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FDRE TECHNICAL & VOCATIONAL TRAINING INSTITUTE

FDRE TECHNICAL AND VOCATIONAL TRAINING INSTITUTE (FTVTI)

SCHOOL OF GRADUATE STUDIES

MSc THESIS

EFFECTS OF VERMICOMPOST AND PHOSPHORUS FERTILIZER RATES ON YIELD COMPONENTS AND YIELD OF SOYBEAN (*Glycine max* L. (Merrill) IN BAKO DISTRICT, WESTERN ETHIOPIA.

BY ISIHAK KADIR

APRIL, 2026

ADDIS ABABA, ETHIOPIA

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A THESIS SUBMITTED TO THE TECHNICAL AND VOCATIONAL EDUCATION AND TRAINING INSTITUTE, FACULTY OF AGRO-PROCESSING TECHNOLOGY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN CROP PRODUCTION TECHNOLOGY

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Final approval and acceptance of the thesis are contingent upon submission of its final copy to the Council of Graduate Studies (CGS) through the candidate's department Graduate Committee (DGC).

DEDICATION

This MSc thesis is dedicated to my lovely wife, Lalise Atinafu, and my mother and father, Alima Maskobi and Kadir Dufera, respectively.

STATEMENT OF THE AUTHOR

First, I declare that this thesis is my genuine work and all sources of materials used for this thesis have been duly acknowledged. This thesis has been submitted in partial fulfillment of the requirements for the MSc degree at FTVTI and deposited at the institute's library to be made available to borrowers under the rules of the library. I declare that this thesis was not submitted to any other institution anywhere for the award of any academic degree, diploma, or certificate.

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BIOGRAPHICAL SKETCH

The author, Isihak Kadir Dufera, was born on March 5, 1986, at Wabera Kebele, in Begi District, West Wollega Zone, Oromia National Regional State, which is located 663 km west of Addis Ababa. He attended his primary school education at Wabera Elementary School from 1993 to 2001 (Grades 1-8). In the subsequent years, he enrolled at Begi Secondary and Preparatory School from 2002 - 2004 (Grades 9-12) in Begi town. Finally, he joined Wollega University in 2005 and graduated with Bsc Degree in Plant Sciences on June 30, 2008. He was then employed at the Yubdo Agricultural office and worked for three years. After three years again employed at Nunu kumba TVTI College, and he was given a study leave to pursue a study leading to the degree of Master of Science in crop production technology at FTVTI.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
BNF	Biological Nitrogen Fixation
BARC	Bako Agricultural Research Center
CEC	Cation Exchange Capacity
CIMMYT	International Maize and Wheat Improvement Center
C : N	Carbon to Nitrogen Ratio
CRBD	Randomized Complete Block Design
DAFF	Department of Agriculture, Forestry, and Fisheries
ECX	Ethiopia Commodity Exchange
ETB	Ethiopian Birr
EthioSIS	Ethiopian Soil Information System
FAO	Food and Agriculture Organization
LSD	Least Significant Difference
MEQ	Milli equivalent
MoARD	Ministry of Agriculture and Rural Development
MRR	Marginal Rate of Return
SOM	Soil Organic Matter
VC	Vermicompost

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Effects of Vermicompost and Phosphorus Fertilizer Rates on Yield Components and Yield of Soybean (*Glycine max* L. (Merrill) **in Bako District, Western Ethiopia**

