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FDRE TECHNICAL & VOCATIONAL
TRAINING INSTITUTE

FACULTY OF AGRICULTURE AND AGRO-PROCESSING TECHNOLOGY

DEPARTMENT OFFRUIT AND VEGETABLE PROCESSING TECHNOLOGY

MSc THESIS

EFFECTS OF RHIZOBIUM INOCULATION RATE ON YIELD & YIELD COMPONENTS OF FABA BEAN (*Vicia faba L.)* VARIETIES IN DANGLA DISTRICT, AWI ZONE, ETHIOPIA

DESTAW SHUMET TIGABIE

APRIL 2026

ADDIS ABEBA, ETHIOPIA

EFFECTS OF RHIZOBIUM INOCULATION RATE ON YIELD & YIELD COMPONENTS OF FABA BEAN (*Vicia faba L.)* VARIETIES IN DANGLA DISTRICT, AWI ZONE, ETHIOPIA

Thesis Submitted to the Technical and Vocational Training Institute, Faculty of Agriculture and Agro-Processing Technology, Department of Fruit and Vegetable Processing

In Partial Fulfillment of the Requirements for the Degree of

Master of Science in Crop Production Technology

By

Destaw Shumet Tigabie

Advisor: Desalew Fentie (PhD.)

DECLARATION

This is to certify that this thesis entitled "Effects of Rhizobium Inoculation Rate on Yield & Yield Components of Faba Bean (*Vicia faba* L.*)* Varieties in Dangla District, Awi Zone, Ethiopia," which was submitted in partial fulfillment of the degree of Master of Science in "Crop Production Technology" to the Graduate Program of the Faculty of Agriculture and Agro-Processing Technology, FDRE Technical and Vocational Training Institute, by Mr. Destaw Shumet Tigabie, is an authentic work carried out by him under my guidance. The matter embodied in this thesis work has not been submitted earlier for the award of any degree or diploma to the best of our knowledge and belief.

Name of the student

Destaw Shumet Tigabie Signature_____ Date 05/04/26

Name of the advisor

Desalew Fentie (PhD.) Signature _____Date 05/04/26

BIOGRAPHICAL SKETCH

The author, Destaw Shumet, was born in October 1985 in the Woreta district, located in the South Gondar Zone of the Amhara Region, Ethiopia. He attended his primary education at Alember Primary School and his secondary education at Tewodros Preparatory School, completing his high school education in 2005.

In 2005, he joined Bahir Dar University and graduated with a Bachelor of Science degree in Plant Science in July 2009. Following his graduation, he was employed at the Addis Zemen Woreda Agricultural Office. He later transitioned to a role as an assistant instructor at the Dangila Technical and Vocational Education and Training (TVET) College. He served in this position until he joined the School of Graduate Studies at the Federal Technical and Vocational Education and Training Institute to pursue his Master of Science degree in the Crop Production Technology program.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this thesis is my own work. I have followed all ethical and technical principles of scholarship in the preparation, data collection, data analysis and compilation of this Thesis. Any scholarly matter that is included in the Thesis has been given recognition. This thesis has been submitted in partial fulfillment of the requirements for MSc. degree at FDRE technical and vocational training institute. The Thesis is deposited at the institute library to be made available to borrowers under rules of the library. I solemnly declare that this thesis has not been submitted to any other institution anywhere for the award of any academic degree, diploma or certificate. Brief quotations from this thesis may be made without special permission provided that accurate and complete acknowledgement of the source is made. Requests for permission for extended quotation from or reproduction of this Thesis in whole or in part may be granted by the Head of the School or Department when in his or her judgment the proposed use of material is in the interests of scholarship. In all other instances, however, permission must be obtained from the author of the Thesis.

Name Destaw Shumet Tigabie

Place FDRE TVET Institute

Date of Submission 05/04/26

Signature 

THESIS APPROVAL SHEET

As members of the board of examiners of the Masters of Science (M.Sc.) thesis open defense examination, we have read and evaluated this thesis prepared by Mr. DESTAW SHUMET TIGABIE entitled "Effects of Rhizobium Inoculation Rate on Yield & Yield Components of Faba Bean (*Vicia faba L.)* Varieties in Dangla District, Awi Zone, Ethiopia." We hereby certify that this thesis is accepted for fulfilling the requirements for the award of the degree of Master of Science (M.Sc.) in crop production technology.

Board of Examiner

Name of the Advisor

Desalew Fentie (PhD.) Signature 

Date 21/05/26

Name of External Examiner

Girma Megersa (PhD.) Signature 

Date-05/21/2026

Name of Internal Examiner

Habtamu Ashagrie (Asso.prof.) Signature ----------

Date----------

Name of Chairperson

---------- Signature ----------

Date----------

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ABBREVIATIONS AND ACRONYMS

ANOVA: Analysis of Variance

BNF: Biological Nitrogen Fixation

CEC: Cation Exchange Capacity

CIMMYT: Centro Internacional de Mejoramiento de Maíz y Trigo

CV: Coefficient of Variation

DAP: Diammonium Phosphate

EAL110: A specific Rhizobium inoculant strain

ETB: Ethiopian Birr (currency)

FDRE: Federal Democratic Republic of Ethiopia

GLM: General Linear Model

HARC: Holetta Agricultural Research Centre

LSD: Least Significant Difference

MRR: Marginal Rate of Return

pH: Potential of Hydrogen (soil acidity/alkalinity)

RCBD: Randomized Complete Block Design

TVET: Technical and Vocational Education and Training

Effects of rhizobium inoculation rate on yield & yield components of faba bean(Vicia faba l.) varieties in dangla district, awi zone, Ethiopia

ABSTRACT

Faba bean is a critical pulse crop in Ethiopia, but productivity remains significantly low due to soil nitrogen deficiency and a lack of optimized bio-fertilizer application rates. A study was conducted to evaluate the combined effects of Rhizobium inoculation rates and faba bean varieties on yield and yield components in the Dangla District, Awi Zone, Ethiopia. The treatments consisted of three faba bean varieties (Dosha, Welki, and Local) and five Rhizobium inoculation rates (0, 450, 500, 550, and 600 g/ha). The experiment was laid out in a Randomized Complete Block Design (RCBD) with a factorial arrangement and three replications.

The results showed that while phenological parameters were not significantly affected by the treatments, the interaction between variety and inoculum rate was highly significant for all yield and yield components. The combination of the Dosha variety with the 600 g/ha Rhizobium inoculation rate produced the highest grain yield (3084.73 kg/ha), biological yield (8313.00 kg/ha), and hundred-seed weight (66.33 g). In contrast, the lowest biological yield (6506.60 kg/ha) was recorded from the Local variety without inoculation.

Economic analysis confirmed that the Dosha variety with a 600 g/ha inoculation rate yielded the maximum net benefit of 249,588ETB/ha. The study demonstrates that optimizing the Rhizobium inoculation rate and variety selection is a crucial and highly profitable strategy for enhancing faba bean productivity in the Dangla District. Accordingly, the combination of the Dosha variety with a 600 g/ha inoculation rate is recommended for farmers in the study area to maximize both yield and economic returns.

Keywords: *Faba bean, Rhizobium Inoculation Rates, Synergistic Interaction, Variety*

1. INTRODUCTION

The journey of the faba bean (*Vicia faba L.)* in Ethiopia began around 5000 B.C., believed to have been introduced from the Middle East via Egypt. This deep history has cemented the crop not only as a staple food but also as an integral part of Ethiopia's agricultural heritage(Yitayih & Azmeraw, 2017). Currently, the faba bean ranks as one of the most globally significant legume crops, maintaining its position as the fourth most produced cool-season pulse worldwide, following peas, chickpeas, and lentils (Alharbi & Adhikari, 2020). Within the Ethiopian agricultural landscape, it continues to serve as the nation's primary pulse crop in terms of both area coverage and total production volume (Kassa & Giziew, 2021**).** Biologically, the faba bean is a cool-season legume valued for its resilience and adaptability. It thrives in the diverse climatic conditions of the Ethiopian highlands, typically in areas receiving 700-1000 mm of annual rainfall (Merga et al.**,** 2019).

Nutritionally, it is abundant in protein, fiber, starch, minerals, and essential amino acids, making it a valuable protein source for human diets **(**Jithesh et al., 2024). Beyond nutrition, its cultivation plays a crucial role in sustainable agriculture. By fixing atmospheric nitrogen, the crop enhances soil fertility, benefits subsequent crops in rotation cycles(Geleta & Bekele, 2022**)**, which Reduces the need for chemical fertilizers and promotes environmental health **(**Threatt& Rees, 2024).

Globally, faba bean is cultivated on about 2.4 million hectares with an annual production of approximately 4500 million kg **(**AlharbiandAdhikari**,** 2024**)**. Ethiopia stands as the second-largest producer in the world, following China. Nationally, the crop is predominantly grown in highland areas, covering over 500,000 hectares and occupying a significant 28% of the total land designated for pulse cultivation**(**CSA 2021**)**.

The primary producing regions are Amhara and Oromia, with Amhara holding the largest pulse area at 43.7 percent (van Berkum et al., 2026). In the 2019/20 season alone, Ethiopia’s faba bean crop yielded 1,006,752000 kg, with approximately one-third originating from the Amhara region **(**Wondaferew et al**.,** 2024**)**.

Despite its importance, historical heritage, and favorable agro-ecological conditions, faba bean productivity in Ethiopia faces significant challenges. The national average yield remains relatively low, hovering around 1800 to 2160 kg per hectare (Mulugeta et al., 2019)**.** In key

areas like the Amhara Region, average yields are often between 1500 to 2000 kg/ha, and in specific study areas, yields dropped to less than 1000 kg/ha(Genetu et al.**,** 2021**)**.

Even at zonal and district levels specifically in the Awi Zone and Dangla District yields remain below potential. This low productivity stems from various constraints common in Ethiopian agriculture, including labor-intensive smallholder practices and low input use (Belachew et al., 2022). A critical biological constraint is nitrogen deficiency in soils (FAO, 2025). Because many farmers cannot afford inorganic fertilizers, production suffers from issues like over 50% nitrogen loss, increased costs, and environmental contamination **(**Geleta & Bekele, 2022**).** Specifically, in the Dangla District, productivity is limited by low soil fertility, limited adoption of Rhizobium inoculants, a lack of optimized inoculation rates, poor access to improved varieties, and vulnerability to diseases such as chocolate spot and rust (Tadele**,** 2020). These factors collectively contribute to the observed yield gap between farmers' fields and research stations. To address these food security challenges in both urban and rural Ethiopia, improving crop productivity per unit area through farmland intensification and improved inputs is crucial. Potential agronomic interventions include the use of improved disease-resistant varieties, the application of effective Rhizobium strains, and the adoption of integrated soil and disease management practices.

Optimization of inoculation rates tailored to specific varieties and local conditions has the potential to significantly enhance nitrogen fixation, plant growth, and ultimately grain yield (Abd-Alla et al., 2023)**.** Consequently, this study is guided by the hypothesis that there is a significant interaction between faba bean variety and Rhizobium inoculation rate, which affects nodulation, nitrogen fixation efficiency, and grain yield under the agro-ecological conditions of Dangla District.

1.1. Statement of the problem

Sustainable crop production often relies on combining inputs like bio-fertilizers, suitable cultivars, and chemical fertilizers. However, faba bean (*Vicia fabae* L.*)* yields in Ethiopia, particularly in the Dangla district (study area), remained low, falling below the world average of 1700 kg /ha (Mulugeta et al., 2019).

This low productivity was often linked to inadequate agronomic practices, including suboptimal variety selection and biofertilizer application rates, alongside challenges like pests, diseases, soil fertility decline, erosion, and incorrect weed management (Fanadzo et al., 2018). Limited information on effective nutrient management strategies, specifically the integrated use of biofertilizers and appropriate cultivars, hampered extension services and farmer adoption(Biramo, 2018). Nitrogen deficiency was a significant constraint, particularly for resource-poor farmers unable to afford sufficient inorganic fertilizers. Conventional nitrogen application often suffered from low efficiency, with potential losses exceeding 50%, leading to economic loss and environmental concerns**(**Jithesh et al., 2024).

While faba beans can fix atmospheric nitrogen through symbiosis with Rhizobium bacteria, native rhizobia populations in the study area may not have been sufficiently competitive or effective to meet the nitrogen demands of improved, high-yielding varieties (Muleta & Mebratu, 2024). The survival and effectiveness of native microbial populations are progressively diminished by several compounding factors, such as the repeated application of herbicides like glyphosate (Kepler, 2019), persistent low phosphorus levels (Pan and Cai,2023), and the practice of continuous cropping without adequate rotation(Ding et al., 2024)).

