some extent, a more pronounced effect on plant height was only achieved when all three components lime, rhizobia inoculation, and starter nitrogen were applied together. The absence of significance in the two-way interactions at Injebara could be attributed to site-specific factors such as soil texture, organic matter content, or background fertility, which may have masked the effects of partial treatments.

This result clearly show that the combined application of rhizobia strains, lime, and starter nitrogen produced significantly greater plant height compared to sole treatments and the control (Table 4.4). The tallest plant heights 104.1 cm at Koga and 189.9 cm at Injebara were recorded from the treatment with FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ N. Conversely, the shortest plant heights 55.7 cm at Koga and 157.7 cm at Injebara were observed in the control, with a similarly low value from the sole application of FB-37 (56.9 cm) at Koga (Table 4.4).

The enhanced vegetative growth of Faba bean under combined treatments is likely due to the ability of lime to raise soil pH, reduce exchangeable Al³⁺, and create favorable conditions for microbial activity and nutrient availability. In addition, rhizobia inoculation and starter nitrogen application improve nitrogen availability, further supporting plant growth. This finding is consistent with the results of Abebe Zerihun *et al.* (2014), Hafez *et al.* (2021) and Liu *et al.* (2022), who observed improved plant height from the combined use of bio fertilizer, nitrogen, and phosphorus fertilizers. Likewise, Endalkachew Fekadu (2018) reported a synergistic effect on Faba bean growth from the integration of bio fertilizer, organic and inorganic fertilizers, and lime. Similar effects

were found by Abera Tolera and Abebe Zerihun (2018), who noted that field pea plant height was significantly increased when rhizobia inoculants and nitrogen were applied in combination with lime, compared to lime alone.

Table 4.4 Interaction effects of rhizobia strains, lime and starter nitrogen fertilizer on flowering and maturity of Faba bean (*Vicia Faba L.*) in the study areas.

Treatments	DF (days)		DM (days)		PH (cm)	
	Koga	Injebara	Koga	Injebara	Koga	Injebara
R ₀ + L ₀ + N ₀	42.3 ^a	55.33 ^{ba}	105.6 ⁱ	142.3 ^{gfh}	55.7 ^m	157.7 ^h
R ₀ + L ₀ + N ₁	42.6 ^a	54.0 ^{ba}	106.3 ^{ih}	143.6 ^{gfh}	66.1 ^{lk}	179.4 ^{bedc}
R ₀ + L ₀ + N ₂	43.3 ^a	55.0 ^{ba}	112.6 ^{de}	141.6 ^{gh}	70.1 ^{jk}	177.5 ^{bedc}
R ₀ + L ₁ + N ₀	44.3 ^a	57.3 ^{ba}	117.6 ^{ba}	141.0 ^h	73.5 ^{ji}	178.5 ^{bedc}
R ₁ + L ₀ + N ₀	44.6 ^a	56.6 ^{ba}	111.6 ^{def}	144.6 ^{egdfh}	56.9 ^m	163.5 ^{hg}
R ₂ + L ₀ + N ₀	46.3 ^a	57.3 ^{ba}	113.3 ^{dc}	141.3 ^h	63.4 ^l	166.4 ^{fg}
R ₀ + L ₁ + N ₁	44.0 ^a	56.0 ^{ba}	108.6 ^{gh}	148.3 ^{bdac}	82.0 ^{gf}	181.5 ^{bac}
R ₀ + L ₁ + N ₂	42.6 ^a	56.3 ^{ba}	106.3 ^{ih}	143.0 ^{gfh}	86.6 ^{ef}	174.6 ^{fedc}
R ₁ + L ₀ + N ₁	45.3 ^a	56.3 ^{ba}	108.3 ^{gh}	149.0 ^{bac}	74.9 ^{jhi}	171.5 ^{fedg}
R ₂ + L ₀ + N ₁	45.0 ^a	54.6 ^{ba}	115.3 ^{bc}	145.3 ^{egdfc}	77.1 ^{ghi}	178.8 ^{bedc}
R ₁ + L ₀ + N ₂	45.0 ^a	56.6 ^{ba}	109.3 ^{gf}	145.6 ^{ebdfc}	79.9 ^{gh}	166.1 ^{fhg}
R ₂ + L ₀ + N ₂	43.6 ^a	55.3 ^{ba}	111.3 ^{def}	142.0 ^{gfh}	80.9 ^{gf}	171 ^{feg}
R ₁ + L ₁ + N ₀	46.6 ^a	57.3 ^{ba}	117.6 ^{ba}	149.3 ^{ba}	92.1 ^{ecd}	176.5 ^{edc}
R ₂ + L ₁ + N ₀	46.0 ^a	58.6 ^{ba}	110.0 ^{gf}	145.6 ^{ebdfc}	94.1 ^{bcd}	177.9 ^{bedc}
R ₁ + L ₁ + N ₁	45.6 ^a	57.6 ^{ba}	116.3 ^b	148.0 ^{ebdac}	98.7 ^{ba}	185.5 ^{ba}
R ₁ + L ₁ + N ₂	46.6 ^a	57.3 ^{ba}	110.6 ^{gef}	144.3 ^{egfh}	88.8 ^{ed}	180.0 ^{bdc}
R ₂ + L ₁ + N ₁	48.0 ^a	56.3 ^{ba}	113.3 ^{dc}	150.6 ^a	104.1 ^a	189.9 ^a
R ₂ + L ₁ + N ₂	46.6 ^a	56.3 ^{ba}	119.6 ^a	151.3 ^a	94.7 ^{bc}	181.7 ^{bac}
CV (%)	4.27	1.59	1.26	1.498	4.36	2.96
SE	1.92	2.32	1.409	2.209	3.48	5.198
LSD(p≤0.05)	3.190	3.894	2.338	3.852	5.788	8.626

R₀ = no rhizobia, R₁= FB-37, R₂=FB-1035, L₀ = 0 t/ha lime, L₁ = 2 t/ha lime, N₀= 0kg/ha N, N₁= 10kg/ha N and N₂ = 20kg/ha N, LSD= List significant difference, CV= Coefficient of variation, SE= standard error, DF= Days to flowering, DM=Days to maturity and PH= Plant height. Means with the same letter in the column indicates non-significant variation.

4.5. Interaction Effects of Soil Amendments on Nodulation

4.5.1. Nodule number

Total nodule number was significantly ($p \leq 0.05$) affected by the three-way interaction of lime, starter nitrogen, and rhizobia strain at both locations (Appendix Tables 4). However, the combined application of rhizobia and starter nitrogen without lime did not significantly affect nodule number at Koga and all the two way interactions did not

affects this parameters at Injebara (Appendix Table 4). Hence, at the Koga site, the combined application of rhizobia and starter nitrogen without lime did not significantly affect total nodule number. This suggests that the acidic soil conditions at Koga may have limited the effectiveness of the inoculant and hindered nitrogen uptake, preventing substantial nodulation. In acidic soils, low pH and associated aluminum toxicity can reduce rhizobia survival and activity, and may also interfere with root hair development both of which are essential for successful nodulation. At Injebara, none of the two-way interactions significantly affected nodule number. This could be attributed to site-specific factors such as a relatively less acidic soil pH, the presence of effective native rhizobia populations, or higher baseline soil nitrogen content. These conditions may have reduced the crop's dependence on inoculation or external nitrogen sources, thereby minimizing the response to partial amendment treatments.

The combined application of lime, rhizobia strain, and starter nitrogen had a superior effect on nodule number compared to individual treatments and the control (Table 4.5). The highest nodule numbers per plant (78.0 and 81.5) were recorded from the plot receiving FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ nitrogen at Koga and Injebara, respectively (Table 4.5). These results were statistically comparable to those from the treatments FB-1035 + 2 t ha⁻¹ lime + 20 kg ha⁻¹ nitrogen and FB-37 + 2 t ha⁻¹ lime + 20 kg ha⁻¹ nitrogen (Table 4.5). In contrast, the lowest nodule numbers per plant (5.2 and 50.0) were recorded from the control treatments at Koga and Injebara, respectively (Table 4.5). The variation in nodule number between the two locations may be attributed to differences in initial soil conditions (Table 4.1). The synergistic effect is likely due to the role of lime in correcting soil acidity, which improves conditions for rhizobia survival, proliferation, and symbiotic efficiency. Lime application raises soil pH, which enhances the availability of essential elements like calcium and molybdenum critical for rhizobia function and nodule development. When this is complemented by starter nitrogen and rhizobia inoculation, the early growth of the plant is supported, and effective nodulation is established more rapidly. This finding is aligned with the results of Abiyot Abeje *et al.* (2022), who reported that lime and Brady rhizobium inoculation combined with inorganic fertilizer significantly improved nodule number, effective nodules, and nodule biomass. Dereje Geleta *et al.* (2022) also reported significant increases in nodule number with the combined use of lime, NPSB fertilizer, and rhizobia inoculation in the Kiremu District of Western Ethiopia. Similarly, Sadiq *et al.* (2023) and Abebe Zerihun *et al.* (2014)

observed increased Faba bean nodulation with combined applications of fertilizer, rhizobium, and lime.

4.5.2. Effective nodule number

The number of effective nodules per plant was highly significantly ($p < 0.05$) affected by the three-way interaction among lime, rhizobia strain, and starter nitrogen at both experimental sites (Appendix Table 4). In contrast, the interaction between rhizobia strains and starter nitrogen at Koga, as well as all two-way interactions at Injebara, did not significantly ($p < 0.05$) affect the number of effective nodules. This suggests that without lime to correct soil acidity, the benefits of rhizobia inoculation and nitrogen supplementation are limited. At Koga, acidic soil conditions may have hindered the survival or effectiveness of the inoculated strains, while also limiting nitrogen uptake. At Injebara, the lack of significant two-way interaction effects could be due to more favorable native soil conditions, including moderately acidic pH, higher populations of indigenous rhizobia, or sufficient baseline nitrogen levels, which may have minimized the crop's response to partial treatments.