ABSTRACT

*Soybeans (Glycine max L. (*Merrill*) are a significant crop in Ethiopia, but their productivity is limited by poor fertilizer management and decreasing soil fertility. Therefore, a study was conducted at the Bako Agricultural Research Center (BARC) during the 2025 main cropping season to evaluate the effects of phosphorus and vermicompost fertilizer on the phenology, growth, yield components, and yield of soybean. The experiments consisted of four phosphorus rates (0, 23, 46, and 69 kg ha⁻¹) and four vermicompost rates (0, 1.25, 2.5, and 3.75 t ha⁻¹). The experiment was laid out as a randomized complete block design (RCBD) in a factorial arrangement with three replications. Data were collected on the growth, yield components, and yield of the crop, and all agronomic data were subjected to analysis of variance. The results revealed that most of the studied variables were significantly affected by the main effects of rates of Phosphorus, Vermicompost, and their interactions. The highest grain yield (2,713.53 kg ha⁻¹) was recorded with the combined application of 69 kg P ha⁻¹ and 3.75 t VC ha⁻¹, while the lowest yield (1,901.00 kg ha⁻¹) was obtained from the control treatment. Similarly, the highest biomass yield (8146.43 kg ha⁻¹) was obtained at combined applications of 69 kg P ha⁻¹ and 3.75 t VC ha⁻¹, while the lowest value (6780.93 kg ha⁻¹) was observed at the control treatment. Furthermore, prolonged days to flowering and days to maturity were recorded at 69 kg P ha⁻¹ and 3.75 t VC ha⁻¹. Economic analysis indicated that the application of 46 kg P ha⁻¹ with 3.75 t VC ha⁻¹ provided the highest net benefit of 316,285.4 ETB with an acceptable marginal rate of return (1220%). Therefore, the combined application of 46 kg of P ha⁻¹ with 3.75 t VC ha⁻¹ is tentatively recommended for soybean production in the Bako and similar agro-ecological areas. Further, the tested rates of Vermicompost and Phosphorus fertilizer should be evaluated at multiple seasons and locations to give conclusive recommendations.*

Keywords*: Economic Analysis; Grain Yield; Phosphorus fertilizer; Rates of fertilizer; Soybean; Vermicompost.*

1.INTRODUCTION

Soybean (*Glycine max* (L.) Merill) is one of the most important and widely grown legume crops worldwide due to its multi-purpose use, particularly in the animal feed industries and human nutrition (Achamyelh *et al*., 2020). It contains high-quality protein and balanced amino acid profile used in ration formulation and human diets (Shea *et al*., 2020). The global average production of soybeans reached 334.89 million tons per annum (Chetna *et al*., 2025). Soybean producing in the continent in the world, followed by Asia, Europe, and Africa. The findings of this study indicate that 87.1% of global soybean production is covered by the Americas. Soybean was introduced to Sub-Saharan Africa through Chinese traders in the 19^{th} century for the first time. It was cultivated as a commercial crop in the early 1903 in South Africa (Khojely *et al*., 2018).

Worldwide soybean production has continued to increase over time, largely because of it has high demand as a nutritious food and industrial raw material. The Seeds of Soybean contain 18–22% oil, 40- 45% protein, 30-35% carbohydrate, and 4-6% ash, depending on variety and growing Conditions (Modgil *et al.*, 2020). According to Gao *et al.*(2022), soybeans are valued for their high nutritional content, diverse range of potential as a bioenergy source, and extensive agro-ecological flexibility. Owing to its wide adaptability and economic value, soybeans have significant potential for agricultural and economic development, particularly in developing regions such as Africa (Abate *et al*., 2023). Ethiopia has huge potential for soybean production, although the current production status is not comparable to the existing potential(Tesfaye *et al*., 2018).

Soybean cultivation in Ethiopia began during the 1950s, after which the crop gradually expanded in to several agro-ecological zones, particularly in the western and south western parts of the country (Bako, Jimma, and Assosa areas) (Asfaw *et al.*, 2022). Currently, soybeans are grown on about 54,543 hectares, with a total production of 125,623 tons and an average national productivity of about 2.30 tons ha^{-1}, which is lower than the global average yield of 2.79 tons per ha^{-1} (Abebe and Ayana, 2023). Even if it is important, soybean productivity in Ethiopia is still low compared to its potential yield, which can reach up to 4.5 t ha^{-1} with better management practices (Wu *et al*., 2023).

In Ethiopia, the average yield of soybeans are low due to a decline in soil fertility, or nutrient deficiencies, particularly phosphorus deficiency, limited use of organic and

inorganic fertilizers, poor agronomic practices, low varietal stability, and limited access to improved seed variety (Aleminew and Alemayehu, 2020). Continuous cropping, without adequate nutrient replenishment has further reduced soil fertility, especially in the acidic soil of western Ethiopia, including the Bako area.