Previous research suggested that optimal inoculation rates for Rhizobium could vary. For instance, a 2019 study by Mitiku et al. found that rates of 500 g/ha led to significant increases in nitrogen fixation, plant growth, and yield. Subsequent recommendations from Genetu et al. (2021) for the broader research region suggested using 500 g/ ha or 750 g /ha in conjunction with chemical fertilizer to maximize productivity.

Supporting these findings, recent trials showed that inoculated faba beans yielded 3160 – 4680kg/ ha at farmers' fields and 3730 – 5105 kg/ ha at the research center (Mekonnen &

Mnalku, 2021). Because both settings showed significant improvements compared to uninoculated controls, these results confirmed the benefits of the practice. Therefore, inoculation with selected, effective Rhizobium strains was crucial. The persistent low yields and observed variation in response to inoculation in the study area may have been due to agro-ecological differences, soil type variations, and the specific interactions between faba bean varieties and inoculation rates. This highlighted a critical need to determine the optimal Rhizobium inoculation rates for specific faba bean varieties suited to the conditions of the Dangla District.

1.2. Objectives

1.2.1. General objective

To enhance the productivity and agronomic performance of faba bean through the identification of optimum Rhizobium inoculation rates for selected faba bean varieties under the agroecological conditions of Dangla District, Awi Zone, Ethiopia.

1.2.2. Specific Objectives

To evaluate the performance of selected faba bean varieties in response to Rhizobium inoculation with respect to growth, yield, and yield-related traits in the study area.

To assess the interaction effects of Rhizobium inoculation rates and faba bean varieties on the yield and yield components of faba bean under the environmental conditions of the study area.

To determine the agronomically effective and economically optimum Rhizobium inoculation rates for improving the yield and yield components of faba bean in Dangla District, Awi Zone, Ethiopia.

1.3. Significance of the research

This research holds profound significance for Ethiopia's agricultural landscape by offering a data-driven strategy to bridge the gap between current low production averages and the faba bean's true genetic potential. The study offers a recommended technology package that aims to maximize smallholder farmers' economic returns by finding the best combination of certain improved varieties and compatible rhizobium inoculation rates. Beyond immediate

yield gains projected to rise from the current national average of 1,800–2,160 kg/ha to over 3,000 kg/ha, this approach addresses the critical challenge of soil nitrogen deficiency through Biological Nitrogen Fixation (BNF). This transition toward biofertilizers not only reduces the financial burden of expensive chemical inputs but also fosters long-term environmental sustainability. Furthermore, by confirming that symbiotic efficiency is genotype-dependent, the findings contribute vital scientific data to the field of crop production technology. Ultimately, this research promotes a more resilient food system where enhanced soil fertility benefits entire crop rotation cycles, providing a clear economic and ecological incentive for the adoption of sustainable farming practices in the region.

1.4. Research scope

The scope of this study is focused on evaluating the synergistic effects of biological nitrogen fixation and crop genetics to enhance faba bean productivity within a specific agro-ecological framework. Geographically, the research was delimited to the Dangla District in the Awi Zone of Ethiopia and specifically conducted during the 2025/2026 main cropping season at the Dangla TVET College training area. The study's biological scope involved a factorial combination of three faba bean varieties the improved Dosha and Wolk' cultivars and a local landrace against five distinct Rhizobium inoculation rates, ranging from an uninoculated control to a maximum of 600 g/ha using the EAL110 strain.

1.5. Application of the research

This research serves as a strategic roadmap for enhancing faba bean productivity and economic viability for farmers in the Dangla District and similar agro-ecological zones. By optimizing the integration of improved crop varieties with biological fertilizers, the study demonstrates that farmers can achieve significantly higher yields while reducing their reliance on costly synthetic nitrogen fertilizers. Specifically, the combination of improved varieties and rhizobium inoculation is recommended as the most effective technology package, as it produces superior grain yield and biological mass.

Beyond immediate productivity gains, the application of these findings supports long-term sustainable agriculture by leveraging biological nitrogen fixation to naturally restore soil fertility. This process creates a carry-over effect that benefits subsequent crops in rotation

cycles and promotes overall environmental health. From an economic perspective, the research provides a clear incentive for adoption by maximizing returns through lower input costs and higher outputs.

2. LITERATURE- REVIEW

2.1 Taxonomy and botanical description of faba bean (*Vicia faba* L.)

Faba bean (*Vicia faba* L.) is a prominent annual herbaceous legume belonging to the family Fabaceae (alternatively Leguminosae), specifically within the subfamily Faboideae and the tribe Fabeae (formerly *Vicieae)* **(**Jayakodi et al., 2023**).** As a member of the genus *Vicia*, it stands out as one of the most globally significant cultivated pulse crops. Genetically, cultivated *V. faba* is characterized as a diploid species, typically possessing a chromosome number of 2n = 2x = 12, although variations of 14 have been documented (Kementerian et al., 2023). It is distinguished by an exceptionally large genome, which is significantly larger than many of its related legume counterparts. While primarily considered a self-pollinating species, its reproductive biology allows for varying degrees of cross-pollination depending on environmental factors and pollinator activity.

2.2. Origin and center of diversity

The precise geographical origin of *Vicia faba* L. remains a subject of ongoing academic debate, primarily because its wild progenitor is currently unknown or presumed extinct (Avramidou et al., 2023). Unlike other pulses, *V. faba* does not produce fertile hybrids with any extant wild *Vicia* species, suggesting a long history of isolated evolution (Jayakodi et al., 2023**)**. Despite the missing progenitor, the Near East is widely recognized as the primary center of origin and domestication, with archaeological evidence in the Levant dating back approximately 10,000 years (Skovbjerg et al., 2023). From this primary center, the crop dispersed along four main historical routes: Northward into Europe and Central Asia; Westward along the North African coast to the Iberian Peninsula; Eastward toward Mesopotamia and the Indian subcontinent; Southward along the Nile Valley into Ethiopia**(**Gutaker & Purugganan, 2023)

2.3. Global production and importance

Faba bean has a long history as a globally cultivated cool-season legume. In 1961, it was grown on 7.5 million hectares worldwide; however, due to biotic and abiotic stresses, the cultivated area decreased to 2.56 million hectares (Chetto et al., 2025). Despite this reduction, global average grain yields nearly doubled over 50 years due to industrialized farming practices (Alemayehu, 2020). Today, it is grown in over 66 countries. China dominates global production, particularly along the Yangtze River. Ethiopia is the second-largest producer globally, contributing approximately 18.89% of the global supply (Mekonnen et al., 2025)**.** Other significant producers include Egypt, France, and Australia. The crop serves as a critical nutritional resource, providing starch, plant-based proteins, dietary fiber, and antioxidants. Consumption is associated with the prevention of obesity, diabetes, and poor cholesterol profiles. Agronomically, it is indispensable for improving soil health through biological nitrogen fixation, which enhances soil fertility and supports higher yields for subsequent crops.

2.4. Faba bean production in Ethiopia

In Ethiopia, faba bean (*Vicia faba* L.*)* is a vital legume, valued for its use in various food forms. Despite its importance, faba bean productivity in the country is constrained by low soil fertility, acidity, inadequate plant density, and insufficient fertilizer application. Early research from 2019 to 2021 focused on identifying optimal agricultural practices. A

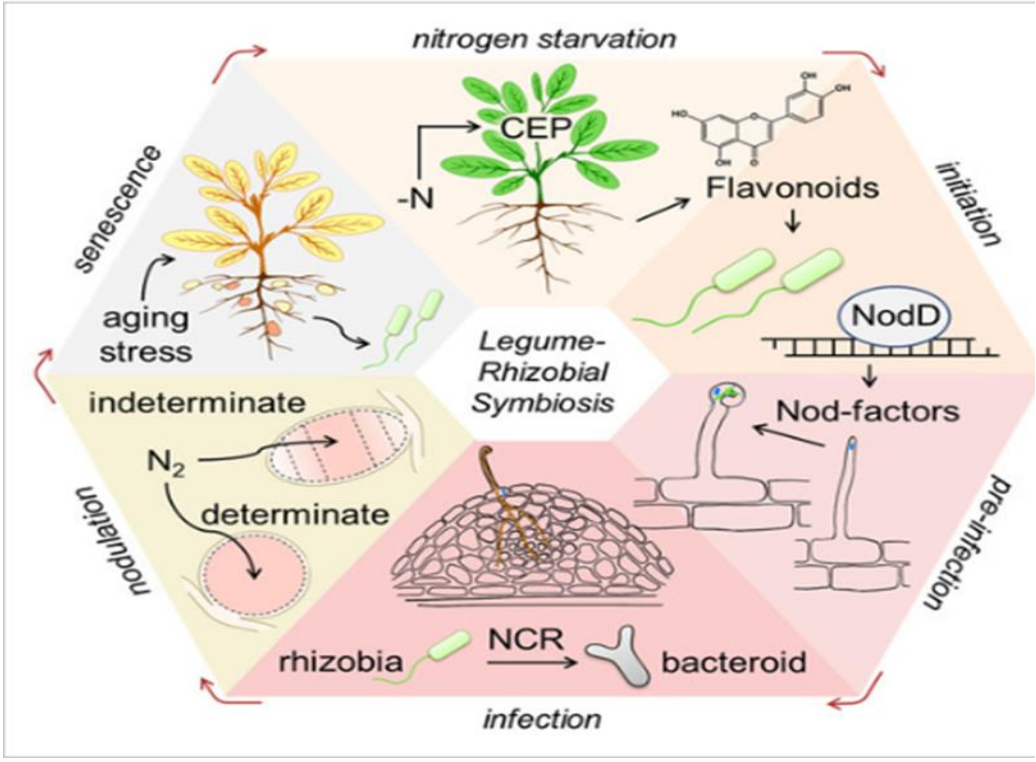
More recently, Muleta & Mebratu (2024) investigated the profitability of faba bean production, confirming its economic viability with a profit efficiency score of 86.10%. Their study, based on data from 334 producers in the Amhara and Oromia regions, identified key factors such as vocational training, access to off-farm income, and appropriate pricing as crucial for improving profit efficiency among faba bean farmers.

These studies collectively underscore the ongoing efforts to address challenges in faba bean production, moving from optimizing cultivation practices to improving economic efficiency.

2.5. Fundamentals of rhizobium-faba bean symbiosis

The symbiotic relationship between Rhizobium bacteria and legumes, such as faba bean (*Vicia faba. L.*), is a cornerstone of sustainable agriculture, primarily due to its capacity for

biological nitrogen fixation (BNF). This intricate process initiates through complex signaling and interaction between the host plant and the bacteria (Abd-Alla et al., 2023).



Source:(Abd-Alla et al., 2023)

Figure 1: the stage of the legume-rhizobium symbiosis.

2.5.1. Signal exchange and nodule formation

Under nitrogen-limited conditions, faba bean roots release flavonoids. These chemical compounds act as signaling molecules that attract compatible rhizobium- bacteria. In response, the rhizobium synthesize and secrete nod factors (Nodulation factors), which subsequently trigger the plant's nodulation signaling pathway (Liu et al., 2017).

Following this recognition, the bacteria invade the root system, typically utilizing infection threads. This invasion stimulates cell division within the root cortex, leading to the organogenesis of specialized structures known as nodules(Sexauer, 2024).

Within the protected, micro-aerophilic environment of the nodule, the bacteria differentiate into Bacteroides. The bacterial enzyme nitrogenase then facilitates the conversion of atmospheric nitrogen (N_2) into ammonia (NH_3). As nitrogenase is highly sensitive to

oxygen, the nodule maintains an oxygen-limited environment essential for this energy-intensive conversion (Threatt & Rees, 2023**).**

A true symbiosis is defined by reciprocal exchange, the host plant supplies the Bacteroides with carbohydrates derived from photosynthesis, providing the necessary energy (ATP) for nitrogen fixation. In return, the Bacteroides supply the plant with fixed nitrogen (ammonia), which is vital for plant growth and development (Abd-Alla et al., 2023)**.**

2.6. Factors influencing the symbiotic process

The efficiency of the Rhizobium -faba bean symbiosis is not guaranteed; it is governed by a multitude of interacting biotic, abiotic, and nutritional factors.

2.6.1. Biotic factors

Strain Diversity: Soil naturally contains diverse Rhizobium populations that exhibit varying levels of competitiveness for nodule occupancy and fixation efficiency (Mendoza-Suarez et al., 2024). Highly effective strains, such as NGB-FR 126, have demonstrated the potential to surpass traditional inorganic fertilizers in increasing seed and nitrogen yield **(**Youseif et al., 2017)**.**

Host Plant Genetics: The genetic makeup of the host plant dictates compatibility. Different faba bean varieties exhibit specific affinities for different rhizobia strains, which directly influences nodulation success (Allito et al., 2021). Genetic variability within genotypes also affects nodulation patterns; for instance, varietal differences have been documented with the Welki variety producing 41–122 nodules per plant, compared to 45–131 in the Hachallu variety (Amha & Fassil, 2018**).**

2.6.2. Environmental (abiotic) factors

Soil pH plays a critical role in the symbiotic relationship between plants and nitrogen-fixing bacteria. Extreme conditions are detrimental, as both acidic soils (pH < 6) and alkaline environments (pH > 8) impede the survival and colonization of rhizobium. These pH imbalances further negatively impact the activity of nitrogenase, the essential enzyme for nitrogen fixation (Fu et al., 2025). Consequently, maintaining a neutral pH range is ideal, as it supports superior microbial health and generally leads to better crop yields (Godoy Mayoral et al., 2017).