The treatment FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ nitrogen resulted in the highest number of effective nodules per plant 77.4 at Koga and 76.0 at Injebara. This was statistically comparable to FB-37 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ nitrogen, which recorded 72.2 and 69.5 effective nodules per plant at Koga and Injebara, respectively. In contrast, the minimum effective nodule numbers per plant (4.3 and 39.9) were observed in the control treatments at Koga and Injebara respectively (Table 4.5). The three-way synergy likely stems from lime's role in improving soil pH, which enhances rhizobia survival and efficiency, while starter nitrogen supports early vegetative growth before nodulation becomes fully active. Rhizobia inoculation ensures the presence of effective strains capable of forming functional nodules. Together, these factors create optimal conditions for effective nodulation, which is crucial for sustainable nitrogen acquisition. This finding corroborate the results of Sadiq *et al.* (2023) and Abiyot Abeje (2022), who found that lime and rhizobium inoculation combined with inorganic fertilizer significantly increased effective nodulation and related traits. Likewise, Dereje Geleta and Getachew Bekele (2022) demonstrated that the integration of lime, NPSB fertilizer, and rhizobia inoculation improved the effective nodule number of Faba bean in the Kiremu District.

4.5.3. Nodule dry weight (NDW)

Nodule dry weight was also highly significantly ($p < 0.05$) affected by all two- and three-way interactions at both locations (Appendix Table 4). The enhancement of nodule dry weight across all interaction levels suggests that both the quality and functionality of nodules improved under better soil chemical and biological conditions.

The highest nodule dry weights 109.4 g/plant at Koga and 115.3 g/plant at Injebara were recorded from the combined application of FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ nitrogen. In contrast, the lowest dry weights 11.7 and 26.4 g plant⁻¹ were recorded from the control treatments at Koga and Injebara, respectively (Table 4.5). The higher nodule dry weight observed under combined treatments may be due to an increased number and size of nodules, as the applied treatments likely promoted rhizobia infection and nodule development. This finding supports the results of Woldekirkos Bezabih (2018) found that Faba bean nodule dry weight increased with the combined application of rhizobia inoculation and potassium fertilizer in the Alichu Wuriro Highlands. Similarly, Athul *et al.* (2022) and Abiyot Abeje (2022), who reported increased nodule dry weight with the combined application of lime and rhizobium plus inorganic fertilizers.

Table 4.5. Interaction Effects of Rhizobia Strains, Lime and Starter Nitrogen on NN, ENN and NDW in the Study Areas.

Treatments	NN		ENN		NDW(g/p)	
	Koga	Injebara	Koga	Injebara	Koga	Injebara
R ₀ L ₀ N ₀	5.2 ⁱ	53.0 ^{cb}	4.3 ⁱ	36.9 ^e	11.7 ^l	26.4 ^m
R ₀ L ₀ N ₁	17.8 ^h	57.8 ^{cb}	17.2 ^h	45.8 ^d	23.6 ^{jk}	43.5 ^l
R ₀ L ₀ N ₂	7.5 ⁱ	51.5 ^{cb}	6.16 ⁱ	42.9 ^{ed}	15.9 ^{lk}	39.3 ^l
R ₁ L ₀ N ₀	37.8 ^f	50.1 ^{cb}	33.0 ^f	40.6 ^{ed}	34.7 ⁱ	56.7 ^{jk}
R ₁ L ₀ N ₁	49.8 ^{de}	59.2 ^{cb}	48.4 ^e	55.4 ^c	73.5 ^{de}	72.7 ^{gf}
R ₁ L ₀ N ₂	41.9 ^f	59.1 ^{cb}	35.2 ^f	54.5 ^c	55.4 ^g	68.4 ^{gih}
R ₂ L ₀ N ₀	41.1 ^f	59.1 ^{cb}	38.8 ^f	42.6 ^{ed}	65.1 ^f	55.8 ^k
R ₂ L ₀ N ₁	63.4 ^{bc}	57.5 ^{cb}	61.2 ^{dc}	56.3 ^{cb}	86.6 ^{dc}	86.6 ^c
R ₂ L ₀ N ₂	42.6 ^{fe}	52.3 ^{cb}	36.1 ^f	55.3 ^c	67.3 ^{fe}	70.1 ^{gfh}
R ₀ L ₁ N ₀	28.6 ^g	56.1 ^{cb}	25.3 ^g	40.3 ^{ed}	34.8 ⁱ	37.5 ^l
R ₀ L ₁ N ₁	40.3 ^f	57.2 ^{cb}	37.7 ^f	53.4 ^c	44.2 ^h	64.2 ^{ih}
R ₀ L ₁ N ₂	10.2 ^{ih}	62.4 ^b	8.1 ⁱ	57.2 ^{cb}	27.8 ^{ji}	62.3 ^{ji}
R ₁ L ₁ N ₀	65.6 ^b	59.6 ^{cb}	62.6 ^c	56.4 ^{de}	81.1 ^{dc}	85.1 ^e
R ₁ L ₁ N ₁	75.1 ^a	77.7 ^a	72.2 ^{ba}	69.5 ^a	97.7 ^b	107.3 ^b
R ₁ L ₁ N ₂	56.2 ^{dc}	66.3 ^b	55.2 ^d	59.5 ^{cb}	81.6 ^{dc}	99.7 ^c
R ₂ L ₁ N ₀	70.2 ^{ba}	58.4 ^b	67.5 ^{bc}	58.0 ^{cb}	85.7 ^c	92.9 ^d
R ₂ L ₁ N ₁	78.0 ^a	81.5 ^a	77.4 ^a	76.0 ^a	109.4 ^a	115.3 ^a
R ₂ L ₁ N ₂	71.2 ^{ba}	77.0 ^a	65.1 ^c	62.3 ^b	95.3 ^b	95.7 ^{dc}

LSD(p<0.05)	7.82	12.4	6.66	6.72	8.37	6.35
CV(%)	10.5	12.7	9.62	7.57	8.32	5.42
SE	4.71	7.48	4.01	4.05	5.04	3.82

R₀ = no rhizobia, R₁= FB-37, R₂=FB-1035, L₀ = 0 t/ha lime, L₁ = 2 t/ha lime, N₀= 0kg/ha N, N₁= 10kg/ha N and N₂ = 20kg/ha N, NN= nodule number, ENN =effective nodule number, NDW= nodule dry weight, LSD= List significant difference, CV= Coefficient of variation, SE= standard error. Means followed by the same letter in a column are not significantly different at $p \leq 0.05$.

4.6. Interaction Effects of Soil Amendments on Yield and Yield Components of Faba Bean

4.6.1. Number of pods per plant (PNP)

Pod number per plant was highly significantly ($P<0.001$) affected by all two and three way interaction of lime, rhizobia strain and starter nitrogen at both locations (Appendix Table 5).

The interaction of all three factors consistently produced a significantly higher number of pods compared to the sole or two-way applications of lime, rhizobia, and nitrogen, as well as the control. The highest pod number per plant was recorded in the treatment that received rhizobium strain FB-1035 combined with 2 t ha⁻¹ lime and 10 kg ha⁻¹ starter nitrogen, resulting in 18.4 pods per plant at Koga and 25.0 at Injebara. This was followed by FB-37 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ N (16.2 and 22.9 pods at Koga and Injebara, respectively), and FB-1035 + 2 t ha⁻¹ lime + 20 kg ha⁻¹ N (14.7 and 20.6 pods at the respective sites) (Table 4.6a). In contrast, the lowest pod numbers per plant—2.4 at Koga and 7.8 at Injebara were observed in the untreated control plots (no lime, no inoculation, and no nitrogen). These values were statistically similar to plots that received nitrogen alone without lime or inoculant (2.63 pods at both locations), indicating that the application of starter nitrogen without biological or chemical soil amendments had minimal impact on pod formation.

The significantly greater pod numbers under full treatment combinations can be attributed to improved plant nutrition, particularly enhanced nitrogen availability through both starter nitrogen and effective rhizobia symbiosis, supported by optimal soil pH conditions created by lime application. Increased pod number is closely associated with improved vegetative growth, better root development, and efficient nutrient uptake, all facilitated by

the integrated amendment approach. This result is consistent with the findings of Dereje Geleta *et al.* (2022), Bekalu Abebe *et al.* (2023) and Samrawit Mebrhatu (2024), who reported that the combined application of lime, NPSB fertilizer, and *Rhizobium* inoculation significantly increased the number of pods per plant in Faba bean grown in the Kiremu District of Western Ethiopia. This finding is supported by Yoseph Tarekegn (2011) and Mekonnen Asrat *et al.* (2020), who reported that integrated nutrient management using both organic and inorganic sources positively influenced number of pods per plant in Faba bean.

4.6.2. Number of seed per plant (NSPP)

The number of seeds per plant was highly significantly ($p < 0.01$) affected by both two-way and three-way interactions among rhizobia strains, lime, and starter nitrogen at both experimental sites (Appendix Table 5). These results indicate that the combined application of soil amendments had a substantial impact on seed development compared to the sole application of individual treatments and the untreated control.

The highest number of seeds per plant 41.5 at Koga and 65.1 at Injebara was obtained from the treatment combination of rhizobium strain FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ nitrogen (Table 4.6a). This was significantly higher than seed numbers recorded under individual treatments. In contrast, the lowest seed count at Koga (5.3 seeds per plant) was recorded in the control plot, which was statistically similar to the treatment without rhizobium and lime but with 10 kg ha⁻¹ nitrogen (5.4 seeds per plant). At Injebara, the lowest seed number (21.25) was observed in the treatment with lime alone (2 t ha⁻¹) and no rhizobia or nitrogen fertilizer, which was statistically on par with the untreated control (21.55 seeds per plant).

The substantial increase in seed number under the combined treatments may be attributed to the synergistic effect of lime, starter nitrogen, and rhizobium inoculation. Lime likely improved soil pH, enhancing the availability of key nutrients such as phosphorus, which plays a vital role in flowering, seed formation, and grain filling. Rhizobium inoculation boosted nitrogen fixation, while starter nitrogen supported early vegetative growth. Together, these amendments improved nutrient uptake, leading to better reproductive development and seed set. This result is in agreement with the findings of Wendesen

Melak (2019), Addisu Ebbisa *et al.* (2021), Samuel Adissie *et al.* (2021) and Athul *et al.* (2022), who reported that positive response of integrated application of lime, bio fertilizer, organic and NPS fertilizer on number of seeds per plant, number of pods per plant and grain yields of Faba bean. In contrary to this finding Abebe Zerihun *et.al.*(2014) number of pods per plant, number of seeds per pod and per plant and thousand seed weight of Faba bean were not significantly affected by interaction effects of fertilizer rate, rhizobium inoculation and lime rate at Gedo highland, Western Ethiopia.