Phosphorus is a necessary macronutrient for root growth, early maturation, seed development, cell division, genetic information transfer, carbohydrate metabolism, and overall yield enhancement (Panigrahi *et al*., 2024). However, in acidic soils, phosphorus availability is severely decreased due to fixation by iron and aluminum oxides, leading to poor nodulation and lower soybean production (Delgado *et al*., 2024). On the other hand, Vermicompost is an organic fertilizer created by earthworms that improves the physical, chemical, and biological qualities of soil. It improves soil organic matter content, nutrient availability, microbial activity, and soil pH, thus increasing crop growth, production, and productivity (Atiye *et al*., 2023).

Integrated nutrient management, which combines the use of organic and inorganic fertilizers, has been identified as an effective method for raising soil fertility and maintaining production(Hailu and Feyissa, 2023). The combined use of vermicompost and phosphorus fertilizer can increase phosphorus availability, nutrient absorption, reduce soil acidity, and raise soybean production more effectively than either input alone (Selim, 2020; Debela *et al.*, 2021).

1.1 Statement of the problem

Soybean (*Glycine max* L. (Merrill) is an increasingly significant crop grown in different agro-ecological zones of western Ethiopia. However, its productivity is lower than that of the world average productivity (Wondefiraw and Tesfaye, 2023). The major reasons for the low productivity of soybeans in Ethiopia were low soil fertility, low varietal stability, a narrow genetic base of cultivars, insect pests and diseases, limited access to improved soybean seed, and poor agronomic practices (Mengistu, 2022; Chakelie *et al*., 2024).

Soybeans are highly responsive to chemical and organic fertilizers (Asefa and Wegari, 2021; Hailu and Feyissa, 2023). However, farmers in the area do not apply even the recommended fertilizer rates due to high costs, confusion about the economic returns of fertilizing food crops, and more often, lack of knowledge as to which types and rates of fertilizers are suitable. Besides, to enhance climate change adaptation and to improve the

yield of soybean, farmers are now being offered the option to integrate rates of vermicompost and phosphorus fertilizer for profitability and maintaining soil fertility.

However, no sufficient research has been done recently on the effects of the rates of phosphorus and vermicompost in the Bako district. Therefore, there was a need to generate a location-specific optimal combination of vermicompost and phosphorus fertilizer rates that can improve soybean productivity and profitability while maintaining soil fertility. In this study, it was hypothesized that increasing combined rates of mineral phosphorus and vermicompost fertilizer rates would increase the grain yield of soybeans. Therefore, this study was initiated with the following general and specific objectives.

1.2. Objectives

1.2.1 General objective

- To improve the production and productivity of soybean through identifying optimal combinations of phosphorus and vermicompost fertilizer rates in western Ethiopia.

1.2.2 Specific objectives

- To investigate the effects of phosphorus and vermicompost fertilizer rates on yield components and yield of soybean in the study area.
- To estimate the economic feasibility of soybean yield in response to the combined application of phosphorus and vermicompost fertilizer rates.

2. LITERATURE REVIEW

2.1 Origin and distribution of Soybean

Soybean (*Glycine max* L.(Merrill) is believed to have been first domesticated in East Asia, Particularly in China,which is widely recognized as the primary Center of origin for this crop (Kumari *et al*., 2025). China served as the primary center of origin, with early cultivation spreading to neighboring regions such as Korea and Japan. Soybeans are indigenous to China and have long been valued for their higher nutritional value (Singh *et al.*, 2019). Historical evidence indicates that soybean was domesticated more than 3000-5000 years ago and have long been cultivated as a staple crop due to their high nutritional value. Early utilization of soybean used for various food which remain important components of traditional diets in East Asian countries (Pate *et al*., 2019).