The optimal temperature range for nodulation is generally 20–30°C, as high temperatures often delay nodule development while low temperatures reduce formation rates (Yeremko et al., 2025). Furthermore, water stress is detrimental to symbiosis because drought leads to decreased nodulation and waterlogging disrupts metabolic processes, yet specific strains like 'QHCD11' have shown potential in enhancing drought tolerance (Sun et al., 2025). Regarding nutrient availability, adequate phosphorus is critical for nodule development and overall energy transfer (Li et al., 2021), while molybdenum serves as a structural component of the nitrogenase enzyme, meaning its deficiency directly reduces fixation efficiency **(**Zhou et al., 2023). However, the presence of high levels of exogenous soil nitrogen from synthetic fertilizers negatively regulates symbiosis by inhibiting nodule formation and reducing the energy supplied to rhizobium (Lyu et al., 2022). Consequently, excessive nitrogen fertilization can reduce rhizobium motility and population numbers, which necessitates that farmers carefully manage application rates to maintain an effective symbiotic environment (Abd-Alla et al., 2023).

2.7. Rhizobium inoculation strategies

To maximize agricultural productivity, particularly in areas where native soil bacteria are absent or ineffective, applying highly effective rhizobium inoculants is essential. This strategy begins by selecting a peat-based strain tailored to the specific legume variety, local soil pH, and regional climate. While standard application rates are common, increasing the dosage up to 100 times the normal rate in rhizobium-deficient soils can dramatically boost grain yield and shoot nitrogen (Nodulation et al., 2023).

The practical application is typically achieved through seed inoculation, which involves coating the seed for early colonization, or soil inoculation to assist in low-fertility conditions. To prepare the inoculant, 125g of peat is mixed with 10kg of seed using an adhesive and clean, non-chlorinated water to create a uniform slurry(Ishaq et al., 2022) . Because these bacteria are sensitive to desiccation, treated seeds must be sown into moist soil within a few hours, ideally when temperatures are between 15–25°C. Furthermore, productivity can be optimized by co-inoculating with Plant Growth-Promoting Rhizobacteria (PGPR) to improve nutrient uptake or by applying inoculants before environmental stress to help plants withstand water and phosphorus deficits(Hami et al., 2025).

Higher rates correlate with higher nodule counts; for example, specific trials showed nodule counts increasing from 21 to 129 per plant with increased rates (Allito et al., 2021). Recommended rates often range from 500–750 g/ha, adjusted for local conditions(Abate, 2023).

2.8. Impact of rhizobium inoculation and phosphorus fertilization on faba bean (*Vicia faba* L.)

In the Ethiopian highlands, particularly within the Amhara region, faba bean productivity is frequently limited by poor soil fertility and a lack of effective indigenous rhizobium. Research indicates that applying rhizobium inoculation rates significantly enhances nodulation and yield components, especially when working synergistically with phosphorus (P) or blended fertilizers.

Rhizobium inoculation rates maintain a direct, positive correlation with nodule development and subsequent plant biomass. Research conducted in Northwestern Ethiopia demonstrates that increasing inoculation rates from zero to 500 or 750 g/ha significantly improves nodule abundance and weight. This proliferation of desired strains within the rhizosphere leads to higher nodule counts compared to uninoculated controls(Muleta & Mebratu, 2024). The efficiency of specific strains, such as EAL-110, further enhances nodule dry weight due to superior competitiveness over native populations. Furthermore, nodule weight is maximized through nutrient interactions, particularly when inoculation is paired with phosphorus. Peak dry weights are often observed at 500 g/ha of inoculant combined with blended NPS ZnB fertilizers, as phosphorus provides the essential energy required for nitrogen fixation. These successful symbiotic relationships are reflected in physiological markers, including significantly greater plant height and total biomass in both shoot and root dry weights.

The application of higher inoculation rates and effective strains substantially boosts nitrogen fixation efficiency and overall nutrient uptake. Studies indicate that nitrogen fixation can increase from 132 to 218 kg shoot N/ha, even in environments with high background rhizobium levels (Lai et al., 2024). Specialized strains like NSFBR-12 and NSFBR-15 have been shown to account for over 85% of total nitrogen uptake (Allito et al., 2021). Additionally, increased inoculation rates contribute to a rise in seed nitrogen content by at least 30 kg/ha, ensuring higher protein quality in the resulting harvest.

These biological improvements translate into measurable gains in the primary determinants of yield. Hundred seed weight (HSW), which reflects the efficiency of dry matter partitioning during the grain-filling stage, responds positively to the improved nitrogen supply provided by rhizobium (Mekonnen et al., 2025). In Dangila, the interaction between bio-fertilizers and blended NPSZnB fertilizers significantly increases HSW, contributing to a higher harvest index (Dagne, 2016). Inoculation also positively impacts the number of pods per plant, a critical component in determining final productivity (Geleta & Bekele, 2022).

Grain yield serves as the ultimate measure of inoculation success, with inoculated plots consistently outperforming controls in the Amhara region. In Northwestern Ethiopia, sole inoculation can increase seed yields by 1,000–1,200 kg/ha over untreated plots, while maximum yields reaching 3,300 kg/ha have been recorded using 750 g/ha of inoculant paired with 180 kg/ha of blended fertilizer (Genetu et al., 2021). Field trials show yield increases ranging from 35% to 48% compared to crops treated only with inorganic fertilizers (Zewdu & Samuel, 2018). The ecological competence of specific strains, such as FB 1018 and FB 1035, has resulted in grain yield increases of 44-47% over native nitrogen fixation (Youseif et al., 2017). Ultimately, a strong positive correlation (r_2=0.78) exists between the number of active nodules and total grain yield, confirming that these gains are a direct result of improved symbiotic N_2 fixation(Genetu et al., 2021).

2.9. Effects of Rhizobium Inoculant Rate on Phenology, Growth & Nodulation of Faba Bean

The application of Rhizobium inoculants serves as a pivotal strategy in Climate-Smart Agriculture, specifically designed to mitigate the critical biological constraint of nitrogen deficiency in terrestrial soils (Adnan et al., 2020).Recent research emphasizes that while the rate and efficiency of inoculation significantly modulate the physiological and morphological development of faba bean (*Vicia faba* L.), certain developmental markers remain more stable than others. For instance, field evaluations of various faba bean genotypes indicate that phenological stages including days to emergence, flowering, and maturity often show no significant differences (P>0.05) across inoculation rates(Abebe andTolera, 2021). This underscores that faba bean phenological timelines are primarily driven by environmental

factors such as temperature and photoperiod and genetic predispositions rather than variations in nitrogen supply from symbiotic fixation (Neugschwandtner et al., 2019).

Despite the stability of phenological timelines, the vegetative and reproductive growth of faba bean is highly responsive to efficient Rhizobium strains. In Ethiopia, where soil nutrient mining is a prevalent challenge, inoculation has been shown to significantly increase plant height and overall shoot biomass (Degife and Kiya, 2018). Empirical assessments confirm that these bio-based inputs optimize plant performance by modulating nutrient uptake, enhancing chlorophyll content, and improving biomass allocation (Kassaw and Assefa, 2019).Furthermore, controlled trials demonstrated that seed inoculation with Rhizobium leguminosarum bv. viciae can result in an 18.8% increase in seed weight per plant and a 12.3% increase in total seed yield(Serafin-Andrzejewska et al., 2023).

Nodulation remains the primary indicator of successful symbiosis and is directly influenced by the inoculant rate. Data from sub-Saharan field trials reveals that applying effective strains can increase nodule counts to over 90 per plant, a stark contrast to the significantly lower counts observed in uninoculated control plots (Geremu et al., 2023).However, the effectiveness of external inoculants is often mediated by the presence of indigenous soil rhizobia. Studies suggest that understanding localized soil biology is essential to ensure that applied strains are not outcompeted by well-adapted but less efficient native populations, which can otherwise negate the benefits of higher inoculation rates(Thilakarathna & Raizada, 2018).

2.10. Effects of rhizobium inoculant rate on yield & yield components of faba bean

The transition from vegetative growth to reproductive success in faba bean (*Vicia faba* L.) is heavily dictated by the efficiency of the symbiotic relationship between the plant and Rhizobium bacteria. As a critical pillar of Climate-Smart Agriculture. The calibration of Rhizobium inoculant rates is essential for maximizing yield and yield components, particularly in nitrogen-depleted soils where traditional synthetic inputs are either ecologically damaging or economically unfeasible (Santos, 2023).Yield components, including the number of pods per plant, seeds per pod, and thousand-seed weight (TSW), are the most responsive metrics to varying rates of Rhizobium inoculation. Recent field

evaluations in 2024 and 2023 indicate that increasing the density of viable rhizobia at the time of planting significantly enhances the sink capacity of the crop. Inoculation rates optimized for specific soil types have been shown to increase the number of pods per plant by over 15% compared to uninoculated controls(Geremu, 2023).

This is attributed to the sustained nitrogen supply during the critical "pod-fill" stage, which reduces flower abortion. Furthermore, recent controlled trials (2023) demonstrated that seed inoculation with Rhizobium leguminosarum bv. Vicia resulted in an 18.8% increase in seed weight per plant (Serafin-Andrzejewska, 2023).

This enhancement is often a result of improved nutrient harvest index and higher nitrogen accumulation in the grain.

The ultimate measure of inoculant efficacy is the total grain yield. In nitrogen-limited environments across Sub-Saharan Africa, current data highlights a significant "yield gap" that can be partially bridged through strategic inoculation. Meta-analyses from 2024–2023 report that total seed yield increases by an average of 12.3% to 20% following the application of high-quality inoculants (Asrat, 2023). In the pulse-growing highlands of Ethiopia (Amhara and Oromia), where faba bean is a staple, yield responses to inoculation are highly significant due to the prevalence of acidic soils that naturally inhibit native rhizobial activity

However, the effectiveness of a specific inoculant rate on yield is not absolute; it is frequently mediated by soil high-resolution heterogeneity and competition with indigenous microbes. Recent research suggests that while higher rates can improve nodule occupancy, the yield benefits may plateau if phosphorus (P) or potassium (K) levels are deficient (Zhao, 2023). Additionally, studies in 2023 emphasize that the rate of inoculation must be high enough to allow the introduced elite strains to outcompete well-adapted but less efficient indigenous soil rhizobia(Geremu, 2023).

2.11 Varietal Response of Faba Bean to Rhizobium Inoculation

The symbiotic relationship between faba bean (*Vicia faba* L.) and nitrogen-fixing Rhizobium bacteria plays a critical role in sustainable agriculture by augmenting soil fertility, improving nitrogen cycling, and reducing reliance on synthetic nitrogen inputs (Lele, 2021). However, extensive research underscores that the success of this biological interaction is highly dependent on the specific genetic background of the faba bean cultivars, demonstrating a

pronounced varietal response to inoculation. Legume-rhizobium symbiosis relies heavily on a complex genotype-by-strain interaction, which directly dictates the efficiency of nodule formation, shoot biomass accumulation, and overall grain yield. Distinct faba bean genotypes exhibit varying levels of compatibility with specific rhizobial isolates; for instance, certain cultivars demonstrate remarkable increases in shoot and root dry weights when paired with host-specific commercial or native Rhizobium leguminosarum symbiovar viciae strains, whereas others show minimal response under identical conditions (Allito et al 2021).

Furthermore, this varietal responsiveness is tightly linked to genotype-by-environment interactions, as soil bio-physical parameters such as native rhizobial populations, soil pH, and phosphorus availability can heavily alter how a specific cultivar reacts to inoculation(Genetu et al., 202). In certain soil profiles, native isolates demonstrate robust symbiotic efficiency that matches or outperforms introduced commercial inoculants, a factor influenced by the cultivar's capacity to select highly competitive strains within the rhizosphere (Lele, 2021). Recent field evaluations confirm that pairing genetically receptive faba bean varieties with targeted single or multi-strain inoculants significantly optimizes agronomic traits, including the number of active nodules per plant, thousand-seed weight, and total grain yield (Patil, 2018). Selecting the right varietal-rhizobial combination has also been shown to maintain efficient physiological processes and sustain nitrogen fixation even when genotypes face severe abiotic stress conditions, such as combined salinity and hypoxia (Benmoussa et al., 2022). Consequently, maximizing the agro-ecological benefits of faba bean cultivation requires an integrated selection approach that pairs site-specific, stress-resilient rhizobial strains with genetically compatible faba bean varieties.