Table 4.6a. Interaction Effects of Lime, Rhizobia Strains and Starter Nitrogen Fertilizer on PNP, NSP and NSPP at Both Locations

L ₀		PNP		NSP		NSPP	
Rhizobium strains	N(kgha ⁻¹)	Koga	Injebara	Koga	Injebara	Koga	Injebara
R ₀	N ₀	2.40 ^k	7.80 ⁱ	2.20 ^a	2.76 ^a	5.31 ^j	21.55 ^j
	N ₁	2.63 ^k	10.36 ^g	2.10 ^a	2.63 ^a	5.42 ^j	27.23 ^h
	N ₂	3.16 ^{kj}	12.00 ^f	2.56 ^a	2.63 ^a	8.01 ^{ji}	31.55 ^h
R ₁	N ₀	3.50 ^{kj}	9.83 ^{gh}	2.33 ^a	2.53 ^a	8.21 ^{ji}	25.03 ^{ji}
	N ₁	4.20 ^{ij}	14.66 ^e	2.43 ^a	2.63 ^a	10.25 ^h	38.62 ^e
	N ₂	6.63 ^{fg}	15.26 ^e	2.30 ^a	3.10 ^a	15.29 ^h	47.09 ^c
R ₂	N ₀	5.10 ^{ih}	10.76 ^{gf}	2.26 ^a	2.60 ^a	11.61 ^h	27.90 ^h
	N ₁	7.26 ^{efg}	14.90 ^e	2.53 ^a	2.70 ^a	18.50 ^{edf}	40.02 ^d
	N ₂	8.00 ^{ef}	17.63 ^d	2.10 ^a	2.63 ^a	16.72 ^{egf}	46.51 ^c
L ₁							
R ₀	N ₀	5.83 ^{hg}	8.20 ^{ih}	2.13 ^a	2.60 ^a	12.78 ^h	21.25 ^j
	N ₁	6.63 ^{fg}	14.96 ^e	2.20 ^a	2.26 ^a	14.48 ^h	33.58 ^{egf}
	N ₂	7.23 ^{efg}	14.90 ^e	2.30 ^a	2.46 ^a	16.60 ^{egf}	36.83 ^{edf}
R ₁	N ₀	8.36 ^{ed}	14.13 ^e	2.50 ^a	2.40 ^a	21.31 ^{ed}	33.70 ^{egf}
	N ₁	16.23 ^b	22.96 ^b	2.43 ^a	2.30 ^a	39.48 ^{ba}	52.08 ^{cb}
	N ₂	12.46 ^c	19.26 ^{dc}	2.36 ^a	2.76 ^a	29.42 ^c	53.19 ^b
R ₂	N ₀	9.63 ^d	15.10 ^e	2.46 ^a	2.26 ^a	23.88 ^d	34.33 ^{edf}
	N ₁	18.40 ^a	25.03 ^a	2.26 ^a	2.60 ^a	41.58 ^a	65.10 ^a
	N ₂	14.73 ^b	20.60 ^c	2.40 ^a	2.53 ^a	35.34 ^b	52.23 ^{cb}
LSD (p ≤ 0.05)		1.50	1.75	0.54	0.40	5.45	6.03
CV (%)		11.44	7.09	14.09	9.48	17.71	9.52
SE		0.90	1.05	0.32	0.24	3.28	3.63

R₀ = no rhizobia, R₁= FB-37, R₂=FB-1035, L₀ = 0 t/ha lime, L₁ = 2 t/ha lime, N₀= 0kg/ha N, N₁= 10kg/ha N and N₂ = 20kg/ha N, LSD= least significant difference, CV= coefficient of variation and SE= standard error, PNP = pod number per plant, NSP= number of seed per pod and NSPP=number of seed per plant. Means in the same letter along the column are not statistically difference.

4.6.3. Aboveground dry biomass (AGBY)

Highly significant variation ($p \leq 0.0$) in above ground dry biomass was observed by all the interactions of rhizobia strains, lime and starter nitrogen at both locations except the combination of rhizobia strains with starter nitrogen at Injebara site (Appendix Table 6). This indicates that the combined application of these inputs substantially enhances biomass production, likely due to improved nitrogen fixation, soil pH correction, and early nitrogen availability. However, the inconsistent response at Injebara suggests that local soil conditions may affect the efficiency of these interactions.

From the interaction effects of treatments on above ground biomass yield, the effect of application of lime, rhizobia strains and starter nitrogen fertilizer together was by far superior over the sole application as well as the control. Thus the highest aboveground biomass yields of 6122.2 kg/ ha were produced in response to the application of FB-1035 + 2 t ha⁻¹ + 10 kg ha⁻¹ N fertilizer which was statically in par with FB-37 + 2 t ha⁻¹ + 10 kg ha⁻¹ N (5970.2kg/ ha) at Koga (Table 4.6b). Similarly, the interaction of FB-1035 + 2 t ha⁻¹ + 10 kg ha⁻¹ N produced the maximum biological dry biomass yield of 8711.1 kg ha⁻¹ at Injebara location, whereas the lowest aboveground dry biomass yield of (2622.2 & 5833.3 kg ha⁻¹) was obtained from the control treatment which was statically in par with the application of FB-37 rhizobia strain alone (2827.4 and 6000 kg ha⁻¹) at Koga and Injebara locations respectively (Table 4.6b). This implies that rhizobium strains alone without addressing the soil acidity and limited inorganic N content of the initial soils didn't have any effects. The increase in soil pH due to lime together with additional supply of nitrogen helped the inoculation to work and were responsible for better biological yields of Faba bean. At Injebara, the lack of a significant interaction between rhizobia and starter nitrogen likely indicates that other factors, such as natural soil nitrogen levels or highly efficient rhizobia strains, reduced the need for additional nitrogen. This result is in agreement with the findings of Dereje Geleta *et al.* (2022), Bekalu Abebe *et al.* (2023) Abiyot Abeje *et al.* (2022) and Samrawit Mebrhatu (2024) who found that combined application of lime with balanced inorganic fertilizer and bio fertilizers increased biomass and grain yield. Similarly, Endalkachew Fekadu *et al.* (2018) suggested combined application of lime with bio fertilizer and inorganic fertilizer as effective amendment to improve the biomass yield of Faba bean. Another author, Wafula *et al.* (2013) also reported that the combined application of lime with bio fertilizers and

inorganic fertilizers at the same time increased the biomass yield, grain yield, and harvest index of soybean.

4.6.4. Grain yield (GY)

Grain yield was highly significantly influenced ($p < 0.05$) by both the three-way interaction among lime, rhizobia strains, and starter nitrogen, as well as by most two-way interactions at both experimental sites. The exception was the two-way interaction between lime and rhizobia strains at Injebara, which did not significantly ($p < 0.05$) affect grain yield (Appendix Table 6). The significant effect of the three-way interaction may be lime improves soil pH, enhancing nutrient availability and promoting rhizobia activity, while starter nitrogen supports early crop growth until biological nitrogen fixation is fully established. The absence of a significant lime–rhizobia interaction at Injebara may be attributed to site-specific factors such as relatively better soil pH, differences in native rhizobia populations, or other soil fertility parameters that reduced the need for liming or minimized its effectiveness in enhancing rhizobia performance.

The interaction of all three factors consistently produced a significantly higher grain yield compared to the sole or two-way applications of lime, rhizobia, and nitrogen, as well as the control. The highest grain yield at Koga ($2,877.8 \text{ kg ha}^{-1}$) was obtained from plots treated with FB-1035 + 2 t ha^{-1} lime + $10 \text{ kg ha}^{-1} \text{ N}$, followed by FB-37 + 2 t ha^{-1} lime + $10 \text{ kg ha}^{-1} \text{ N}$ ($2,488.9 \text{ kg ha}^{-1}$) (Table 4.6b). At Injebara, the maximum grain yield ($3,388.9 \text{ kg ha}^{-1}$) was recorded from the FB-1037 + 2 t ha^{-1} lime + $10 \text{ kg ha}^{-1} \text{ N}$ treatment, which was statistically at par with FB-1035 + 2 t ha^{-1} lime + $10 \text{ kg ha}^{-1} \text{ N}$ ($3,344.3 \text{ kg ha}^{-1}$). Conversely, the untreated control plots produced the lowest grain yields at both locations 588.9 kg ha^{-1} at Koga and 955.6 kg ha^{-1} at Injebara (Table 4.6b). The significant three-way interaction indicates a conditional synergy, where the full benefit of lime and rhizobia is realized only when starter nitrogen is also applied. This highlights the importance of a balanced and integrated nutrient management approach, particularly in field conditions where soil acidity, microbial efficiency, and early nitrogen demand interact to determine crop performance. This result align with the findings of Abebe Zerihun and Abera Tolera (2014), Allito *et al.* (2020) Addisu Ebbisa and Tadele Amdemariam (2021), Dereje *et al.* (2022), and Samrawit Mebrhatu (2024) who reported that the combined application of lime, rhizobia, and inorganic nitrogen significantly improved Faba bean yields. Similarly, Abiyot Abeje *et al.* (2022) observed increased

soybean yields in response to integrated application of bio-fertilizers, lime, and NPSB fertilizers. Abera Tolera *et al.* (2016) and Workneh Bekere (2013) also noted yield improvements in legumes following the joint use of chemical fertilizers and rhizobium inoculation. Furthermore, Wafula *et al.* (2013) confirmed that the combined use of lime, bio-fertilizers, and inorganic fertilizers significantly enhanced soybean grain yield.

Table 4.6b. Interaction effects of treatments on biomass yield, grain yield and straw yield.