The crop was presented to the Indian subcontinent around 1000 AD via the Silk Road, which ran through the Himalayan region and north eastern India before spreed. Similarly, Traditionally, soybean seeds were cultivated in the northern and north-eastern india before spreading throughout the country(Daba *et al*., 2021).When scientists tested yellow-seeded material to generate high-yielding cultivars fit for the country's agro-ecological circumstances, India's soybean industry exploded (Chandra *et al*., 2022). Staniak *et al*.(2023) also revealed that soybeans can survive in tropical, subtropical, and temperate locations as long as the temperature and rainfall requirements are met. This rise accelerated in the 1970s, particularly in Madhya Pradesh's monsoon fallow lands, which created an ideal environment for soybean growing (Patidar, 2021).

Globally, soybeans are among one of the most significant oilseed and legume crops, grown in tropical, subtropical, and temperate countries (Kumari *et al*., 2025). Similarly, soybeans have become one of the world's most commonly produced oilseed crops, owing to rising demand for food oil, animal feed, and industrial applications (Dilawari *et al.*, 2022). Soybean crop growth is due to increased planted area, yield enhancement through better varieties, and rising worldwide demand for animal feed and edible oil. China and India's outputs are gradually growing due to land constraints and competition with other crops (Jiang *et al*., 2025).

The crop's present role has taken over the top place in the nation's oilseed yield, placing it sixth in the world (Mishra *et al*., 2024). By modifying 20% of the edible oil generated in

the nation and earning around 40,000 million dollars through soymeal exports, it contributes significantly to the national economy(Tiwari, 2022).

In Africa, Soybean cultivation ir relatively recent, compared to Asia and the Americas. In Ethiopia, the crop was introduced in the 1950s and has since grown in importance as a food, feed, and cash crop (Asfaw *et al*., 2022). Despite increased cultivation areas, Soybean distribution in Ethiopia remains constrained by issues such as input availability, market access, processing facilities, and farmer knowledge (Delele *et al*., 2022).

Soybean production and productivity in Ethiopia have shown positive trends over the past two decades, supported by government policy initiatives aimed at diversifying agricultural production and reducing edible oil imports (Mekonen *et al*., 2025). The crop has become an important component of the national oilseed sector and contributes significantly to house hold income and food security. Ethiopia has continued to increase soybean production through understanding global production trends and adapting successful management practices to local conditions, which is essential for improving productivity and sustainability (Siamabele, 2021). Soybean is now farmed mostly in the country's western and southwestern regions, including Bako, Jimma, and Assosa, where rainfall and temperatures are good (Mussema *et al*., 2022).

2.2 Botanical description of the soybean crop

The soybean belongs to the family Fabaceae and is classified as an angiosperm dicotyledon plant(Singh *et al*., 2020). According to Kumari *et al*.(2025), soybean is an annual crop, self-pollinates, and has significant morphological variety depending on genotype and environmental conditions. The soybean plant typically grows to a height ranging from 0.3 to 1.5 m and may display erect or semi-erect, depending on genotype and environmental factors (Soni, 2021). The crop's well-developed Tap root system that provides nitrogen by collaborating with Bradyrhizobium bacteria. The nodules play an important role in converting atmospheric Nitrogen in to forms that can be used by the plant, thereby improving soil fertility and supporting plant growth(Martin *et al.,* 2023). The stem of the soybean is generally erect, cylindrical, and pubescent, with extensive branching depending on plant density, nutrient availability, and varietal characteristics. The leaf structure of soybean typically consist of three leaflets forming a trifoliate arrangement(Soni, 2021). leaf color ranges from light to dark green, reflecting the plant’s

nutritional status and growth condition. Soybean plant produce small flowers that usually appear in clusters a long the leaf axils. The flower are commonly white or purple in color and are typical of legumes crops. Most soybean flowers are self-pollinated, meaning fertilization occurs within the same flower without the need for external pollination agents.(Barela *et al*., 2022). The fruit of soybean is a pod that develops after successful fertilization of the flower. The Pods are usually slightly curved and covered with fine hairs. Each pod commonly contains between one and four seeds, depending on the variety and growing conditions. The pod color are changed at maturity, from green to yellow or brown. Soybean Seeds are may vary in size, shape, and color depending on the variety and agro-ecological conditions.The seeds generally round to oval in shape and may appear yellow, green, brown, or black. Each seed consist of protective seed coat, two cotyledons, and an embryo that develops in to a new plant under suitable environmental conditions (Bello, 2021).