2.12. Chronological development of rhizobium strain in Ethiopia

Research regarding faba bean productivity in Ethiopia has progressively identified specific rhizobium strains tailored to the country's diverse agro-ecological landscapes. Initial findings highlighted the indigenous strains FBD5, FBS2, FBS5, and FBA5 as effective candidates for increasing plant height, biomass, and grain yield, particularly when utilized in acidic soil conditions (Melak, 2018). Subsequent studies furthered this progress, such as the identification of FB-AR-13, which demonstrated a strong symbiotic performance comparable

to exotic strains; this strain significantly improved nutrient uptake and overall growth, especially when integrated with appropriate fertilizer treatments (Mitiku et al., 2019).

Further advancements in strain-specific effectiveness were documented at Kulumsa, where the EAL-110 strain was tested under acidic conditions. When combined with phosphorus fertilizer, EAL-110 produced the highest grain and biomass yields, maintaining its effectiveness even amidst variable weather conditions (Admasu, 2020). Similarly, in the Wereillu district, the EAL-1018 strain provided a substantial 45.6% yield advantage over un-inoculated controls, delivering the highest economic net benefit and becoming the recommended inoculant for that specific agro-ecology (Gedamu et al., 2021).

Despite these successes, the efficacy of rhizobium inoculation remains highly context-dependent, relying on a complex interaction between soil chemistry, host genetics, and management practices (Sellami et al., 2021). Consequently, continued research into genetic factors and local environmental conditions remains essential to optimize inoculation strategies. Such efforts are critical for maximizing biological nitrogen fixation and reducing the agricultural sector's reliance on synthetic nitrogen fertilizers (Suzaki et al., 2021).

2.13. Adoption status &economic potential of rhizobium inoculation

Despite the documented agronomic benefits of rhizobium inoculation, its adoption within the Ethiopian faba bean production sector remains suboptimal. Kassa et al. (2021) report that the adoption rate of improved faba bean cultivars including those utilizing Rhizobium inoculation is approximately 23% among rural households. Consequently, a substantial majority (77%) of farmers continue to rely on local landraces, resulting in lower productivity. This low adoption rate stands in unambiguous contrast to the economic viability of the practice; recent findings by Tadesse et al. (2025) indicate that Rhizobium inoculation offers significant economic incentives, with some treatments demonstrating a marginal rate of return as high as 1972.6%. Several structural and educational factors hinder the transition from traditional practices to modern inoculation techniques. Kassa et al. (2021) identify the limited availability of certified seeds as a primary constraint. Furthermore, the lack of farmer awareness regarding the benefits of improved cultivars and inoculation serves as a critical barrier. Strengthening agricultural extension services is therefore essential to bridge the knowledge gap and encourage the uptake of this innovative practice. poor nodulation status

in faba bean fields, suggesting low adoption of inoculation with rhizobium bacteria among farmers in Ethiopia. Factors influencing this include weak symbiotic properties of indigenous strains and low input agricultural practices (Geremu et al., 2025)**.** These findings collectively highlight the need for targeted interventions to overcome persistence in traditional farming methods.

3.MATERIALS & METHODS

3.1 Description of the study area

The study was conducted during the 2025 main cropping season at Dangla TVET College's practical training area, located in 05 Kebele, Dangla District, Awi Zone, Amhara National Regional State. This site sits 85 km southwest of Bahir Dar and 485 km northwest of Addis Ababa, situated **11° 16′ N** latitude and **36° 50′ E** longitude (Gebeyehu, 2021).

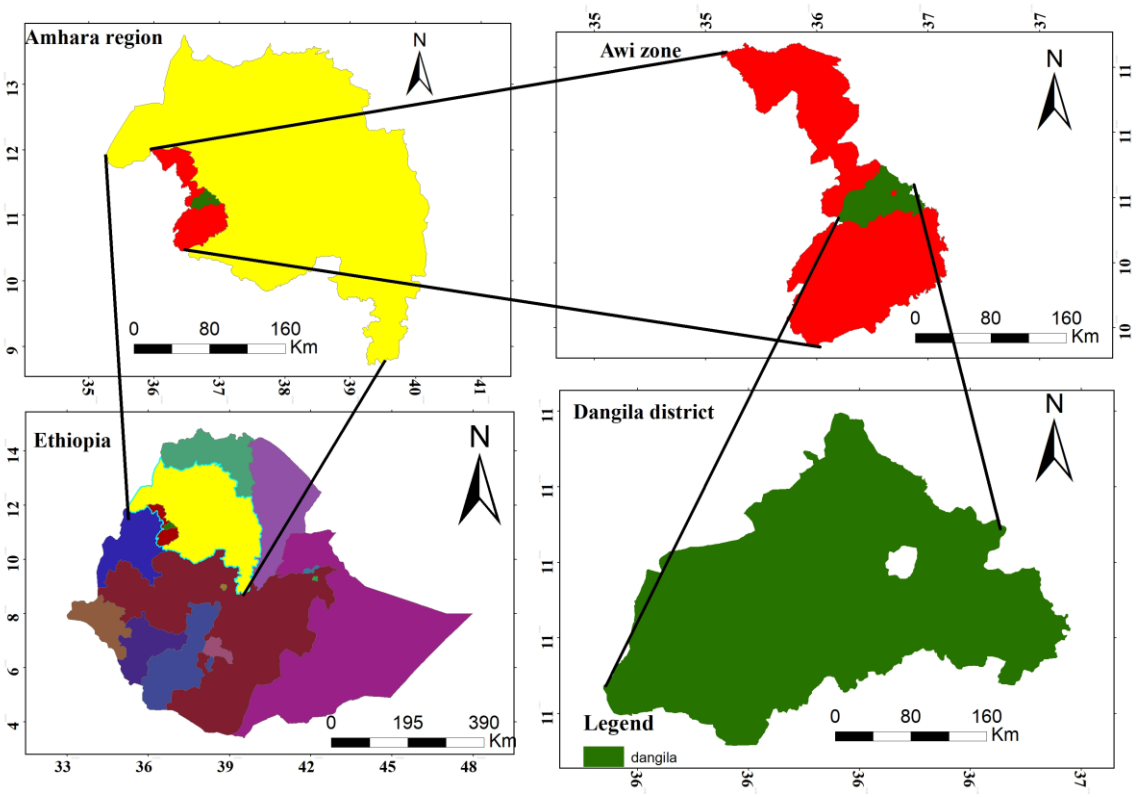


Figure 2: Map of study area

The study area's geomorphology is generally plain, with mound ranging from 2,130 to 2,145.m a.s.l. It falls generally within the Wina-Dega agro-ecological zone, characterized by a mono-modal downfall pattern (May-October), with 700-1000 mm mean periodic downfall, with 88% being between May and August (Birhanu, 2014). Average minimum and maximum temperatures were 15 °C and 21 °C, respectively(Genetu et al., 2021). Nitisols (red soil) were the dominant soil type (80%), with some Vertisols (20%) (Nyssen et al., 2019). Soils in the

district were noted for being relatively degraded, with low organic matter and macro nutrient levels (N, P, K) (Gebeyehu, 2021).

3.2 Experimental materials

Variety	Release Year	Altitude Suitability (m.a.s.l)	Annual Rainfall (mm)	Research Center Yield (t/ha)	Farmers' Field Yield (t/ha)	Reference
Dosha	2009	1900 – 2800	700 – 1200	3.0 – 5.4	1.8 – 2.5	(Amanu, 2021))
Welki	2008	1900 – 2800	700 – 1000	2.5 – 4.5	1.5 – 2.2	(Genetu et al .,2021)
Local	Landrace	Variable	Variable	1.2 – 2.0	0.8 – 1.4	(Amanu, 2021)

Inoculant EAL110 inoculant was obtained from Menagesha Biotech in Addis Ababa. Starter fertilizer diammonium Phosphate (DAP) served as the primary source for nitrogen (N) and phosphorus (P) at rate of 100kg/ha. A uniform starter application of 18kg/ha N and 20 kg/ha P was applied to all experimental plots at the time of planting(Mitiku et al., 2019).

3.3. Experimental treatments, design

The experiment utilized a factorial arrangement within a Randomized Complete Block Design (RCBD) with three replications. The treatments comprised combinations of three faba bean varieties (Dosha, Welki, and Local) and five rhizobium inoculation rates (0, 450, 500, 550, and 600 g/ha). This resulted in 15 treatment combinations per block, totaling 45 experimental plots across the three replications, which occupied a gross area of 429.2 m² (11.6 m* 37.0 m).

Treatments were assigned randomly within each replication. Faba beans were sown with a spacing of 0.4 m between rows and 0.1 m between plants. While each plot had a gross size of 3.2 m × 2.0 m (6.4 m²), data collection was confined to a net area of 2.8 m × 1.9 m (5.32 m²**)**

to minimize edge effects. This net area, which contained six rows and 108 plants, was established by excluding the outer rows and the plants at the row ends as buffers. Consequently, the cumulative net experimental area across the study was 239.4 m².

Table 1: Treatment combination

Treatment Code	Faba Bean Variety	Rhizobium Inoculation Rate (g /ha)
T1	Dosha	0
T2	Dosha	450
T3	Dosha	500
T4	Dosha	550
T5	Dosha	600
T6	Welki	0
T7	Welki	450
T8	Welki	500
T9	Welki	550
T10	Welki	600
T11	Local	0
T12	Local	450
T13	Local	500
T14	Local	550
T15	Local	600

3.4. Experimental procedures

3.4. 1. Field preparation

The experimental field, which had been recently used for growing of maize, was first ploughed three times using oxen driven local ploughing implement called a Marsha. Following ploughing, the prepared land was further divided into plots according to the study design. The plots were then manually leveled. Finally, the experimental treatments were assigned randomly across the plots in each replication.

3.4.2. Seed inoculation

The faba bean seeds underwent a systematic inoculation process to ensure maximum bacterial viability and a competitive advantage. Initially, seeds were moistened by brief immersion in lukewarm water. The inoculation was then performed by mixing a specific rate of Rhizobium slurry, combined with a sticker to facilitate adhesion, directly with the moistened seeds.

To protect the biological integrity of the inoculant, the entire procedure was conducted under shade, mitigating the lethal effects of ultraviolet (UV) radiation on the Rhizobium cells. While the primary experimental objective was to achieve a high-density coating of approximately 10^8 cells per seed to out-compete less efficient indigenous soil bacteria, standard application rates were also documented for comparative analysis. Following coating, the seeds were air-dried in the shade for 30 minutes and sown immediately. Control plots were maintained using uninoculated seeds (0 g/ha) to establish a baseline for nitrogen fixation efficiency.

Following the standard recommendations for the Dangla District, faba beans were sown with a spacing of 40 cm between rows and 10 cm between plants. This configuration results in an individual plant area of 0.04 m² and a total population of 250,000 plants per hectare.

The concentration of viable cells per seed was determined based on a carrier-based inoculant standard of $1x10^9$ (1 billion) cells per gram. The calculation was derived using the following

formula: $\text{Cells per Seed} = \frac{\text{Application Rate (g/ha)} \times 10^9}{\text{Seed Population (seeds/ha)}}$

The table below details the specific application rates and the resulting cellular concentration per seed used during the study.

Inoculant Rate (g/ha)	Total Cells/ha	Cells per Seed	Scientific Notation
450 g/ha	450×109	1,800,000	1.8×106
500 g/ha	500×109	2,000,000	2.0×106
550 g/ha	550×109	2,200,000	2.2×106
600 g/ha	600×109	2,400,000	2.4×106

Source (Allito., 2021).

3.4.3. Planting

The selection of varieties for this study included Dosha, Welki, and Local varieties, which were paired with rhizobium inoculation. These varieties were chosen based on their proven ability to improve nitrogen fixation, survive in stressful conditions, and compete effectively (Genetu et al**.**, 2021).

Seeds were sown at a depth of 0.6m in plots consisting of 8 rows, with an inter-row spacing of 0.4m and an intra-row spacing of 0.1m(Mitiku et al**.,** 2019).

3.4.3.1. Pre-Planting and Prevention

The methodology commenced with pre-planting establishment activities focused on cultural controls to minimize pest pressure. A key decision at this stage involved avoiding early sowing; while earlier planting might maximize potential yield, delaying it significantly decreased the crop's exposure to initial aphid flights.

To provide a preventative barrier against early-season infestations, the study utilized reflective mulches typically silver or aluminized plastic sheets to deter aphids upon seedling emergence. These mulches work by reflecting ultraviolet (UV) light, which interferes with the aphids' visual navigation and prevents them from colonizing the young plants, thereby replacing the need for synthetic seed treatments.