	AGBY(Kg/ha)		Grain yield(kg/ha)	
	Koga	Injebara	Koga	Injebara
R ₀ + L ₀ + N ₀	2622.2 ^h	5833.3 ^k	588.9 ^l	955.6 ⁱ
R ₀ + L ₀ + N ₁	2890.4 ^{thg}	7322.2 ^{hg}	710.9 ^{kl}	1377.8 ^h
R ₀ + L ₀ + N ₂	3184.3 ^{feg}	7466.7 ^{fg}	766.7 ^{kl}	1422.2 ^h
R ₁ + L ₀ + N ₀	2827.4 ^{hg}	6000.0 ^k	755.6 ^{kl}	1233.4 ^h
R ₁ + L ₀ + N ₁	3066.0 ^{theg}	6533.3 ^{ji}	1043.3 ^{ij}	1844.4 ^g
R ₁ + L ₀ + N ₂	3388.3 ^{fe}	6800.0 ⁱ	1155.6 ^{igh}	1988.9 ^{gf}
R ₂ + L ₀ + N ₀	2888.9 ^{thg}	6188.9 ^{jk}	853.3 ^{kj}	1288.9 ^h
R ₂ + L ₀ + N ₁	3103.7 ^{theg}	6555.6 ^{ji}	1111.1 ^{ih}	1911.1 ^g
R ₂ + L ₀ + N ₂	3425.9 ^e	6866.7 ^{hi}	1355.6 ^{fgh}	2188.9 ^{ef}
R ₀ + L ₁ + N ₀	3276.4 ^{ed}	7533.3 ^{fge}	1055.6 ^{ij}	1444.4 ^h
R ₀ + L ₁ + N ₁	3509.8 ^e	7877.8 ^{dfce}	1400.0 ^{fg}	2566.7 ^{cd}
R ₀ + L ₁ + N ₂	4223.7 ^d	8088.9 ^{bc}	1477.8 ^{te}	2755.6 ^{cb}
R ₁ + L ₁ + N ₀	3527.4 ^e	7400.0 ^g	1677.8 ^{de}	2377.8 ^{ed}
R ₁ + L ₁ + N ₁	5245.8 ^c	8555.6 ^{ba}	2488.9 ^b	3388.9 ^a
R ₁ + L ₁ + N ₂	5970.2 ^{ba}	8000.0 ^{dce}	1888.9 ^{dc}	2811.1 ^b
R ₂ + L ₁ + N ₀	4229.3 ^d	7611.1 ^{dfge}	1800.0 ^d	2511.1 ^d
R ₂ + L ₁ + N ₁	6122.2 ^a	8711.1 ^a	2877.8 ^a	3344.3 ^a
R ₂ + L ₁ + N ₂	5559.6 ^{bc}	8033.3 ^{dc}	2133.3 ^c	2911.1 ^b
LSD(P<0.05)	503.7	472.25	251.4	216.8
CV (%)	7.9	3.89	10.8	6.11
SE	303.5	284.6	151.5	130.28

R₀ = no rhizobia, R₁= FB-37, R₂=FB-1035, L₀ = 0 t/ha lime, L₁ = 2 t/ha lime, N₀= 0kg/ha N, N₁= 10kg/ha N and N₂ = 20kg/ha N, LSD= least significant difference, CV= coefficient of variation and SE= standard error, AGBY= above ground biomass yield, GY = Grain yield. Means in the same letter along the column are not statistically difference.

4.6.5. Straw yield

At the Koga site, straw yield was significantly ($p < 0.05$) influenced by both the three-way and most two-way interactions among lime, rhizobia strains, and starter nitrogen, except for the interaction between rhizobia strains and starter nitrogen, which did not have a significant, effect (Appendix Table 7). At Koga, the responsiveness of straw yield to most interactions likely reflects a more nutrient-deficient or acidic soil condition,

where combined inputs strongly enhanced biomass production. The lack of a significant rhizobia $\times$ starter nitrogen interaction may indicate redundancy in nitrogen supply or limited rhizobia effectiveness under existing soil conditions. In contrast, at Injebara, straw yield was significantly affected ($p < 0.05$) only by the three-way interaction and by the two-way interaction between lime and rhizobia strains; other two-way interactions did not show a significant effect (Appendix Table 7). At Injebara, fewer significant two-way interactions imply that one or more factors may have already been sufficiently available, reducing the additive benefit of combined inputs.

At the Koga site, the highest straw yield ($4,081 \text{ kg ha}^{-1}$) was obtained from FB-37 + 2 t ha^{-1} lime + $20 \text{ kg ha}^{-1} \text{ N}$, while the lowest straw yield ($1,849.7 \text{ kg ha}^{-1}$) was observed from FB-37 + 2 t ha^{-1} lime which was statistically similar with FB-1035 + 10 kg/ha N , FB-37 + 10 kg/ha and the control ($1992.6, 2022.7, 2033.3 \text{ kg/ha}$) respectively (Table 4.6c). The highest straw yield at Injebara ($6,088 \text{ kg ha}^{-1}$) was obtained from plots treated with 2 t ha^{-1} lime (Table 4.6c). This was statistically comparable to straw yields from plots treated with $20 \text{ kg ha}^{-1} \text{ N}$ ($6,044 \text{ kg ha}^{-1}$) and $10 \text{ kg ha}^{-1} \text{ N}$ ($5,944.4 \text{ kg ha}^{-1}$). In contrast, the lowest straw yield ($4,644.4 \text{ kg ha}^{-1}$) was recorded from FB-1035 + $10 \text{ kg ha}^{-1} \text{ N}$ at Injebara (Table 4.6c). The observed increases in straw yield under integrated treatments may be due to in acidic soils, low pH hampers both rhizobia survival and nitrogen fixation and Lime raises pH, creating a better environment for rhizobia strains to nodulate effectively. Additionally Starter nitrogen supports early plant growth before nodulation is established. When all three are combined at Koga and Injebara, they likely complement each other, overcoming acidity stress leading to significantly higher straw yield. This finding is supported by Dereje Geleta *et al.* (2022), who reported increased straw yield of Faba bean under combined application of lime, NPSB fertilizer, and rhizobia inoculation. Similarly, Abiyot Abeje *et al.* (2022) found that the integration of bio-fertilizers, lime, and NPSB fertilizers enhanced straw yields in Faba bean.

4.6.6. Harvest index (HI)

The harvest index (HI), a key indicator of nutrient partitioning and crop productivity, was highly significantly ($p < 0.05$) influenced by the interaction among rhizobia strains, lime, and starter nitrogen at the Injebara site. However, at Koga, no significant ($p < 0.05$) effect was observed (Appendix Table 7).

At Injebara, the highest harvest index value (39.64%) was recorded from the FB-37 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ N treatment, followed by FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ N (38.39%). The lowest HI (16.46%) was observed in the untreated control plots (Table 4.6c). The elevated harvest index values from integrated treatments suggest a more efficient allocation of assimilates to grain rather than vegetative biomass, with 39.64% of the total biomass allocated to seed production and 60.36% to straw and husk (Table 4.6c). This result is in agreement with those of Dereje Geleta *et al.* (2022), who found that integrated application of lime, NPSB, and bio-fertilizers significantly improved harvest index by enhancing grain yield. Consistent findings were also reported by Workneh Bekere (2013), who observed improved HI in soybean due to integrated nutrient management involving lime, rhizobia inoculation, and nitrogen fertilizer.

Table 4.6c. Interaction effects of rhizobia strains, lime and starter nitrogen on straw yield and harvest index

	SY(Kg/ha)		HI (%)	
	Koga	Injebara	Koga	Injebara
R ₀ + L ₀ + N ₀	2033.3 ^e	4877.8 ^{cebd}	22.9 ^h	16.5 ⁱ
R ₀ + L ₀ + N ₁	2179.6 ^{ed}	5944.4 ^a	25.2 ^{gfh}	18.8 ^{ih}
R ₀ + L ₀ + N ₂	2417.7 ^{ed}	6044.4 ^a	23.9 ^{gh}	19.0 ^{ih}
R ₁ + L ₀ + N ₀	2071.9 ^e	4766.6 ^{ed}	27.1 ^{gfeh}	20.7 ^h
R ₁ + L ₀ + N ₁	2022.7 ^e	4688.9 ^{ed}	34.7 ^{gfdec}	28.2 ^g
R ₁ + L ₀ + N ₂	2232.8 ^{ed}	4811.1 ^{ced}	34.3 ^{gfdec}	29.3 ^{efg}
R ₂ + L ₀ + N ₀	2035.5 ^e	4900.0 ^{cebd}	29.5 ^{gfdeh}	20.9 ^h
R ₂ + L ₀ + N ₁	1992.6 ^e	4644.4 ^e	36.7 ^{bdec}	29.2 ^{fg}
R ₂ + L ₀ + N ₂	2070.4 ^e	4677.8 ^{ed}	39.7 ^{bdac}	31.9 ^{efdg}
R ₀ + L ₁ + N ₀	2220.9 ^{ed}	6088.9 ^a	32.3 ^{gfdech}	19.2 ^{ih}
R ₀ + L ₁ + N ₁	2109.8 ^e	5311.1 ^{cb}	40.4 ^{bdac}	32.6 ^{efdc}
R ₀ + L ₁ + N ₂	2745.9 ^{cd}	5333.3 ^b	35.9 ^{fdec}	34.1 ^{dc}
R ₁ + L ₁ + N ₀	1849.7 ^e	5022.2 ^{cebd}	47.3 ^{ba}	32.2 ^{efd}
R ₁ + L ₁ + N ₁	2756.9 ^{bc}	5166.7 ^{cbd}	47.7 ^a	39.6 ^a
R ₁ + L ₁ + N ₂	4081.3 ^a	5188.9 ^{cbd}	31.7 ^{gfdeh}	35.1 ^{bdc}
R ₂ + L ₁ + N ₀	2429.4 ^{ed}	5100.0 ^{cebd}	43.1 ^{bac}	33.0 ^{edc}
R ₂ + L ₁ + N ₁	3244.5 ^{cb}	5366.8 ^b	47.3 ^{ba}	38.4 ^{ba}
R ₂ + L ₁ + N ₂	3426.3 ^b	5122.2 ^{cebd}	38.6 ^{bdac}	36.2 ^{bac}
LSD(p<0.05)	630.1	519.8	10.9	3.7
CV (%)	15.5	6.1	18.5	7.7
SE	379.7	313.2	6.58	2.2

R₀ = no rhizobia, R₁= FB-37, R₂=FB-1035, L₀ = 0 t/ha lime, L₁ = 2 t/ha lime, N₀= 0kg/ha N, N₁= 10kg/ha N and N₂ = 20kg/ha N, SY= straw yield, HI= harvest index, LSD= least significant difference, CV= coefficient of variation and SE= standard error. Means in the same letter along the column are not statistically difference.