In Ethiopian agro-ecological conditions, these morphological traits are essential for varietal selection and adaptability. Compared to the good type, which is typically bushy, erect, and has limited plant development, domesticated soybeans are more upright and better suited for breeding as well as certain characteristics like yield, disease resistance, and environmental adaptability (Erol, 2023). The growth habit and general form of the plant have a significant impact on its ability to adapt to various agro-ecological zones and production systems, including those in Ethiopia (Asfaw *et al*., 2022).

2.3 Economic importance of Soybean

Soybeans are regarded as one of the world's most valuable legume crops due to its numerous applications and high nutritional value. Soybean seeds contain 40-45% protein and 18-22% oil (Modgil *et al*., 2020). Abate *et al.* (2023) highlighted the importance of soybeans in alleviating malnutrition by adding them into traditional meals such as kolo and shiro.They showed that while soybeans have nutritional benefits, family consumption has decreased due to processing restrictions and a lack of awareness

Globally, soybeans play a crucial role in addressing protein and energy demands, particularly in developing countries where animal protein is limited. In Ethiopia, Soybeans have contributed to farm income and livelihoods, which is consistent with findings by Asefa *et al*.(2021), who reported that soybean production significantly

increased farm income in western and south-western Ethiopia, due to its relatively low production cost and stable market demand. Similarly, Gawęda *et al*.(2020) found that soybeans generated high net returns compared to some cereal crops. In contrast, Voora *et al*.(2020) reported that profitability varies across regions due to differences in yield level, market access, and input availability.

In Ethiopia and other developing nations, soybean farming significantly increases crop expansion, improves soil fertility (via biological nitrogen fixation), and boosts smallholder farmers' incomes(Dabesa *et al*., 2026). The crop is a significant export both locally and abroad, mostly to the animal feed and oil processing sectors (Voora *et al.,* 2020). Soybeans are increasingly successfully used in cosmetics, biofuels, and pharmaceuticals, enhancing value in many different kinds of industries (Rahman *et al*., 2024). It has increasing potential to promote the expansion of the agro-industrial sector and replace imports in the production of edible oil and feed (Medina, 2022).

According to Abate *et al*.(2023) and Abebe and Ayana (2023), Soybeans can greatly increase household income, food security, and market participation. Ethiopia's export and domestic agro-processing sector has benefited from the increase in Soybean output (Molla *et al., 2*024; Simabele, 2021). Soybeans significantly enhance rural livelihoods by generating income and reaching markets (Abate *et al*., 2023). However, the main reasons for output disparities are inadequate soil fertility and poor agronomic practices (Miti *et al*., 2024).

2.4 Agro-Ecological of soybean

Soybean grows well under a wide range of environmental conditions, but optimum growth is achieved in areas with moderate temperatures and adequate rainfall. The crop is a warm-season crop that develops in 120 to 130 days, depending on the cultivar, and grows best at temperatures between 10°C and 30°C (Alsajri *et al.,* 2022). Soybeans also give the best production between 1300 to 1800 meters above sea level, producing a lot of food (Negash and Biru, 2024). Soybean performs best in moderately acidic to neutral soil with 4.5 to 8.5 pH and strongly acidic soil acidity limits phosphorus availability and nodulation. This agrees with Issifu(2020) and Owaresat *et al*.(2023), who reported reduced nitrogen fixation and yield in soybean under strongly acidic soil conditions. Studies conducted in non-acidic soil or well-buffered soils give higher absolute yields

compared to Ethiopian conditions (Staniak *et al*., 2023). Low pH levels can decrease the availability of essential nutrients like molybdenum, which is important for the nitrogen fixation process, thereby limiting the conversion of atmospheric nitrogen into forms usable by the plant (Kafeel *et al.*, 2023).