Regarding the impact on Rhizobium, reflective mulches generally support these beneficial nitrogen-fixing bacteria. By reflecting solar radiation, the mulch helps maintain cooler, more stable soil temperatures compared to dark mulches, which prevents heat stress on the bacteria. Additionally, by eliminating the need for synthetic chemical seed treatments, the soil environment remains more hospitable for Rhizobium colonization and the subsequent development of root nodules.

3.4.4. Fertilization

At the time of planting, a uniform starter dose of diammonium phosphate (DAP) was applied to all plots to supply 18 kg/ha of nitrogen and 20 kg/ha of phosphorus. To ensure baseline nutrient availability and supplement inoculation effects during early crop establishment while

avoiding the salt burn effect, the fertilizer was applied via band placement at a depth of 5 cm and 5 cm apart from the seed(Mnalku, 2020).

3.4.5. Growing season and maintenance

Throughout the production cycle, management integrated typical agronomic practices with exhaustive monitoring. Weed management was a priority, as specific weeds can harbor pests; consequently, manual weeding was performed three times during the growing season. Regular field monitoring was maintained to facilitate the early detection of insect and disease issues. During this period, specific ecological observations noted that the presence of ants was directly attributable to honeydew excreted by sap-sucking aphids.

3.4.6. Pest Intervention and Control

When pest issues arose despite preventative measures, direct interventions were employed through a combination of cultural and biological strategies. During the growth phase, cultural practices such as the adjustment of planting densities proved highly effective in reducing initial pest pressure and improving airflow. To specifically manage Faba Bean Aphids (FBAs) and ensure successful crop development, biological controls were utilized, primarily focusing on a home-pressed neem extract. This process began by air-drying neem seeds in the shade and shelling them to isolate the kernels, which were then ground into a fine powder and soaked at a ratio of 50g per 1 liter of water for 12 hours.

After straining the mixture through a fine cloth, the resulting milky extract was emulsified by mixing 1–2 ml of mild soap into the solution to ensure proper adhesion to the foliage. This solution was applied at a spray rate of 400–600 liters per hectare (L/ha), depending on the canopy density, to guarantee thorough coverage of the crop. The application specifically targeted the undersides of leaves and growing tips where aphids congregate, and was repeated every 7 days during active infestations. To protect the plants from leaf burn and prevent the UV degradation of the oil, all spraying was scheduled for the early morning or late afternoon. This integrated approach provided a robust defense against FBAs while supporting healthy, organic crop maturation.

3.5. Data collected

3.5.1 Soil sampling

Before planting, soil samples were collected from the 429.2 m² experimental site to establish a baseline. Using a diagonal sampling pattern across the plot, primary samples were taken from ten distinct spots at a depth of 0–30 cm. These individual samples were then thoroughly mixed to create a single composite sample. To achieve a manageable volume for analysis, this composite was reduced to a final weight of 1 kg using the quartering (1/4) method.

The sample were subsequently undergo several analyses to determine key soil properties, including bulk density (core method(Tamrat et al., 2024**)**, pH (potentiometric, using a 1:2.5 soil: water ratio(Mitiku et al., 2019), cation exchange capacity (1M ammonium acetate, pH 7)(Allito et al., 2021), organic carbon (dichromate oxidation)(Melese et al., 2015), total nitrogen (micro-Kjeldahl)**(**Tsige et al., 2023**)**, and available phosphorus (Olsen method) (Mebrahtu, 2024).

The results of this analysis were providing essential data for understanding the soil's nutrient profile and its suitability for the intended crops. Based on these findings, appropriate amendments and fertilizers ware be recommended to optimize growth conditions and enhance overall productivity.

3.5.2 Phenological parameter

Days to 50% emergence the number of days until 50% of plants in a plot emerged was recorded.

Days to 50% flowering the number of days from planting until 50% of plants in a net plot showed extruded flowers was recorded.

Days to maturity the number of days until 90% of plants in a net plot showed signs of maturity (leaves yellowing/senescence, pods turning black) was recorded.

3.5.3. Nodule parameter

Number of nodules per plant at 50% flowering, roots of ten randomly selected plants were carefully dug up, and all nodules on these roots were visually counted to determine the number of nodules per plant (Kebede, 2010).

Effective nodule number to assess nodule effectiveness, each nodule was sliced open to inspect its internal color. Those displaying a pink, reddish, or brown interior were classified as effective, as these colors indicate the presence of leghemoglobin and active nitrogen (N2)

fixation. Conversely, nodules with green, yellow, or white interiors were recorded as ineffective, signifying a lack of functional symbiotic activity (Fogelberg et al., 2023).

Nodules volume to determine the volume of faba bean nodules, the first ten plants were randomly selected from distractive rows of plots. The Water Displacement Method was chosen due to the irregular shape of the nodules. The procedure involved harvesting, washing, and excising the nodules, then measuring their volume by submerging them in a known volume of water in a graduated cylinder. The nodule volume was calculated by the difference between the initial (V1) and final (V2) water levels (V2 - V1). This method is crucial for assessing nodulation (Allito et al., 2021).

Nodule fresh weight (g/plant) Using destructive sampling, ten plants were uprooted from destructive rows. A hoe was used to loosen the soil, and a shovel was used to dig approximately 20 cm deep and 12 cm from the central stem. The roots were then cleaned with a washing bottle to remove surrounding soil, and the fresh weight of effective nodules in grams was measured (Mebrahtu, 2024)**.**

Nodule dry weight (g/plant) During the faba bean flowering stage, plants were uprooted and separated into three parts: roots, shoots, and nodules.

To determine the accurate dry biomass, these components were oven-dried at 65°C for 48 hours (until the weight remained constant). This specific temperature removes all moisture without damaging the organic material (Sánchez et al., 2020)**.**

3.5.4. Plant growth parameters

Plant height (cm) Plant height was measured vertically from the soil surface to the tip of the main stem on ten randomly selected plants per net plot at 90% physiological maturity (Deb & Paul, 2024)**.**

3.5.5. Yield parameter

At harvest, from ten randomly selected plants within the net plot area, the following data were taken

Number of pods per plant the total quantity of pods counted on each individual plant at harvest.

Number of seeds per pod the average number of seeds counted from a sample of pods per plant at harvest.

Biomass-yield (kg/ ha) Plants from the net plot area (5.32 m²) were harvested manually near ground level, sun-dried for three days, and the total aboveground biomass was weighed. This value was converted to kg/ ha.

Grain yield (kg/ ha) Pods harvested from the six middle rows of each net plot were threshed, cleaned, and weighed. The resulting grain yield was converted to kg/ha and adjusted to a standard 10% moisture content. To ensure uniform drying, faba bean grains were spread on a clean mat and stirred frequently under the sun. The moisture reduction was then monitored using the crack test method, which involved selecting grains from the mat and attempting to break them with the teeth. Grains that proved difficult to break and shattered cleanly were determined to have reached a moisture content of below 10% (Deb & Paul, 2024).

Straw yield (kg/ ha) Straw yield was calculated by subtracting seed yield from the total biological yield (Belachew et al., 2022).

Harvest index (%) The harvest index was calculated as the ratio of dry weight of grains to total aboveground biomass (Seed Yield / Biological Yield) * 100. This calculation helped to assess the efficiency of a crop in converting biomass into grain. A higher harvest index indicated a more productive crop, which is crucial for maximizing agricultural output (Genetu et al., 2021).

100-Seed weight (g) one hundred seeds were randomly sampled from the harvested seeds of each net plot and weighed.

3.6. Data analysis

Prior to analysis, data normality was verified by comparing mean and median values. While descriptive statistics such as frequency distributions were generated using Microsoft Excel, inferential statistical analyses were conducted using SAS software (version 9.4). A two-way Analysis of Variance (ANOVA) using the General Linear Model (GLM) procedure was applied to assess the effects of variety, rhizobium rate, and their interactions on phenology and growth parameters. When significant differences were detected ($P < 0.05$), mean

separation was performed using the Least Significant Difference (LSD) test. Additionally, Pearson correlation coefficients were calculated to examine relationships between variables.

3.7. Economic analysis

The economic viability of the experimental treatments was evaluated using the CIMMYT (1988) partial budget analysis methodology, where net benefits were derived by subtracting total variable costs (cost of inoculant and seed cost) from the gross field benefits of faba bean seeds and straw. Based on market prices collected during the 2025 season, the costs of fertilizers were similar across all treatments and were therefore excluded from the variable cost calculations, while the cost of inoculants was accounted for as a variable cost at 0.4 Birr/g, and seed costs were incorporated into the input costs at 100 ETB/kg for both the Dosha and Welki improved varieties and 85 ETB/kg for the local variety. Revenue projections utilized a seed price of 92 Birr/kg and a straw price of 250 Birr/100 kg. To determine the most profitable option, treatments were ranked by ascending total variable cost and subjected to a dominance analysis. Within this analysis, the adjusted yield (AjY) was calculated by reducing the average yield by 10% to reflect the difference between experimental yield and the yield obtained in farmers' fields (Nelson et al., 2014). The gross field benefit (GFB) was calculated by multiplying the farm-gate price that farmers received for the crop by this adjusted yield. Total cost (TC) represented the cost of the inoculant and seed applied to the treatments, as the costs of other inputs and production practices were similar among treatments and considered insignificant. Net benefit (NB) was computed as the gain achieved by subtracting the total variable cost from the gross field benefit, while marginal return (MR) indicated the amount of increase in return due to an increase in input. Finally, the marginal rate of return (MRR%) was estimated as the ratio of the change in net benefit to the change in total variable costs, as indicated in Table 12, and was calculated using the formula $MRR=(\Delta NB/\Delta TC)\times100$, where ΔNB is the difference in net benefit compared with the control and ΔTC is the difference in input cost compared with the control (Abebe & Feyisa, 2017). According to the CIMMYT (1988) methodology, treatments exhibiting the minimum acceptable level of MRR (>100%) were considered for the comparison of their NB, and the one exhibiting the highest NB was recommended.

4. RESULTS AND DISCUSSION

4.1. Soil physicochemical properties of the experimental site

The soil particle size analysis of the experimental site indicated that the soil is clay loam, comprising 17% sand, 22% silt, and 61% clay. Clay loam soils are generally favorable for faba bean production due to their relatively high water and nutrient-holding capacities; however, their productivity strongly depends on adequate soil fertility management. The soil reaction (pH = 6.8) falls within the near-neutral range, indicating that the soil is not affected by acidity and is suitable for faba bean growth and rhizobium activity. This pH range is also optimal for nutrient availability, particularly phosphorus and nitrogen transformations. Despite the favorable soil texture and pH, the total nitrogen content (0.14%) was low, indicating poor native nitrogen fertility of the soil. Since faba bean is a nitrogen-demanding crop, low soil nitrogen can significantly limit growth and yield, especially in the absence of effective biological nitrogen fixation. Similarly, the available phosphorus content (11.9 mg/kg) was below the critical level required for optimum faba bean production, suggesting that phosphorus deficiency is another major yield-limiting factor at the site. Phosphorus is particularly important for root development, nodulation, and energy transfer processes in legumes.

Other soil physiochemical parameters, including bulk density, cation exchange capacity (CEC), and organic carbon content, as presented in (Table:2), further confirmed the low fertility status of the experimental soil. Low organic carbon content is often associated with reduced microbial activity, poor soil structure, and limited nutrient reserves, while low CEC reflects a reduced capacity of the soil to retain and supply essential cations to plants.

The combined effects of low nitrogen, low available phosphorus, low organic matter, and moderate CEC indicate that the soil of the experimental site is inherently infertile and requires appropriate soil fertility management interventions. Therefore, the use of integrated faba bean production strategies, including rhizobium inoculation, improved faba bean

varieties, and judicious application of mineral fertilizers, is essential to enhance soil fertility, improve biological nitrogen fixation, and increase faba bean productivity at the study sit.

Table 2: Physio-chemical properties of the experimental site's soil

Soil Parameter	Unit	Value	Rate	Reference	
Physical Properties					
Sand	%	17	-	(Tamrat et al., 2024)	
Silt	%	22	-	(Tamrat et al., 2024)	
Clay	%	61	-	(Tamrat et al., 2024)	
Textural Class	-	Clay	Fine texture	(USDA Texture Triangle)	
Chemical Properties					
pH (H2O)	-	6.8	Neutral	(Mitiku et al., 2019)	
Organic Carbon (OC)	%	1.595	Low to Medium	(Melese et al., 2015)	
Organic Matter (OM)	%	2.74	Medium	(Calculated: OC × 1.72)	
Total Nitrogen (N)	%	0.14	Low	(Tsige et al., 2023)	
Available Phosphorus	mg/kg	11.9	Medium	(Mebrahtu, 2024)	
CEC	cmol (+)/kg	18.0	Medium	(Allito et al., 2021)	

4.2. Effects of rhizobium inoculation and faba bean varieties on phenological traits

Analysis of variance showed that neither the main effects nor the interaction effects of Rhizobium inoculation rates and faba bean varieties had a significant influence ($P > 0.05$) on phenological parameters, namely days to 50% emergence (DE), days to flowering (DF), and days to physiological maturity (DM (Appendix Tabe: l and Table 3**)**. This lack of response may be attributed to the fact that phenological traits in faba bean are predominantly governed by genetic characteristics and environmental factors, such as temperature and photoperiod, rather than by rhizobium inoculation rates. Similar results were reported by Girma (2015),

who found that rhizobium inoculation did not significantly affect the phenological development of faba bean.