4.7. Correlation Analysis of Agronomic Parameters and Soil Properties

Correlation analysis measures the degree of association between variables and provides insight into how agronomic traits contribute to crop performance. In the current study, grain yield was found to be the cumulative result of various agronomic and physiological traits. The analysis revealed highly significant ($p \leq 0.001$), significant ($p \leq 0.05$), and non-significant ($p > 0.05$) positive and negative correlations among the yield and yield-related components of Faba bean (Table 4.7a).

Specifically, grain yield showed significant positive correlations with several key traits: days to flowering ($r = 0.44$), days to maturity ($r = 0.37$), nodule number ($r = 0.74$), effective nodules ($r = 0.75$), nodule dry weight ($r = 0.77$), plant height ($r = 0.88$), number of pods per plant ($r = 0.93$), number of seeds per plant ($r = 0.92$), biomass yield ($r = 0.84$), straw yield ($r = 0.45$), and harvest index ($r = 0.77$) at Koga (Table 4.7a). Whereas, grain yield was significantly and positively correlated with days to maturity ($r = 0.57$), nodule number ($r = 0.43$), effective nodule ($r = 0.89$), nodule dry weight ($r = 0.87$), plant height ($r = 0.63$), number of pod per plant ($r = 0.89$), number of seed per plant ($r = 0.79$), biomass yield ($r = 0.80$) and harvest index ($r = 0.96$) at Injebara (Table 4.7a).

The presence of significant and positive correlations among most growth and yield-related traits except for the number of seeds per pod suggests that the combined application of rhizobium strains, lime, and starter nitrogen fertilizer played a vital role in improving yield components, thereby enhancing overall Faba bean productivity. However, number of seed per pod was the only plant parameter that had insignificant relationship with other growth parameters and yield and yield components at both locations (Table 4.7a). These findings are consistent with previous reports by Shiferaw Boke and Anteneh Fekadu (2014), who noted strong correlations among growth, nodulation, and yield parameters in legumes.

Table 4.7a Correlation analysis between and among yield and yield components Faba bean in the study areas

Parameters	DF	DM	NN	ENN	NDW	PH	PNP	NSP	NSPP	BY	GY	SY	HI
DF	1.00												
DM	0.42 [*]	1.00											
NN	0.57 ^{**}	0.54 ^{**}	1.00										
ENN	0.59 ^{**}	0.52 ^{**}	0.99 ^{**}	1.00									
NDW	0.58 ^{**}	0.51 ^{**}	0.96 ^{**}	0.96 ^{**}	1.00								
PH	0.42 [*]	0.38 [*]	0.71 ^{**}	0.72 ^{**}	0.74 ^{**}	1.00							
PNP	0.44 ^{**}	0.46 ^{**}	0.77 ^{**}	0.77 ^{**}	0.80 ^{**}	0.86 ^{**}	1.00						
NSP	0.06 ^{ns}	0.15 ^{ns}	0.19 ^{ns}	0.18 ^{ns}	0.17 ^{ns}	0.13 ^{ns}	0.10 ^{ns}	1.00					
NSPP	0.46 ^{**}	0.48 ^{**}	0.78 ^{**}	0.78 ^{**}	0.81 ^{**}	0.85 ^{**}	0.98 ^{**}	0.27 [*]	1.00				
BY	0.47 ^{**}	0.30 [*]	0.58 ^{**}	0.59 ^{**}	0.63 ^{**}	0.79 ^{**}	0.87 ^{**}	0.06 ^{ns}	0.85 ^{**}	1.00			
GY	0.44 ^{**}	0.37 [*]	0.74 ^{**}	0.75 ^{**}	0.77 ^{**}	0.88 ^{**}	0.93 ^{**}	0.10 ^{ns}	0.92 ^{**}	0.84 ^{**}	1.00		
SY	0.36 [*]	0.15 ^{ns}	0.24 [*]	0.28 [*]	0.33 [*]	0.48 ^{**}	0.57 ^{**}	0.008 ^{ns}	0.55 ^{**}	0.86 ^{**}	0.45 ^{**}	1.00	
HI	0.24 ^{ns}	0.30 [*]	0.65 ^{**}	0.64 ^{**}	0.64 ^{**}	0.68 ^{**}	0.62 ^{**}	0.12 ^{ns}	0.62 ^{**}	0.33 [*]	0.77 ^{**}	-0.16 ^{ns}	1.0

Injebara

Parameters	DF	DM	NN	ENN	NDW	PH	PNP	NSP	NSPP	BY	GY	SY	HI
DF	1.00	0.16 ^{ns}	0.02 ^{ns}	0.05 ^{ns}	0.25 ^{ns}	0.01 ^{ns}	0.05 ^{ns}	0.08 ^{ns}	0.08 ^{ns}	0.07 ^{ns}	0.20 ^{ns}	-0.16 ^{ns}	0.23 ^{ns}
DM		1.00	0.4 [*]	0.58 ^{**}	0.61 ^{**}	0.38 [*]	0.58 ^{**}	-0.08 ^{ns}	0.52 ^{**}	0.38 [*]	0.57 ^{**}	-0.18 ^{ns}	0.58 ^{**}
NN			1.00	0.48 ^{**}	0.41 [*]	0.29 [*]	0.48 ^{**}	0.07 ^{ns}	0.49 ^{**}	0.35 [*]	0.43 ^{**}	-0.02 ^{ns}	0.39 [*]
ENN				1.00	0.88 ^{**}	0.62 ^{**}	0.90 ^{**}	-0.20 ^{ns}	0.82 ^{**}	0.69 ^{**}	0.89 ^{**}	-0.12 ^{ns}	0.87 ^{**}
NDW					1.00	0.54 ^{**}	0.88 ^{**}	-0.19 ^{ns}	0.82 ^{**}	0.59 ^{**}	0.87 ^{**}	-0.26 ^{ns}	0.88 ^{**}
PH						1.00	0.56 ^{**}	-0.29 [*]	0.49 ^{**}	0.77 ^{**}	0.63 ^{**}	0.38 [*]	0.51 ^{**}
PNP							1.00	-0.15 ^{ns}	0.93 ^{**}	0.63 ^{**}	0.89 ^{**}	-0.17 ^{ns}	0.87 ^{**}
NSPP									1.00	0.55 ^{**}	0.79 ^{**}	-0.20 ^{ns}	0.79 ^{**}
BY										1.00	0.80 ^{**}	0.52 ^{**}	0.62 ^{**}
GY											1.00	-0.07 ^{ns}	0.96 ^{**}
SY												1.00	-0.32 [*]
HI													1.0

Grain yield of Faba bean was also significantly and positively correlated with soil pH ($r = 0.73$), available phosphorus (av. P) ($r = 0.89$), and organic carbon (OC) ($r = 0.74$), while it was significantly and negatively correlated with exchangeable acidity (ex. A) ($r = -0.63$) and exchangeable aluminum (ex. Al^{3+}) ($r = -0.60$) at Koga (Table 4.7b). These correlations suggest that soil acidity parameters (ex. A and ex. Al^{3+}), low soil pH, and poor nutrient availability especially low av. P and OC are among the major limiting factors for above-ground dry biomass and grain yield in the acid soils of the Koga site.

Moreover, the correlation analysis among soil physico-chemical properties revealed several strong associations. Specifically, soil pH was strongly and positively correlated with available phosphorus ($r = 0.89$) and organic carbon ($r = 0.74$) at Koga (Table 4.7b). A similarly strong and positive correlation was observed between available phosphorus and organic carbon ($r = 0.81$), as well as between exchangeable acidity and exchangeable aluminum ($r = 0.93$) at this location. In contrast, exchangeable acidity and exchangeable aluminum were strongly and negatively correlated with soil pH, available phosphorus, and organic carbon at Koga (Table 4.7b). These results underscore the importance of managing soil acidity and enhancing nutrient availability to improve Faba bean productivity in acidic soils such as those found in Koga.

Grain yield of Faba bean was positively and strongly correlated with soil pH ($r=0.81$), av. P ($r=0.61$) and OC ($r=0.54$) while it was negatively and strongly correlated with exchangeable acidity ($r=-0.58$) and exchangeable Al^{3+} ($r=-0.45$) at Injebara (Table 4.7b). Similarly, the correlation analysis between soil physic-chemical properties indicated significant correlation coefficients at Injebara (Table 4.7b). Accordingly, strong and positive correlation was obtained between soil pH and Av. P ($r=0.73$), soil pH and soil OC ($r=0.40$), available P and OC ($r=0.39$) and ex. A and ex. Al ($r=0.73$) while ex. A and ex. Al were strong and negative correlated with soil pH, OC av. P at Injebara (Table 4.7b).

Table 4.7b. Pearson correlation coefficients between selected soil properties, grain yield and above ground biomass yield and straw yield in the study areas

Koga						
Parameters	GY	Ph	av. P	OC	ex. A	ex. Al
GY	1.00	0.73**	0.89**	0.74**	-0.63**	-0.60**
Ph		1.00	0.89**	0.74**	-0.83**	-0.76**
Av. P			1.00	0.81**	-0.77**	-0.74**
OC				1.00	-0.65**	-0.62**
Ex. A					1.00	0.93***
Ex. Al						1.00
Injebara						
Parameters	GY	pH	av. P	OC	ex. A	ex. Al
GY	1.00	0.81**	0.61**	0.54**	-0.58**	-0.48**
pH		1.00	0.73**	0.40*	-0.72**	-0.62**
av. P			1.00	0.39***	-0.73***	-0.62***
OC				1.00	-0.31*	-0.45**
ex. A					1.00	0.73**
ex. Al						1.00

GY=grain yield, pH=power of hydrogen, av, P=available phosphorus, OC= organic carbon, ex.A=exchangeable acidity, ex. Al= exchangeable aluminum.