Regarding the necessary temperatures, soybean reaction varies depending on the stage of growth; 25°C may be considered as the overall ideal temperature for all phases of growth (Begum *et al*., 2022; Alsajri *et al.*, 2024). At planting time, soybean seeds require specific soil temperature and moisture conditions to make sure optimal germination and emergence(Begum *et al*, 2022). Soil Temperature Requirements of Soybean seed can begin germination at soil temperatures as low as 10°C. However, germination is typically slow at this temperature. Optimal germination occurs when soil temperatures are around 25°C, leading to faster and more uniform emergence (Begum *et al*., 2022). When the Soil temperatures are below 13°C can delay germination and increase vulnerability to diseases and pests (Roth *et al*., 2020).

According to Sileshi *et al.*(2020), soybeans are regarded as drought-resistant crops that may yield sufficient amounts of water with an annual rainfall range of 500 to 1500 mm, as long as the rainfall is spread uniformly throughout the growing season. For best results, moisture availability must be constant, particularly during vital growth stages like blooming and pod formation. Soboksa *et al*.(2024) said that, for germination, pod development, and grain filling, soybeans need enough moisture, not withstanding their resistance to moisture stress from germination until blooming.

Due to their negative impacts on seed germination and plant growth, heavy soils that are prone to waterlogging are not suitable for growing soybean(Kaur *et al.*, 2020). Similarly, Sathi *et al.*(2022) noted that Significant yield losses can arise from waterlogging during the early stages of development; depending on the length and intensity of the flooding, declines can range from 25% to 68%. Another study by Wu *et al.*(2022) noted that excessive moisture in these types of soils hinders the availability of oxygen, which lowers aerobic respiration in seedlings and increases their vulnerability to soil-borne illnesses, eventually resulting in lower germination rates.

Conversely, sandy loam soils are ideal for soybean production due to their favorable physical and biological properties (De Holanda *et al.*, 2025). These soils offer excellent

drainage and aeration, facilitating healthy root development and efficient nitrogen fixation by symbiotic bacteria like Bradyrhizobium japonicum. sandy loam soils warm up quickly, promoting early seedling emergence and reducing the risk of seedling diseases. Their structure also minimizes erosion risks and supports effective water infiltration, ensuring consistent moisture availability without waterlogging (Abdallah *et al*., 2021).

2.5 Factors Affecting Soybean Production in Ethiopia

Soybean production and Productivity can be affected by biotic and abiotic factors in addition to soil and climate-related variables such drought, high temperatures, and salt (Hossain *et al.,* 2023). The most important aspects for soybean crops are soil fertility, soil pH, nutrient availability, plant density, moisture availability, and crop management practices (Abebe and Ayana, 2023). Nutrient deficiency particularly those related to phosphorus, severely hinder the development of soybeans in tropical and subtropical climates. According to Aliye and Tadesse (2018) and Mokonen *et al.*(2018),insufficient phosphorus significantly affects soybean nodulation, root development, and grain yield in Ethiopian soils. Chen *et al.*(2023) suggest that because phosphorus is necessary for biological nitrogen fixation and energy transmission, it directly affects pulse crops, like soybean crop.

Poor agronomic practices, a lack of improved cultivars, a lack of technology, and a lack of crop care are the main obstacles to soybean production(Sedibe *et al*., 2023) . In tropical and subtropical regions, temperature fluctuations and inappropriate soil moisture conditions can significantly reduce soybean production stability and resilience (Hamza *et al*., 2024). The result corresponds with the findings of Owaresat *et al*.(2023), who found that moisture stress considerably lowers soybean yield throughout the blooming and pod-filling stages. Another significant issue that reduces soybean output is moisture stress. water stress causes poor pod set and reduced seed weight by inhibiting photosynthesis and nitrogen fixation.

In Ethiopia, soybean still being produced, 1.5 t ha^{-1} to 2.4 t ha^{-1} at farmers' fields, but the yields at research facilities under improved management conditions have a potential yield of 1.8 t ha^{-1} to 2.7 t ha^{-1}(Firdisa *et al*., 2025). The major productivity gaps are a lack of low soil fertility, lack of access to better varieties, poor agronomic practices, and

improper application of fertilizers and rhizobium inoculants (Alaminew and Alamayehu, 2020; Ababe and Ayana, 2023).