Table 3: Main effects of rhizobium inoculation rate on phenological parameters of faba bean varieties

Varieties	Days to emergences	Days to flowering	Days to maturity
Welki	7.33	45.07	127.07
Dosha	7.467	45.00	126.87
Local	7.13	45.13	126.47
SEM (±)	0.153	0.181	0.275
LSD (0.05)	NS	NS	NS
P Value	0.1804	0.7620	0.2011
Rhizobium inoculation rate			
0	6.89	44.67	126.11
450	7.44	45.00	126.56
500	7.56	45.11	127.22
550	7.33	45.22	126.89
600	7.33	45.33	127.22
SEM (±)	0.189	0.221	0.340
LSD (0.05)	NS	NS	NS
P value	0.0657	0.0715	0.0689
Mean	7.31	45.07	126.80
CV (%)	6.58	1.09	0.72

DE=days of 50% emergence, DF=days of 50% flowering, DM=days of 90%maturity LSD (0.05) = Least Significant Difference at 5% level; CV = Coefficient of Variation; NS= non-significant. Means with in columns followed by the same letter(s) are not significantly different at 5% level of significance

4.3. Effects of rhizobium inoculation and faba bean varieties on plant growth traits

The statistical analysis reveals that both variety selection and Rhizobium inoculation are pivotal factors in faba bean productivity. While the application of Rhizobium shows a clear linear progression in growth peaking at the 600 g/ha rate with a maximum plant height of 133.22 cm the choice of variety is equally consequential. Among the tested varieties, Dosha demonstrated superior genetic potential, significantly outperforming both Welki and Local varieties by achieving the highest plant height (132.60 cm) and the most prolific pod production (21.87 pods per plant). This performance underscores that improved genotypes like the Dosha variety are a technical necessity to maximize nitrogen fixation and overall growth, a finding that aligns with the study of Chellem et al. (2024). In contrast, the Local variety consistently yielded the lowest results across all parameters, reinforcing the need for high-yielding varieties to capitalize on soil amendments.

The data suggests a synergistic relationship where the benefits of inoculation are most pronounced when paired with high-performing genotypes. For instance, the number of pods per plant nearly doubled from the control group (11.56) to the highest inoculation rate (21.00), a trend that mirrors the performance gap between the Local variety and Dosha. Although the 600 g/ha rate provided the absolute highest numerical values, it was statistically at par with the 550 g/ha treatment, indicating that vegetative growth and yield components begin to stabilize at these higher dosages. Consequently, the integration of the Dosha variety with a Rhizobium application rate in the 550–600 g/ha range represents the most robust strategy for optimizing structural development and yield-forming components.

Table:4. Main Effects of Variety and Rhizobium Rate on Plant Height and Number of Pods Per Plant

Factor	Plant height (cm)	Number of pods per plant
Varieties		
Welki	128.40 b	17.13 b
Dosha	132.60 a	21.87 a
Local	116.80 c	13.20 c
SEM (±)	2.10	1.07

LSD (0.05)	1.7828	1.1344
P-value	<.0001	<.0001
Rhizobium (g/ha)		
0	113.56 d	11.56 d
450	121.56 c	14.78 c
500	129.44 b	19.11 b
550	131.89 a	20.56 ab
600	133.22 a	21.00 a
SEM (±)	2.54	1.38
LSD (0.05)	2.3016	1.4644
P-value	<.0001	<.0001
Grand Mean	125.93	17.40
CV (%)	1.89	8.72

LSD (0.05) = Least Significant Difference at 5% level; CV = Coefficient of Variation; NS= non-significant. Means with in columns followed by the same letter(s) are not significantly different at 5% level.

4.4. Effects of rhizobium inoculation and faba bean varieties on nodulation parameters

The statistical analysis presented in Table 5 demonstrates that both variety and *Rhizobium* inoculation rate had a highly significant effect ($P<0.0001$) on the number of nodules per plant and the number of effective nodules. Regarding the main effect of variety, Dosha produced the highest number of nodules per plant (97.53), significantly outperforming Welki (93.00) and the Local variety (81.80). In terms of nodule effectiveness, Dosha and Welki were statistically at par with 57.00 and 55.07 nodules, respectively, while the Local variety recorded the significantly lowest value of 46.13. These results suggest that the Dosha variety possesses a superior genetic potential for establishing symbiotic relationships compared to the other tested varieties.

The application of *Rhizobium* also resulted in a substantial increase in nodulation parameters as the inoculation rate increased. The maximum number of nodules per plant was recorded at the 600 g/ha rate (115.78), which was statistically similar to the 550 g/ha rate (112.56), but significantly higher than the lower rates and the control. Similarly, the highest count of effective nodules was achieved at the 600 g/ha rate (74.89), significantly exceeding all other

treatments. Conversely, the control group (0 g/ha) yielded the lowest values for both total nodules (59.00) and effective nodules (27.56). The data indicates that increasing the *Rhizobium* rate up to 600 g/ha consistently enhances the nitrogen-fixing potential of the crop across the studied varieties.

Table:5. Main Effects of Variety and Rhizobium Rate on Number of nodules per plant & Effective nodule

Varieties	Number of nodules per plant	Effective nodules
Welki	93.00 b	55.07 a
Dosha	97.53 a	57.00 a
Local	81.80 c	46.13 b
SEM (±)	6.45	5.24
LSD	4.1772	4.2974
P value	<.0001	<.0001
Rhizobium rates		
0	59.00 d	27.56 e
450	66.56 c	33.11 d
500	100.00 b	61.11 c
550	112.56 a	67.00 b
600	115.78 a	74.89 a
SEM (±)	2.93	2.51
LSD	5.3927	5.5479
P value	<.0001	<.0001
Mean	90.78	52.73
CV (%)	6.15	10.90

LSD (0.05) = Least Significant Difference at 5% level; CV = Coefficient of Variation; NS= non-significant. Means with in columns followed by the same letter(s) are not significantly different at 5% level of significance.

4.4.1. Effect of variety and rhizobium rate on nodule fresh weight, dry weight, and volume

Based on the data presented in the table:6, the variety of the crop and the application rate of Rhizobium significantly influenced nodule fresh weight, dry weight, and volume. Among the varieties, Dosha and Welki recorded the highest nodule fresh weights (18.98 g and 18.58 g, respectively) and volumes (1.31 mL and 1.26 mL), showing no statistical difference between them, though Dosha significantly outperformed all others in nodule dry weight with a value

of 6.47 g. In contrast, the Local variety consistently produced the lowest values across all three parameters, trailing significantly behind the improved varieties.

Regarding Rhizobium rates, there was a clear upward trend in nodulation as the dosage increased from 0 to 550 g/ha. The highest nodule fresh weight (20.28 g), dry weight (6.66 g), and volume (1.34 mL) were achieved at the 550 g/ha rate. While increasing the rate further to 600 g/ha did not yield additional significant gains showing statistical parity with the 550 g/ha results both higher rates were significantly superior to the lower doses and the control group. The control (0 g/ha) produced the lowest measurements in all categories, highlighting the critical role of Rhizobium inoculation in enhancing nodule development.

Table:6. The main effect of variety and rhizobium rate on nodule fresh weight, dry weight, and volume

Varieties	Nodule fresh weight (g)	Nodule dry weight (g)	Nodule volume (mL)
Welki	18.58 a	6.13 b	1.26 a
Dosha	18.98 a	6.47 a	1.31 a
Local	15.74 b	5.43 c	1.14 b
SEM (±)	0.791	0.218	0.0354
LSD	0.7167	0.3358	0.0746
P value	<.0001	<.0001	0.0002
Rhizobium rates (g/ha)			
0	12.78 d	4.81 d	1.08 b
450	16.69 c	5.72 c	1.16 b
500	18.87 b	6.21 b	1.28 a
550	20.28 a	6.66 a	1.34 a
600	20.21 a	6.64 ab	1.31 a
SEM (±)	0.611	0.218	0.0402
LSD	0.9252	0.4335	0.0963
P value	<.0001	<.0001	<.0001
Grand mean	17.77	6.01	1.23
CV (%)	5.39	7.47	8.07

LSD (0.05) = Least Significant Difference at 5% level; CV = Coefficient of Variation. Means with in columns followed by the same letter(s) are not significantly different at 5% level of significance.

4.5. The main effect of variety and rhizobium rate on yield and yield components

The analysis of the main effects of variety and Rhizobium rate reveals significant differences in both the number of seeds per pod (NSPP) and hundred seed weight (HSW). Among the varieties tested, Dosha exhibited the highest performance, producing significantly more seeds per pod (4.21) and the heaviest seeds (65.07 g) compared to the others. Welki followed with intermediate values of 3.58 seeds per pod and 59.27 g for hundred seed weight, while the Local variety recorded the lowest results for both parameters. These differences were highly significant, as evidenced by $P< 0.0001$, indicating that genetic makeup plays a crucial role in determining these yield components. Regarding the application of Rhizobium, increasing the rates generally led to a progressive improvement in both NSPP and HSW. The highest Rhizobium rate of 600 g/ha resulted in the maximum number of seeds per pod (3.83) and the highest seed weight (62.33 g), though these results were statistically comparable to the 550 g/ha treatment. In contrast, the control group (0 g/ha) produced the lowest values, with only 2.91 seeds per pod and a seed weight of 54.89 g. The steady increase in values from the control to the maximum rate highlights the positive impact of Rhizobium inoculation on the crop's reproductive efficiency and seed development, with the grand mean for the entire study standing at 3.43 for NSPP and 59.16 g for HSW.

Table:7 Main effect of variety and Rhizobium rate on NSPP and HSW

Factors	Number of seeds per pod	Hundred seed weight (g)
Varieties		
Welki	3.58 b	59.27 b
Dosha	4.21 a	65.07 a
Local	2.51 c	53.13 c
SEM (±)	0.160	0.843
LSD (5%)	0.4202	1.037
P-value	<.0001	<.0001
Rhizobium rates (g/ha)		
0	2.91 c	54.89 d
450	3.16 bc	56.89 c
500	3.49 ab	60.22 b
550	3.78 a	61.44 ab
600	3.83 a	62.33 a
SEM (±)	0.305	1.81
LSD (5%)	0.5424	1.3388
P-value	0.0062	<.0001
Grand mean	3.43	59.16
CV (%)	16.36	2.34

LSD (0.05) = Least Significant Difference at 5% level; CV = Coefficient of Variation; NS= non-significant. Means with in columns followed by the same letter(s) are not significantly different at 5% level of significance.

4.5.1. Main Effect of Variety and Rhizobium Rate on Biological and Grain Yield

The statistical analysis of biological and grain yields reveals significant differences across both crop varieties and rhizobium application rates, as evidenced by the high level of significance ($P < .0001$) for both factors. Among the tested varieties, Dosha achieved the highest performance with a biological yield of 7751.10 kg/ha and a grain yield of 2808.85 kg/ha, significantly outperforming Welki and the Local variety, the latter of which recorded the lowest yields in both categories. Regarding the application of rhizobium, a clear incremental trend is observed where increasing the rate from 0 to 600g/ha consistently improved productivity. The highest rhizobium rate of 600 g/ha resulted in the maximum biological yield (7762.89 kg/ha) and grain yield (2817.58 kg/ha), though it remained statistically comparable to the 550 g/ha rate for biological yield. Conversely, the control group (0g/ha) produced the lowest outputs, underscoring the vital role of rhizobium inoculation in enhancing crop biomass and seed production.

Table:8. Main Effect of Variety and Rhizobium Rate on Biological and Grain Yield

Factor / Treatment	Biological Yield (BY)	Grain Yield (GY)
Varieties		
Welki	7377.83 b	2674.54 b
Dosha	7751.10 a	2808.85 a
Local	6856.45 c	2381.27 c
SEM (±)	112.00	44.9
LSD	110.36	31.736
P value	<.0001	<.0001
Rhizobium rates (g/ha)		
0	6733.53 d	2375.91 e
450	7081.11 c	2499.64 d
500	7436.61 b	2660.18 c
550	7628.17 a	2754.47 b
600	7762.89 a	2817.58 a
SEM (±)	143.00	65.5
LSD	142.47	40.971

P value	<.0001	<.0001
Grand mean	7328.46	2621.55
CV (%)	2.01	1.62

LSD (0.05) = Least Significant Difference at 5% level; CV = Coefficient of Variation; NS= non-significant. Means with in columns followed by the same letter(s) are not significantly different at 5% level of significance

4.5.2. Main Effect of Variety and Rhizobium Rate on straw yield and harvesting index

The analysis of straw yield and harvesting index shows significant variations across both faba bean varieties and rhizobium application rates. Among the varieties tested, Dosha produced the highest straw yield at 4942.25 kg/ha, significantly outperforming Welki and the Local variety, the latter of which recorded the lowest yield at 4475.18 kg/ha. Regarding the harvest index, both Welki and Dosha showed statistically similar superior performance with values of 36.27% and 36.23%, respectively, while the Local variety lagged behind significantly at 34.72%.