4.8. Economic Analysis.

The results of the partial budget analysis (Table 4.8a and b) indicated that both rhizobium strains FB-1035 and FB-37 either applied individually or in combination with lime and starter nitrogen, produced acceptable marginal rates of return ($MRR > 100\%$). According to CIMMYT guidelines, when multiple treatments exceed this threshold, the one with the highest net benefit should be selected for recommendation. Accordingly, the application of FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ starter nitrogen generated the highest net benefit of 238143.6 Ethiopian Birr ha⁻¹ at Koga, and 279052.7 Ethiopian Birr ha⁻¹ at Injebara, while maintaining a greater MRR of 3168.9 and 1661.7 at Koga and Injebara respectively making it economically viable for both study locations (Table 4.8a and b). When compared to the control, this treatment offered an additional net benefit of 186,877.6 and 195,153.9 Birr ha⁻¹ at Koga and Injebara, respectively (Table 4.8a and b). Therefore, this combined treatment is not only agronomical effective but also economically justifiable for Faba bean production in the acid soils of both districts.

Table 4.8a. Partial budget analysis of Faba bean influenced by treatments at Koga location

Treatment	AGY (kg/ha)	ASY(kg/ ha)	GI(Et Birr)	TVC(Et Birr)	NB(Et Birr)	MRR (%)
R ₀ + L ₀ + N ₀	530.01	1830.0	51266.0	0.0	51266.0	-
R ₁ + L ₀ + N ₀	680.04	1864.7	65536.2	40.0	65496.2	355.8
R ₂ + L ₀ + N ₀	767.97	1832.0	73873.2	40.0	73833.2	564.2
R ₀ + L ₀ + N ₁	639.80	1961.6	61761.8	560.0	61201.8	D
R ₁ + L ₀ + N ₁	938.97	1820.4	90112.4	600.0	89512.4	707.8
R ₂ + L ₀ + N ₁	999.99	1793.3	95895.7	600.0	95295.7	852.3
R ₀ + L ₀ + N ₂	690.03	2175.9	66640.8	1120.0	65520.8	D
R ₁ + L ₀ + N ₂	1040.04	2009.5	99808.6	1160.0	98648.6	828.2
R ₂ + L ₀ + N ₂	1220.04	1863.4	116835.5	1160.0	115675.5	1253.9
R ₀ + L ₁ + N ₀	950.04	1998.8	91253.2	8700.0	82553.2	D
R ₁ + L ₁ + N ₀	1510.02	1664.7	144284.3	8740.0	135544.3	1324.8
R ₂ + L ₁ + N ₀	1620.00	2186.4	154993.2	8740.0	146253.2	1592.5
R ₀ + L ₁ + N ₁	1260.00	1898.8	120649.4	9260.0	111389.4	D
R ₁ + L ₁ + N ₁	2239.20	2481.2	213964.6	9300.0	204664.6	2331.9
R ₂ + L ₁ + N ₁	2589.30	2920.1	247443.6	9300.0	238143.6	3168.9
R ₀ + L ₁ + N ₂	1330.02	2471.3	127587.6	9820.0	117767.6	D
R ₁ + L ₁ + N ₂	1700.01	3673.2	163337.6	9860.0	153477.6	892.8
R ₂ + L ₁ + N ₂	1919.97	3083.7	183939.0	9860.0	174079.0	1407.8

Table 4.8b: Partial budget analysis of Faba bean influenced by treatments at Injebara

Treatments	AGY (kg/ha)	ASY(kg/ha)	GI(Et Birr)	TVC(Et Birr)	NB(Et Birr)	MRR (%)
R ₀ + L ₀ + N ₀	860.04	4390.02	83898.8	0.0	83898.8	-
R ₁ + L ₀ + N ₀	1099.98	4300.02	106648.1	40.0	106608.1	567.7
R ₂ + L ₀ + N ₀	1160.01	4410.00	112406.0	40.0	112366.0	711.7
R ₀ + L ₀ + N ₁	1240.02	5349.96	120476.9	560.0	119916.9	14.5
R ₁ + L ₀ + N ₁	1659.96	4220.01	159806.2	600.0	159206.2	982.2
R ₂ + L ₀ + N ₁	1719.99	4179.96	165489.0	600.0	164889.0	1124.3
R ₀ + L ₀ + N ₂	1279.98	5439.96	124318.1	1120.0	123198.1	D
R ₁ + L ₀ + N ₂	1819.98	4300.02	175048.1	1160.0	173888.1	1267.3
R ₂ + L ₀ + N ₂	1970.01	4210.02	189256.0	1160.0	188136.0	1623.4
R ₀ + L ₁ + N ₀	1299.96	5480.01	126236.2	8700.0	117536.2	D
R ₁ + L ₁ + N ₀	2140.02	4519.98	205561.9	8740.0	196821.9	1982.1
R ₂ + L ₁ + N ₀	2259.99	4590.00	216994.1	8740.0	208254.1	2267.9
R ₀ + L ₁ + N ₁	2310.03	4779.99	221842.8	9260.0	212582.8	8.3
R ₁ + L ₁ + N ₁	3050.01	4650.03	288352	9300.0	279052.7	1661.7
R ₂ + L ₁ + N ₁	3009.87	4830.12	292076.0	9300.0	282776.0	1754.8
R ₀ + L ₁ + N ₂	2480.04	4799.97	238003.8	9820.0	228183.8	D
R ₁ + L ₁ + N ₂	2529.99	4670.01	242684.1	9860.0	232824.1	116.0
R ₂ + L ₁ + N ₂	2619.99	4609.98	251204.0	9860.0	241344.0	329.0

R₀= no rhizobia, R₁= FB-37, R₂=FB-1035, L₀= 0t lime, L₁= 2 t/ha lime, N₀= 0kg/ha N N₁= 10kg/ha N and N₂= 20kg/ha N, AGY = adjusted grain yield, ASY = adjusted straw yield, TVC = total variable cost, GI = gross income, NB = net benefit and MRR = marginal rate of return, ETB = Ethiopian Birr, Cost of lime = 435 birr/quintal, cost of urea = 5600 birr/quintal and cost of rhizobia strains = 40 birr/one pack, price of faba bean seed = 65 birr/ 1 kg, price of faba bean straw = 50 birr/ quintal as of 2023 year.

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study demonstrated that the integrated application of lime, rhizobia strains, and starter nitrogen significantly improved soil chemical properties and Faba bean productivity in acidic soils of Northwestern Ethiopia. The combined treatment of FB-1035 + 2 t ha⁻¹ lime + 10 kg ha⁻¹ N consistently outperformed other combinations, showing superior improvements in soil pH, reduction of exchangeable acidity and aluminum, and enhanced nutrient availability.

These effects translated into significantly higher grain and biomass yields and improved economic returns, highlighting the importance of synergy among soil amendments, microbial inoculants, and nitrogen inputs. The findings confirm that managing soil acidity through an integrated approach not only restores soil fertility but also enhances biological nitrogen fixation and crop performance.

The implications of this study are substantial for sustainable intensification of Faba bean production. Adoption of such integrated nutrient management practices can reduce dependence on high nitrogen inputs, improve soil health, and increase returns for smallholder farmers in acid-prone areas. Therefore, this approach should be promoted as a practical soil fertility management strategy in similar agro-ecological zones.

5.2. Recommendation

To sustainably improve Faba bean yield and soil fertility in the study areas, the following recommendations are made based on the findings of this study:

- The combined application of FB-1035 rhizobia strain, 2 t ha⁻¹ lime, and 10 kg ha⁻¹ starter nitrogen is recommended, as it significantly improved nodulation, soil fertility, and grain yield.
- Starter nitrogen should be used in small amounts and only when necessary, since excessive nitrogen can suppress nodulation and limit biological nitrogen fixation.
- Lastly, further studies are needed to assess long term effects of treatments on soil fertility and crop productivity across different soil types and seasons.

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7. APPENDIX

Appendix Table 1. ANOVA table showing mean square values of soil properties at Koga.

Source of variation	DF	BD(gcm ⁻³)	pH (H ₂ O)	Av. P(mgkg ⁻¹)	OC%	EX A	EX Al
R	2	0.01 ^{ns}	0.01 ^{ns}	15.9 ^{**}	0.00 ^{ns}	0.07 ^{ns}	0.10 ^{ns}
L	1	0.01 [*]	4.52 ^{**}	265.4 ^{**}	0.42 ^{**}	18.99 ^{**}	10.14 ^{**}
N	2	0.01 ^{ns}	0.13 ^{**}	8.6 ^{**}	0.02 ^{**}	0.67 ^{**}	0.69 ^{**}
R*L	2	0.02 ^{ns}	0.01 ^{ns}	5.1 ^{**}	0.02 ^{**}	0.46 ^{**}	0.23 ^{**}
R*N	4	0.01 ^{ns}	0.04 [*]	1.8 ^{**}	0.00 ^{ns}	0.02 ^{ns}	0.09 [*]
L*N	2	0.03 ^{ns}	0.08 ^{**}	0.7 [*]	0.00 ^{ns}	0.16 ^{**}	0.11 [*]
R*L*N	4	0.03 ^{ns}	0.03 [*]	1.2 ^{**}	0.01 [*]	0.11 ^{**}	0.11 [*]
REP	2	0.00 ^{ns}	0.00 ^{ns}	0.0 ^{ns}	0.00 ^{ns}	0.00 ^{ns}	0.00 ^{ns}

Appendix Table 2. ANOVA table showing mean square values of soil properties at Injebara.

Source of variation	DF	BD (gcm ⁻³)	pH (H ₂ O)	Av. P(mgkg ⁻¹)	OC%	EX A	EX Al
R	2	0.00 ^{ns}	0.33 ^{**}	15.1 ^{ns}	0.02 ^{**}	0.00 ^{ns}	0.00 ^{ns}
L	1	0.01 [*]	2.56 ^{**}	345.2 ^{**}	0.40 ^{**}	0.12 ^{**}	0.09 ^{**}
N	2	0.00 ^{ns}	0.23 ^{**}	37.0 ^{**}	0.15 ^{**}	0.01 ^{**}	0.01 ^{**}
R*L	2	0.00 ^{ns}	0.19 ^{**}	19.0 [*]	0.06 ^{**}	0.00 ^{ns}	0.00 ^{ns}
R*N	4	0.00 ^{ns}	0.02 [*]	10.9 ^{ns}	0.00 ^{ns}	0.00 ^{ns}	0.00 ^{ns}
L*N	2	0.00 [*]	0.03 ^{**}	17.9 [*]	0.02 ^{**}	0.00 ^{ns}	0.00 ^{ns}
R*L*N	4	0.00 ^{ns}	0.02 [*]	14.9 [*]	0.02 ^{**}	0.00 ^{ns}	0.00 ^{ns}
REP	2	0.00 ^{ns}	0.00 ^{ns}	0.78 ^{ns}	0.00 ^{ns}	0.00 ^{ns}	0.00 ^{ns}

Appendix Table 3. Mean Squares of ANOVA for days to flowing, days to physiological maturity and plant height.