The application of rhizobium also had a profound impact on straw yield, which increased progressively with higher application rates. The maximum straw yield of 4945.31 kg/ha was achieved at the 600 g/ha rate, which was statistically comparable to the 550 g/ha rate but significantly higher than the lower rates and the control. Conversely, the rhizobium rates did not significantly influence the harvest index, as evidenced by the non-significant p-value, suggesting that while rhizobium boosts overall biomass production, it does not fundamentally alter the ratio of grain to total straw yield for these specific treatments.

Table: 9. Main Effect of Variety and Rhizobium Rate on straw yield and harvesting index

Factor / Treatment	Straw Yield (SY)	Harvest Index (HI)
Varieties		
Welki	4703.29 b	36.27 a
Dosha	4942.25 a	36.23 a
Local	4475.18 c	34.72 b
SEM (±)	74.6	0.279
LSD	112.77	0.666
P value	<.0001	<.0001
Rhizobium rates (g/ha)		
0	4357.62 d	35.26
450	4581.47 c	35.29

500	4776.43 b	35.76
550	4873.70 ab	36.12
600	4945.31 a	36.27
SEM (±)	88.8	0.420
LSD	145.59	0.8598
P value	<.0001	NS
Grand mean	4706.91	35.74
CV (%)	3.20	2.49

Means followed by the same letter within a column and treatment category are not significantly different at the 5% level of significance according to the LSD test. NS indicates the effect was non-significant.

4.6. Interaction effects of variety &rhizobium inoculation rate on yield &yield components of faba bean

The interaction effects of variety and Rhizobium inoculation rate significantly influenced the yield components of faba bean, as evidenced by the performance of Welki, Dosha, and Local varieties across different treatment levels. For the Welki variety, increasing the Rhizobium rate from 0 to 600 g/ha generally improved performance, with the number of pods per plant (NPPP) nearly doubling from 11.33 to 22.00. Similarly, its hundred-seed weight (HSW) rose from 53.00 g to a peak of 64.00 g, while biological yield (BY) and grain yield (GY) reached their highest values at the 550 and 600 g/ha rates, respectively.

The Dosha variety consistently outperformed the others, particularly at higher inoculation rates. It achieved the highest overall grain yield of 3084.73 kg/ha and the highest biological yield of 8313.00 kg/ha at the 600 g/ha Rhizobium rate. Dosha also showed superior nitrogen-fixing potential or responsiveness, with NPPP peaking at 27.00 when treated with 550 g/ha of Rhizobium.

In contrast, the Local variety exhibited the lowest values across all measured parameters. Even at the highest inoculation rate of 600 g/ha, its grain yield (2528.33 kg/ha) and hundred-seed weight (56.67 g) remained lower than the mid-level performance of the improved varieties. Across all three varieties, the zero-inoculation control groups consistently produced the lowest yields, underscoring the positive impact of Rhizobium application on faba bean.

Table: 10. Interaction Effects of variety & inoculation rate on yield components

Variety	Rhizobium Rate (g/ha)	NPPP (no.)	HSW (g)	BY (kg/ha)	GY (kg/ha)
Welki	0	11.33 ± 0.88ef	53.00± 1.73g	6835.00 ±63.7ij	2475.03± 32.2hi
	450	14.00 ± 1.15d	55.33 ± 0.33ef	7092.00± 107.44gh	2593.48± 39.1fg
	500	17.67± 1.45c	61.00± 0.58d	7486.67± 173.49ef	2689.87± 10.9e
	550	20.67± 1.20b	63.00± 0.58cd	7808.17± 127.1cd	2774.67± 30.1d
	600	22.00± 0.58b	64.00±0.58bc	7667.33± 103.31de	2839.67 ±28.5cd
Dosha	0	13.33 ±0.33de	64.00 ±1.15bc	6859.00± 71.8hij	2478.37 ± 11.4hi
	450	17.33 ± 1.20c	63.33± 0.67c	7513.33± 107.72ef	2641.40 ±24.7ef
	500	25.00 ± 1.7a	66.00 ± 0ab	7946.50 ±86.6bc	2876.33 ±21.5c
	550	27.00± 1.53a	65.67± 0.33ab	8123.67 ±137.84ab	2963.40 ± 33.9b
	600	26.67± 0.33a	66.33± 0.33a	8313.00 ±146.00a	3084.73± 21.1a
Local	0	10.00 ± 0.58f	47.67± 1.45h	6506.60 ± 65.6k	2174.33± 32.8k
	450	13.00 ±0.58de	52.00 ± 1.15g	6638.00± 45.7jk	2264.03± 28.7j
	500	14.67 ±0.88d	53.67 ± 0.67fg	6876.67±28.9hij	2414.33±23.0i
	550	14.00 ±0.58d	55.67 ±0.67ef	6952.67 ±50.02 hi	2525.33 ± 21.1gh
	600	14.33 ±0.88d	56.67± 0.67e	7308.33± 191.72fg	2528.33 ± 18.6gh

NPPP = Number of Pods Per Plant; HSW = Hundred Seed Weight; BY = Biomass Yield; GY = Grain Yield.

4.7. correlation analysis of growth and yield parameters

The correlation matrix reveals a predominantly strong and statistically highly significant (P<0.001, indicated by positive relationship among almost all measured agronomic traits, demonstrating that these growth parameters are the primary drivers of productivity under varying rhizobium inoculation rates. Grain Yield (GY) is exceptionally tightly coupled with Biomass Yield (BY, r=0.94), Plant Height (PH, r=0.90), and most notably, the Number of

Pods Per Plant (NPPP, r=0.91), indicating that taller, more robust plants with higher biomass and pod counts directly translate to superior yields. This pivotal role of pod density is further underscored by its close association with GY (r=0.905), a finding that aligns with studies by Tadele et al. (2020) and Daba et al. (2024), which highlight pod number as one of the most consistent predictors of yield in pulse crops under bio-fertilizer regimes. Furthermore, Straw Yield (SY) shows a strong correlation with both Grain Yield (r=0.816) and Pods Per Plant (r=0.856), confirming that a robust vegetative framework is essential for supporting higher reproductive loads a relationship recently validated in faba bean trials by Mekonnen et al. (2024).

Strong synergies between symbiotic nitrogen fixation and overall plant growth are also evident across the matrix. Effective Nodule Number (EN) shares an incredibly strong correlation with Grain Yield (r=0.878), second only to pod number, which matches the observations of Tadele et al. (2020) and Daba et al. (2024) regarding the importance of effective nodulation. This indicates that the yield-increasing effect of rhizobium is primarily driven by an increase in reproductive sites alongside enhanced nitrogen fixation efficiency. This internal consistency in nodule development is further highlighted by the fact that Nodule Fresh Weight (NFW) shares a near-perfect correlation with Nodule Dry Weight (NDW, r=0.99) and a highly powerful correlation with the number of Effective Nodules (EN, r=0.92). Additionally, the highly significant correlation between the Number of Seeds Per Pod (NSPP) and NPPP (r=0.721) implies that improvements in pod numbers were accompanied by consistent seed development rather than a trade-off in seed fill.

Conversely, the Harvest Index (HI) behaves quite differently from the rest of the parameters, exhibiting a much weaker correlation with Grain Yield (r=0.338) and a non-significant (ns) relationship with Straw Yield (r=0.089 to −0.28). This suggests that while overall yield increased with inoculation, the proportion of biomass partitioned to the grain remained relatively stable a partitioning pattern consistent with observations by Assefa et al. (2024). regarding biomass distribution in improved pulse varieties. While HI displays weak, non-significant correlations with structural biomass indicators like Biomass Yield (BY), Plant Height (PH), Nodule Fresh Weight (NFW), and Nodule Dry Weight (NDW), it does maintain a moderate, highly significant positive correlation with the Number of Seeds Per Pod (NSPP,

r=0.53), Effective Nodules (EN, r=0.49), and Number of Pods Per Plant (NPPP, r=0.42). This suggests that while HI is largely independent of overall plant weight and height, it is positively influenced by efficient nodulation and specific reproductive traits. Collectively, these findings suggest that for improved varieties like Dosha and Welki, selecting for higher pod density and nodule effectiveness is the most effective strategy for maximizing the benefits of rhizobium application, specifically within the environment of the Ethiopian highlands (Getaneh et al., 2024).

Table: 11. Pearson's Correlation Analysis of Growth and Yield Parameters under Variety & rhizobium inoculation rate

Parameter	GY	BY	NPPP	PH	NFW	EN	NDW	HSW	SY	NSPP	HI
GY	1.00										
BY	0.94***	1.00									
NPPP	0.91***	0.92***	1.00								
PH	0.90***	0.87***	0.82***	1.00							
NFW	0.89***	0.90***	0.88***	0.85***	1.00						
EN	0.88***	0.86***	0.80***	0.84***	0.92***	1.00					
NDW	0.88***	0.89***	0.87***	0.86***	0.99***	0.91***	1.00				
HSW	0.87***	0.82***	0.81***	0.85***	0.80***	0.85***	0.81***	1.00			
SY	0.82***	0.95***	0.86***	0.75***	0.81***	0.72***	0.80***	0.69***	1.00		
NSPP	0.78***	0.72***	0.72***	0.73***	0.64***	0.66***	0.65***	0.85***	0.62***	1.00	
HI	0.34***	-0.03ns	0.42***	0.15ns	0.15ns	0.49***	0.17ns	0.29***	-0.28ns	0.53***	1.00

*** Significant correlation, ns = non-significant correlation, at $P < 0.0001$

4.8. Partial budget analysis

The partial budget analysis evaluated the economic feasibility of various faba bean varieties (Local, Welki, and Dosha) under shifting inoculant application rates (Control, 450, 500, 550, and 600 g/ha). Several treatment combinations, specifically Welki Control, Dosha Control, Welki 500, Welki 550, and Welki 600, were dominated (D) because they produced lower net benefits than preceding options with lower or equivalent total variable costs (TVC). For the non-dominated treatments, net benefits consistently advanced alongside incremental increases in variable inputs, driven by improved adjusted grain yields priced at a constant market rate of 92 ETB/kg. While the Local variety responded progressively well up to 600 g/ha, showcasing massive marginal rates of return (MRR) due to low initial production costs, it was heavily outperformed in absolute profitability by the improved varieties. Ultimately, the Dosha variety coupled with an inoculant rate of 600 g/ha achieved the highest overall net benefit of 249,588 ETB/ha, closing its final investment step with a highly viable marginal rate of return of 5,110.00%, well above the standard minimum acceptable threshold for smallholder agricultural adaptations.

Table 12: Partial budget analysis

Variety	Inoculant Rate (g/ha)	Adjusted Yield (kg/ha)	GFB (ETB/ha)	TVC (ETB/ha)	Net Benefit (ETB/ha)	MRR (%)
Local	Control	2,174.33	200,038	10,625	189,413	—
Local	450	2,264.03	208,290	10,805	197,485	4,484.44%
Local	500	2,414.33	222,118	10,825	211,293	69,040.00%
Local	550	2,525.33	232,330	10,845	221,485	50,960.00%
Local	600	2,528.33	232,606	10,865	221,741	1,280.00%
Welki	Control	2,475.00	227,703	12,500	215,203	D
Dosha	Control	2,478.37	228,010	12,500	215,510	D
Dosha	450	2,641.40	243,008	12,680	230,328	473.11%
Welki	450	2495.00	229,540	12,680	216,860	∞ (Shares TVC)
Dosha	500	2,793.00	256,956	12,700	244,256	62,920.00%
Welki	500	2,700.00	248,388	12,700	235,688	D
Dosha	550	2,840.07	261,286	12,720	248,566	21,550.00%
Welki	550	2,764.00	254,257	12,720	241,537	D
Dosha	600	3,084.73	262,328	12,740	249,588	5,110.00%
Welki	600	2,791.33	256,802	12,740	244,062	D

5. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This research demonstrates that the productivity of faba beans in the Dangla District is primarily constrained by low soil nitrogen and phosphorus levels, which can be effectively mitigated through the synergistic use of improved crop genetics and optimized bio-fertilizer application. While phenological traits such as emergence and maturity remain largely unchanged by these treatments, there is a highly significant interaction between faba bean varieties and rhizobium inoculation rates regarding growth and yield performance.

Among the tested cultivars, the improved Dosha variety consistently exhibits superior genetic potential, achieving a mean grain yield of 2,808.85 kg/ha, a 15.2% increase over local landraces. This performance is maximized when Dosha is paired with a rhizobium inoculation rate of 600 g/ha, which produces the highest grain yield of 3084.73 kg/ha and a peak biological mass of 8,313.00 kg/ha. Correlation analysis reveals that these yield gains are directly driven by enhanced nodulation efficiency (r=0.878), which supports a stronger vegetative framework and a higher number of pods per plant.

Economically, the dominance analysis reveals that while several treatments were excluded due to lower returns at higher costs, the Dosha variety consistently provided superior economic returns. Specifically, it achieved a Marginal Rate of Return of 5110.00% and a maximum net benefit of 249,588ETB/ha at the 600 g/ha inoculation rate. Ultimately, adopting this optimized inoculation strategy allows smallholder farmers to bridge the current yield gap while fostering long-term environmental sustainability through natural nitrogen fixation.

5.2. Recommendation

Based on research findings in the Dangla District and similar highland regions, smallholder farmers and extension services should adopt a specific set of practical recommendations to optimize crop performance.

The economic analysis reveals that Dosha achieved the highest peak net benefit of 249,588ETB/ha, significantly outperforming both the local and Wleki varieties under similar management conditions. Hence, Dosha is a superior variety.

To address soil nitrogen deficiencies, farmers should move away from uninoculated traditional practices and adopt a precise Rhizobium inoculation rate. For farmers aiming to maximize absolute profit, the 600 g/ha rate is recommended, as it achieved the maximum net benefit with a Marginal Rate of Return (MRR) of 5110 %, ensuring that the additional investment remains economically viable.

Moving forward, future research should expand upon these findings by conducting multi-location trials across diverse agro-ecological zones to rigorously evaluate strain-by-environment interactions. Testing these inoculation rates across contrasting soil types (e.g., acidic versus neutral) will be critical to understanding how environmental variables influence rhizobial efficacy and survival. Furthermore, evaluating these treatments over multiple cropping seasons will allow researchers to assess the long-term soil fertility effects and quantify the precise residual nitrogen contribution to subsequent non-legume crops. Finally, integrating an economic sensitivity analysis under fluctuating market prices for both inoculants and synthetic fertilizers will ensure that the optimized inoculation strategies are not only agronomically viable but also financially robust for farmers.

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8.APPENDIX

appendix table-1 The mean square value of ANOVA for yield and yield components of faba bean

Appendix table 2: the main effect of variety and rhizobium rate on yield and yield components

Traits	Source of Variations				
	Replication (DF=2)	Variety (DF=2)	Rhizobium (DF=4)	VAR*RZBM (DF=8)	Error (DF=28)
DE	1.756**	0.422ns	0.578ns	0.311ns	0.232
DF	5.60***	0.067ns	0.589ns	0.039ns	0.243
DM	4.467*	1.40ns	2.022ns	1.039ns	0.824
PH	51.80***	1004.60***	614.922***	36.156***	5.681
NNP	106.02*	983.82***	6256.94***	53.128ns	31.189
EN	113.87*	504.07***	4012.98***	40.844ns	33.010
NFW	5.244**	46.707***	88.880***	0.656ns	0.918
NDW	0.721*	4.267***	5.375***	0.224ns	0.201
NV	0.003ns	0.121***	0.111***	0.010ns	0.010
NPPP	14.467**	282.47***	150.48***	17.328***	2.300
NSPP	0.129ns	11.165***	1.421**	0.259ns	0.316
HSW	5.756ns	534.16***	89.589***	11.989***	1.922
BY	246039.62***	3028894.42***	1587078.95***	101317.35**	21768.65
GY	6050.41*	717159.08***	298769.89***	10272.24***	1800.22
SY	181140.22**	818237.86***	511254.17***	76304.34**	22732.31
HI	1.828ns	11.659***	1.941ns	2.052*	0.793

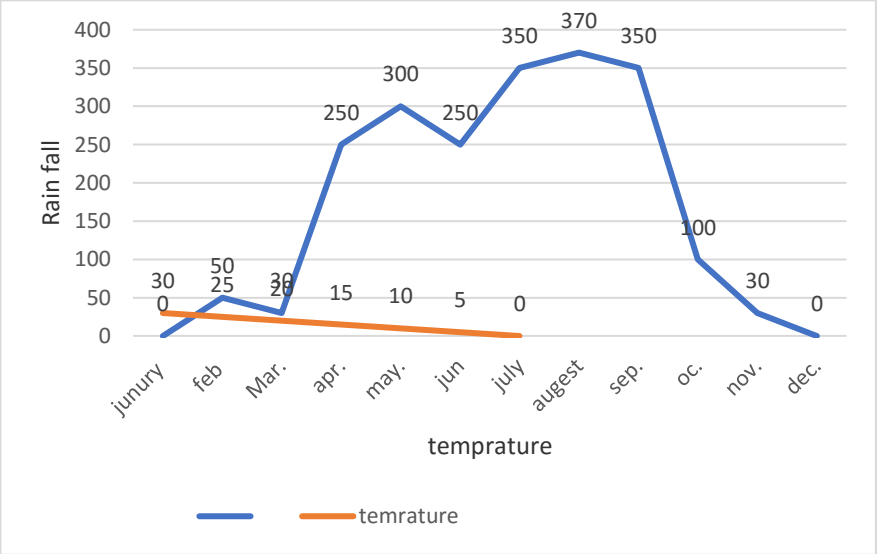
Varieties	PH	NPPP	NSPP	HSW	BY	GY	SY	HI
Welki	128.40 [b]	17.13 [b]	3.58 [b]	59.27 [b]	7377.83[b]	2674.54[b]	4703.29[b]	36.27[a]
Dosha	132.60 [a]	21.87 [a]	4.21 [a]	65.07 [a]	7751.10[a]	2808.85[a]	4942.25[a]	36.23[a]
Local	116.80 [c]	13.20 [c]	2.51 [c]	53.13 [c]	6856.45[c]	2381.27[c]	4475.18[c]	34.72[b]
SEM (±)	2.10	1.07	0.160	0.843	112.00	44.9	74.6	0.279
LSD	1.7828	1.1344	0.4202	1.037	110.36	31.736	112.77	0.666
P value	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001	<.0001
Rhizobium rates								
0	113.56 [d]	11.56 [d]	2.91 [c]	54.89 [d]	6733.53[d]	2375.91[e]	4357.62[d]	35.26
450	121.56 [c]	14.78 [c]	3.16 [bc]	56.89 [c]	7081.11[c]	2499.64[d]	4581.47[c]	35.29
500	129.44 [b]	19.11 [b]	3.49 [ab]	60.22 [b]	7436.61[b]	2660.18[c]	4776.43[b]	35.76
550	131.89 [a]	20.56 [ab]	3.78 [a]	61.44 [ab]	7628.17[a]	2754.47[b]	4873.70[ab]	36.12
600	133.22 [a]	21.00 [a]	3.83 [a]	62.33 [a]	7762.89[a]	2817.58[a]	4945.31[a]	36.27
SEM (±)	2.54	1.38	0.305	1.81	143.00	65.5	88.8	0.420
LSD	2.3016	1.4644	0.5424	1.3388	142.47	40.971	145.59	0.8598
P value	<.0001	<.0001	0.0062	<.0001	<.0001	<.0001	<.0001	NS
Grand mean	125.93	17.40	3.43	59.16	7328.46	2621.55	4706.91	35.74
CV (%)	1.89	8.72	16.36	2.34	2.01	1.62	3.20	2.49

Appendix table 3: the interaction effect of variety and rhizobium rate on yield and yield components

VAR	RHZB	PH	NPPP	HSW	BY	GY	SY
Welki	0	119.67±0.88 ^{i}	11.33±0.88^{ef}	53.00±1.73 ^{g}	6835.00±63.7^{ij}	2475.03±32.2^{hi}	4359.97±37.3^{e}
Welki	450	123.67±1.45^{fgh}	14.00±1.15^{d}	55.33±0.33^{ef}	7092.00±107.44^{gh}	2593.48±39.1^{fg}	4498.52±68.4^{e}
Welki	500	131.33±1.76 ^{cd}	17.67±1.45^{c}	61.00±0.58 ^{d}	7486.67±173.49^{ef}	2689.87±10.9^{e}	4796.80±166.99^{c}
Welki	550	133.67±1.20 ^{bc}	20.67±1.20^{b}	63.00±0.58^{cd}	7808.17±127.15^{cd}	2774.67±30.1^{d}	5033.50±128.92^{a}
Welki	600	133.67±1.20 ^{bc}	22.00±0.58^{b}	64.00±0.58^{bc}	7667.33±103.31^{de}	2839.67±28.5^{cd}	4827.67±91.3^{bcd}
Dosha	0	123.33±0.88^{ghi}	13.33±0.33^{de}	64.00±1.15^{bc}	6859.00±71.8^{hij}	2478.37±11.4^{hi}	4380.63±63.1^{e}
Dosha	450	128.33±1.20 ^{de}	17.33±1.20^{c}	63.33±0.67 ^{c}	7513.33±107.72^{ef}	2641.40±24.7^{ef}	4871.93±127.17^{b}
Dosha	500	136.00±2.31 ^{ab}	25.00±1.73^{a}	66.00±0 ^{ab}	7946.50±86.6^{bc}	2876.33±21.5 ^{c}	5070.17±101.65^{a}
Dosha	550	136.67±2.73 ^{ab}	27.00±1.53^{a}	65.67±0.33^{ab}	8123.67±137.84^{ab}	2963.40±33.9 ^{b}	5160.27±132.75^{a}
Dosha	600	**138.67±1.76 ^{a}**	**26.67±0.33^{a}**	**66.33±0.33 ^{a}**	**8313.00±146.00^{a}**	**3084.73±21.1^{a}**	**5228.27±126.46^{a}**
Local	0	97.67±2.19 ^{k}	10.00±0.58^{f}	47.67± 1.45^{h}	6506.60±65.6^{k}	2174.33±32.8 ^{k}	4332.27±46.4^{e}
Local	450	112.67±1.45 ^{j}	13.00±0.58^{de}	52.00±1.15 ^{g}	6638.00±45.7^{jk}	2264.03±28.7 ^{j}	4373.97±73.3^{e}
Local	500	121.00±2.65 ^{hi}	14.67±0.88^{d}	53.67±0.67^{fg}	6876.67±28.9^{hij}	2414.33±23.0 ^{i}	4462.33±30.3^{e}
Local	550	125.33±0.88^{efg}	14.00±0.58^{d}	55.67±0.67^{ef}	6952.67±50.02^{hi}	2525.33±21.1^{gh}	4427.33±47.4^{e}
Local	600	127.33± 1.45 ^{ef}	14.33±0.88^{d}	56.67±0.67 ^{e}	7308.33±191.72^{fg}	2528.33±18.6^{gh}	4780.00±181.01^{d}

Appendix table 4: partial budget analyses for effects of rhizobia inoculation rate on yield & yield components of faba bean (*Vicia faba* L.) varieties - Ethiopia during 2025/2026 main cropping season.

Variety	Inoculant Rate (g/ha)	Adjusted Yield (kg/ha)	GFB (ETB/ha)	TVC (ETB/ha)	Net Benefit (ETB/ha)	MRR (%)
Local	Control	2,174.33	200,038	10,625	189,413	—
Local	450	2,264.03	208,290	10,805	197,485	4,484.44%
Local	500	2,414.33	222,118	10,825	211,293	69,040.00%
Local	550	2,525.33	232,330	10,845	221,485	50,960.00%
Local	600	2,528.33	232,606	10,865	221,741	1,280.00%
Welki	Control	2,475.00	227,703	12,500	215,203	D
Dosha	Control	2,478.37	228,010	12,500	215,510	D
Dosha	450	2,641.40	243,008	12,680	230,328	473.11%
Welki	450	2495.00	229,540	12,680	216,860	∞
Dosha	500	2,793.00	256,956	12,700	244,256	62,920.00%
Welki	500	2,700.00	248,388	12,700	235,688	D
Dosha	550	2,840.07	261,286	12,720	248,566	21,550.00%
Welki	550	2,764.00	254,257	12,720	241,537	D
Dosha	600	3,084.73	262,328	12,740	249,588	5,110.00%
Welki	600	2,791.33	256,802	12,740	244,062	D



source (Genetu,2021).

Appendix figure 1: mean monthly rainfall, minimum& maximum temperature of study area



Appendix figure 2: land preparation [photo preparation at dangila



Appendix figure 3: during 1st-weeding [photo preparation at dangila].



Appendix figure 4: faba bean during 2nd weeding [photo preparation at dangila



Appendix figure 5: during pod counting