Source of variation	Df	Mean squares					
		Injebara	Koga	Injebara	Koga	Injebara	Koga
		DF	DF	DM	DM	PH	PH
R	2	8.07 ^{ns}	40.4 ^{**}	60.8 ^{**}	84.8 ^{**}	67.9 ^{ns}	856.4 ^{**}
L	1	24.0 [*]	25.4 [*]	112.7 ^{**}	115.6 ^{**}	1478.9 ^{**}	5995.6 ^{**}
N	2	7.9 ^{ns}	1.1 ^{ns}	60.8 ^{**}	8.1 [*]	546.8 ^{**}	731.9 ^{**}
R*L	2	0.9 ^{ns}	1.1 ^{ns}	40.7 ^{**}	19.2 ^{**}	56.4 ^{ns}	64.2 [*]
R*N	4	2.9 ^{ns}	1.1 ^{ns}	11.2 ^{ns}	36.9 ^{**}	15.0 ^{ns}	24.6 ^{ns}
L*N	2	0.5 ^{ns}	0.1 ^{ns}	0.4 ^{**}	16.1 ^{**}	76.3 ^{ns}	251.7 ^{**}
R*L*N	4	0.1 ^{ns}	4.7 ^{ns}	20.4 [*]	94.4 ^{**}	78.9 ^{**}	64.6 ^{**}
REP	2	10.3 ^{ns}	21.5 ^{ns}	5.6 ^{ns}	0.9 ^{ns}	1.9 ^{ns}	16.5 ^{ns}

Appendix Table 4. Mean Squares of ANOVA for NN, ENN and NDW

Source of variation	Df	Mean square					
		Injebara	Koga	Injebara	Koga	Injebara	Koga
		NN	NN	ENN	ENN	NDW	NDW
R	2	206.4 [*]	9552.3 ^{**}	709.7 ^{**}	8829.9 ^{**}	8412.8 ^{**}	16810.1 ^{**}
L	1	499.3 ^{**}	5907.4 ^{**}	1737.4 ^{**}	6050.5 ^{**}	10537.3 ^{**}	8349.2 ^{**}
N	2	274.3 [*]	1258.4 ^{**}	970.3 ^{**}	1603.9 ^{**}	1984.3 ^{**}	2016.5 ^{**}
R*L	2	159.4 ^{ns}	77.2 ^{**}	30.7 ^{ns}	152.2 ^{**}	327.6 ^{**}	214.2 ^{**}
R*N	4	79.4 ^{ns}	41.4 ^{ns}	18.3 ^{ns}	20.2 ^{ns}	51.6 [*]	121.2 ^{**}
L*N	2	108.8 ^{ns}	152.6 ^{**}	38.4 ^{ns}	105.7 ^{**}	48.6 [*]	90.2 [*]
R*L*N	4	320.1 ^{**}	117.4 ^{**}	53.8 [*]	93.6 ^{**}	54.7 [*]	103.9 ^{**}
REP	2	69.1 ^{ns}	1.74 ^{ns}	4.5 ^{ns}	4.9 ^{ns}	18.0 ^{ns}	2.4 ^{ns}

Appendix Table 5. Mean Squares of ANOVA for NPPP, NSP and NSPP at Injebara and Koga

Source of variation	Df	Mean squares					
		Injebara	Koga	Injebara	Koga	Injebara	Koga
		PNP	PNP	NSP	NSP	NSPP	NSPP
R	2	176.9 ^{**}	160.9 ^{**}	0.02 ^{ns}	0.09 ^{ns}	1263.8 ^{**}	962.7 ^{**}
L	1	293.1 ^{**}	534.6 ^{**}	0.68 ^{**}	0.00 ^{ns}	982.8 ^{**}	3064.1 ^{**}
N	2	210.8 ^{**}	61.2 ^{**}	0.16 ^{ns}	0.00 ^{ns}	1624.1 ^{**}	309.0 ^{**}
R*L	2	13.9 ^{**}	20.4 ^{**}	0.00 ^{ns}	0.03 ^{ns}	86.6 ^{**}	151.7 ^{**}
R*N	4	3.38 [*]	10.2 ^{**}	0.21 [*]	0.10 ^{ns}	74.5 ^{**}	55.0 ^{**}
L*N	2	30.8 ^{**}	27.6 ^{**}	0.01 ^{ns}	0.02 ^{ns}	140.2 ^{**}	107.2 ^{**}
R*L*N	4	3.1 [*]	6.1 ^{**}	0.03 ^{ns}	0.08 ^{ns}	40.3 [*]	30.2 [*]
REP	2	0.3 ^{ns}	2.1 ^{ns}	0.03 ^{ns}	0.07 ^{ns}	4.5 ^{ns}	6.4 ^{ns}

Appendix Table 6. Mean Squares of ANOVA for AGBY, GY and SY

Source of variation	Df	Mean squares			
		Injebara AGBY	Koga AGBY	Injebara GY	Koga GY
R	2	196337.26 ^{ns}	4330459.6 ^{**}	1934190.69 ^{**}	2282189.7 ^{**}
L	1	24987741.16 ^{**}	33925816.4 ^{**}	16334263.01 ^{**}	11925993.2 ^{**}
N	2	7827452.14 ^{**}	5404220.1 ^{**}	3307725.92 ^{**}	1111143.1 ^{**}
R*L	2	1090412.26 ^{**}	2370777.1 ^{**}	33502.58 ^{ns}	359449.1 ^{**}
R*N	4	507612.44 ^{ns}	482885.3 [*]	54254.38 [*]	87712.1 [*]
L*N	2	906461.39 ^{**}	1593524.7 ^{**}	281705.10 ^{**}	440352.1 ^{**}
R*L*N	4	1673538.07 ^{**}	509130.1 [*]	210327.46 ^{**}	105503.9 [*]
REP	2	25226.38 ^{ns}	58952.3 ^{ns}	9634.76 ^{ns}	111.98 ^{ns}

Appendix Table 7. Mean square ANOVA for harvest index.

Source of Variation		Mean squares			
		Injebara	Koga	Injebara	Koga
		SY	SY	HI	HI
R	2	2502500.8**	330768.9 ^{ns}	375.6***	407.3**
L	1	916245.4**	5622513.9**	1231.1***	1351.4***
N	2	26337.5 ^{ns}	2389582.7**	320.2***	138.7 ^{ns}
R*L	2	322046.7*	884005.8**	4.24 ^{ns}	22.8 ^{ns}
R*N	4	39592.1 ^{ns}	322239.8 ^{ns}	4.22 ^{ns}	25.7 ^{ns}
L*N	2	319811.1 ^{ns}	1259053.5**	12.2 ^{ns}	182.4*
R*L*N	4	788470.6**	415687.8*	47.9***	62.3 ^{ns}
REP	2	14825.7 ^{ns}	63873.2 ^{ns}	2.1 ^{ns}	55.9 ^{ns}

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Name of laboratory	Assosa Agricultural research Center soil laboratory	Name of customer	Tesema Minale
Address	Assosa	Address	Fogera National Rice Research and Training Center
	Tel: (+251) 577-752451		Email:tesemaaminale37@gmail.com
			Tel: +251918710743

Sample type: Soil sample before planting
Sample condition: air dried

Sampled and submitted by: Tesema Minale
Date of test performed: 07/11/2022- 16/02/2023

Date of sample received: 02/03/2023

Location	Texture	BD(g/cm ³)	pH(1:2.5) H ₂ O	Av P (mg kg ⁻¹)	OC (%)	Ex A (cmolkg ⁻¹)	Ex Al (cmolkg ⁻¹)
Koga	Clay	1.31	4.78	7.06	1.41	2.25	1.77
Injebara	Clay loam	1.23	5.44	30.92	3.94	1.04	0.72

Prepared by: _____

Approved by: _____



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Name of laboratory	Assosa Agricultural Research Center soil laboratory	Name of customer	Tesema Minale
Address	Assosa	Address	Fogera National Rice Research and Training Center
	Tel: (+251) 577-752451		Email:tesemaaminale37@gmail.com
			Tel: +251918710743

Sample type: Soil

Sampled and submitted by: Tesema Minale

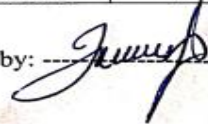
Sample condition: air dried

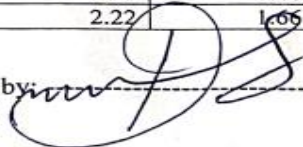
Date of test performed: 24/05/2023- 16/08/2024

Location: Koga

Date of sample received: 02/10/2024

No	Customer ID	BD (g/cm ³)	pH (1:2.5) H ₂ O	Av P mgkg ⁻¹	OC (%)	Ex A (cmol _e kg ⁻¹)	Ex Al (cmol _e kg ⁻¹)
1	S0L0N0	1.24	4.75	7.06	1.57	2.01	1.53
2	S0L0N1	1.25	4.87	8.44	1.61	2.25	1.61
3	S0L0N2	1.25	4.82	8.29	1.65	2.49	1.69
4	S0L1N0	1.25	5.61	11.28	1.72	0.64	0.32
5	S0L1N1	1.25	5.32	11.36	1.73	0.64	0.4
6	S0L1N2	1.23	5.24	10.97	1.70	0.96	0.64
7	S1L0N0	1.22	4.96	7.9	1.69	1.69	1.29
8	S1L0N1	1.27	4.91	8.9	1.69	1.85	1.37
9	S1L0N2	1.24	4.88	8.29	1.61	1.85	1.53
10	S1L1N0	1.21	5.34	11.59	1.79	0.48	0.32
11	S1L1N1	1.21	5.64	14.12	1.82	0.8	0.48
12	S1L1N2	1.27	5.25	13.12	1.80	1.69	1.37
13	S2L0N0	1.21	4.96	8.13	1.66	1.69	1.53
14	S2L0N1	1.24	5.02	10.05	1.59	1.85	1.12
15	S2L0N2	1.28	4.9	8.52	1.62	1.93	1.53
16	S2L1N0	1.29	5.58	13.58	1.77	0.48	0.4
17	S2L1N1	1.21	5.75	14.73	1.85	0.72	0.48
18	S2L1N2	1.22	5.25	13.73	1.82	1.04	0.64
19	S0L0N0	1.27	4.8	7.31	1.57	1.98	1.46
20	S0L0N1	1.22	4.93	8.39	1.79	2.22	1.66

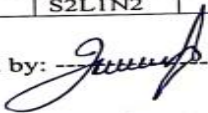
Prepared by: 

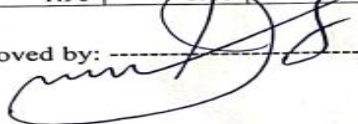
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21	S0L0N2	1.22	4.87	8.19	1.74	2.47	1.64
22	S0L1N0	1.15	5.65	12.62	1.76	0.54	0.36
23	S0L1N1	1.28	5.35	10.66	1.87	0.55	0.39
24	S0L1N2	1.31	5.34	10.07	1.79	0.81	0.69
25	S1L0N0	1.29	4.48	7.82	1.64	1.63	0.88
26	S1L0N1	1.23	4.93	8.48	1.70	2	1.46
27	S1L0N2	1.27	4.88	8.15	1.52	1.78	1.76
28	S1L1N0	1.28	5.38	12.12	1.80	0.72	0.27
29	S1L1N1	1.22	5.69	14.66	1.88	0.7	0.48
30	S1L1N2	1.22	5.33	13.1	1.87	1.38	1.37
31	S2L0N0	1.35	5.05	8.13	1.63	2.09	1.45
32	S2L0N1	1.27	4.94	9.98	1.64	1.72	0.86
33	S2L0N2	1.22	4.88	8.45	1.66	2.02	1.21
34	S2L1N0	1.21	5.46	13.31	1.83	0.86	0.66
35	S2L1N1	1.17	5.63	16.17	1.88	0.73	0.5
36	S2L1N2	1.22	5.33	12.89	1.87	1.03	0.68
37	S0L0N0	1.31	4.83	7.28	1.58	1.96	1.5
38	S0L0N1	1.23	4.98	8.34	1.82	2.27	1.58
39	S0L0N2	1.18	4.88	8.28	1.73	2.42	1.7
40	S0L1N0	1.11	5.61	11.39	1.76	0.57	0.42
41	S0L1N1	1.19	5.4	11.21	1.86	0.6	0.48
42	S0L1N2	1.26	5.3	10.83	1.80	0.84	0.58
43	S1L0N0	1.25	4.99	7.8	1.48	2.26	1.75
44	S1L0N1	1.23	4.98	8.56	1.60	1.72	1.3
45	S1L0N2	1.25	4.86	8.37	1.61	2.12	1.31
46	S1L1N0	1.25	5.34	12.98	1.83	0.48	0.45
47	S1L1N1	1.28	5.67	14.63	1.90	0.88	0.49
48	S1L1N2	1.22	5.35	13.08	1.86	1.39	1.38
49	S2L0N0	1.32	4.46	8.11	1.66	1.76	1
50	S2L0N1	1.28	4.93	9.99	1.64	1.99	1.41
51	S2L0N2	1.29	4.89	8.38	1.68	1.78	1.86
52	S2L1N0	1.24	5.45	12.47	1.75	0.34	0.16
53	S2L1N1	1.18	5.67	15.7	1.94	0.89	0.5
54	S2L1N2	1.26	5.32	12.94	1.90	1.01	0.68

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Name of laboratory	Assosa Agricultural Research Center soil laboratory	Name of customer	Tesema Minale
Address	Assosa	Address	Fogera National Rice Research and Training Center
	Tel: (+251) 577-752451		Email:tesemaaminale37@gmail.com
			Tel: +251918710743

Sample type: Soil

Sample condition air dried

Sampled and submitted by: Tesema Minale

Date of test performed: 24/04/2024- 16/09/2024

Location: Injebara

Date of sample received: 02/10/2024

No	Customer ID	BD(g/cm ³)	pH (1:2.5) H ₂ O	Av P mgkg ⁻¹	OC (%)	Ex A (cmolkg ⁻¹)	Ex Al (cmolkg ⁻¹)
1	S0L0N0	1.24	5.59	31.69	3.77	0.4	0.16
2	S0L0N1	1.1	5.74	31.23	4.04	0.48	0.16
3	S0L0N2	1.13	5.64	31.23	3.91	0.48	0.16
4	S0L1N0	1.21	5.81	36.98	4.13	0.32	0.04
5	S0L1N1	1.22	5.95	35.76	4.24	0.32	0.08
6	S0L1N2	1.24	5.86	35.53	4.24	0.4	0.08
7	S1L0N0	1.25	5.65	34.38	4.06	0.4	0.04
8	S1L0N1	1.19	5.89	33.3	4.08	0.4	0.16
9	S1L0N2	1.21	5.66	32.92	4.01	0.4	0.16
10	S1L1N0	1.15	6.1	36.98	3.89	0.32	0.08
11	S1L1N1	1.14	6.39	40.28	4.22	0.32	0.08
12	S1L1N2	1.14	6.24	36.45	4.17	0.4	0.08
13	S2L0N0	1.19	5.57	34.99	3.85	0.32	0.08
14	S2L0N1	1.2	5.84	33.53	3.92	0.4	0.12
15	S2L0N2	1.17	5.66	33.15	3.81	0.4	0.16
16	S2L1N0	1.18	6.03	37.21	3.92	0.32	0.08
17	S2L1N1	1.13	6.49	46.96	4.16	0.32	0.08
18	S2L1N2	1.26	6.05	36.52	4.13	0.4	0.08
19	S0L0N0	1.19	5.65	33.58	3.79	0.41	0.18
20	S0L0N1	1.17	5.62	36.53	3.95	0.46	0.15

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21	S0L0N2	1.24	5.6	30.06	3.94	0.46	0.21
22	S0L1N0	1.08	5.86	39.81	4.19	0.36	0.06
23	S0L1N1	1.16	5.84	37.66	4.32	0.33	0.05
24	S0L1N2	1.2	5.68	31.59	4.22	0.41	0.11
25	S1L0N0	1.22	5.66	29.93	3.76	0.43	0.17
26	S1L0N1	1.2	5.89	33.43	3.95	0.48	0.17
27	S1L0N2	1.2	5.66	30.97	3.93	0.49	0.21
28	S1L1N0	1.17	6.24	37.46	3.93	0.34	0.06
29	S1L1N1	1.18	6.25	43.54	4.24	0.3	0.05
30	S1L1N2	1.15	6.23	36.12	4.12	0.28	0.12
31	S2L0N0	1.23	5.55	35.01	3.83	0.44	0.13
32	S2L0N1	1.18	5.7	32.46	3.96	0.44	0.11
33	S2L0N2	1.23	5.63	31.21	3.96	0.45	0.18
34	S2L1N0	1.11	6.23	37.85	3.87	0.32	0.07
35	S2L1N1	1.18	6.52	46.11	4.21	0.23	0.04
36	S2L1N2	1.16	6.04	36.89	4.17	0.36	0.06
37	S0L0N0	1.23	5.61	30.74	3.78	0.44	0.14
38	S0L0N1	1.2	5.66	34.19	4.00	0.38	0.19
39	S0L0N2	1.15	5.65	37.53	3.99	0.45	0.20
40	S0L1N0	1.17	5.75	38.88	4.16	0.36	0.04
41	S0L1N1	1.18	6.08	31.72	4.27	0.44	0.07
42	S0L1N2	1.2	5.68	36.48	4.24	0.38	0.13
43	S1L0N0	1.17	5.63	33.79	4.00	0.40	0.14
44	S1L0N1	1.22	5.80	33.55	4.04	0.40	0.11
45	S1L0N2	1.19	5.66	34.17	3.99	0.48	0.19
46	S1L1N0	1.15	6.26	38.28	3.84	0.32	0.04
47	S1L1N1	1.16	6.52	37.42	4.18	0.28	0.05
48	S1L1N2	1.19	6.27	34.22	4.09	0.36	0.10
49	S2L0N0	1.22	5.56	27.33	4.09	0.43	0.14
50	S2L0N1	1.2	5.73	34.14	4.05	0.47	0.21
51	S2L0N2	1.21	5.66	32.95	3.93	0.50	0.20
52	S2L1N0	1.17	5.98	38.59	3.83	0.30	0.07
53	S2L1N1	1.18	6.51	43.29	4.10	0.27	0.06
54	S2L1N2	1.18	6.07	35.94	4.01	0.30	0.16

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Appendix Figure 1: Photo taken during field preparation and early growth of Faba bean



Appendix Figure 2: Photo taken at nodule counting time



Appendix Figure 3: Photo taken during field evaluation of Faba bean by farmers and developmental agents at Koga organized by healthy food Africa project



Appendix Figure 4: Photo taken at the time of harvesting

BIOGRAPHY

The author, Tesema Minale Getahun was born on March 10, 1993 from Mr. Minale Getahun and Mrs. Bezinash Mekonen at Mertule Mariam in Enebsie Sar Mider District, Est Gojjam Zone, Amhara National Regional State. He attended his elementary and primary school studies at Enissa primary School (1- 8th Grade); his high school and preparatory studies at Fitawurarie Yizengaw Wagaye Secondary school (9th-10th) and Abreha Woatsbiha Preparatory School (11th - 12th Grade) between 2000 and 2011. Having successfully passed the Ethiopian Schools Leaving Certificate Examination (ESLCE) in July 2013, he joined then Adama Science and Technology University and graduated with B.Sc. Degree in Natural Resource Management in July 2015. After his graduated with B.Sc. Degree, he was employed as junior researcher of soil and water management research directorate by Adit Agricultural Research Center for a year. In 2019, he joined Ethiopian institute of Agricultural Research Center as Assistance researcher in soil and water management research process in Fogera national rice research and training center. In 2022, he joined the Soil Science M.S.c. program at the Department of Natural Resource Management, Bahir Dar University.