2.6 Response of Soybean growth and yield to Vermicompost Fertilizer

Vermicompost is becoming a popular and practical method of managing organic waste that benefits both the environment and the economy (Ameta *et al*., 2024). This process creates nutrient rich fertilizer that enhances soil fertility and encourages sustainable farming by using earthworms to break down organic materials (Singh *et al*., 2020). Misunderstandings of modern crop production techniques and nutrition may contribute to the low yield of soybeans, along with other factors. Applying vermicompost is said to improve the physical, chemical, and biological characteristics of the soil, resulting in increased soybean production and growth. Previous studies by Asefa and Wagari (2021) indicated that applying 2.5 t h^{-1} of vermicompost on acidic soil in western Ethiopia greatly boosted soybean yield. Similarly, Rahman *et al*.(2023) showed applying vermicompost is improved plant height, pod number, and grain yield in soybean due to improved nutrient availability and microbial activity.

Vermicompost is a major source of microbial diversity and populations, particularly for bacteria, fungi, and actinomycetes (Vuković *et al*., 2021). During this process, microbial activity releases elements that were previously present, such as N, P, K, and Ca, transforming them into forms that are more soluble and accessible to plants than those in the original waste (Singh *et al*., 2020). Ameta *et al.* (2023) found that crops grown in planting soil treated with humic acids, an extract from vermicompost, grew faster. A combination of hormonal and humic responses to plant development was the hypothesis of this research, which suggested that plant growth hormones may adsorb onto humic fractions (Jindo *et al*., 2020).

Vermicompost is an economical and sustainable way to increase production. It improves plant growth, yield, and germination efficiency (Rehman *et al*., 2023). through an integrated nutrient management strategy, increasing soil fertility, and crop productivity. Vermicompost with phosphate fertilizer increased the number of pods per plant, seed weight, and two measures of soybean productivity (Hashi and Munsur, 2025). Studies conducted in Ethiopia found that the development characteristics of soybeans were

generally significantly improved when vermicompost was added to phosphorus supplies (Ibro, 2023).

2.7 Response of Soybean to Phosphorus Fertilizer

Phosphorus(P) is an essential nutrient that plays a critical role in energy transfer, root development, flowering, and, seed formation in soybean. It also necessary for respiration, photosynthesis, cellular energy transmission, root system development, and seed production(Wubie Tasew, 2025). Phosphorus is also accelerates ripening to encourage pod development, flowering, nodulation, and early growth (Aliye and Tadesse, 2016; Adugna, 2021). In phosphorus deficient soils, growth and reproductive processes may be severely impeded, resulting in reduced yields (Khan *et al*., 2023).

Adding phosphorus (46 kg ha^{-1}) to legume crops has a substantial effect on plant height, branch count, root and shoot dry weights, and nodule count(Gebremariam and Tesfay 2021). According to recent research, phosphorus fertilizer increases soybean biomass and seed output while also supporting better nutrient uptake and nodulation efficiency (Mirriam *et al*., 2022). As a result, appropriate phosphorus management remains an important strategy in soybean agronomy, especially in locations with low soil phosphorus availability.

Aliye and Tadesse (2016) and Mokonen *et al*.(2018) reported that, the application of 46 kg phosphorus ha^{-1} significantly enhanced soybean seed yield, achieving yields of up to 2.6 t ha^{-1}. Similarly, Chen *et al*.(2023) found that phosphorus fertilizer improved root development, nodulation efficiency, and biomass accumulation, all of which subsequently increased grain output. However, when phosphorus levels are increased above ideal levels, yield does not rise correspondingly. Agronomic performance, such as plant height, branch count, root and shoot dry weights, and nodule count, is significantly impacted by phosphorus application and legume production(Dikr and Abayechaw, 2022).

2.8 Combined Application of Vermicompost and Phosphorus on Soybean

However, certain studies suggest that vermicompost alone might not supply enough phosphorus to meet crop requirements, particularly in nutrient -deficient soils(Purnama *et al*., 2025). Applying phosphorus and organic fertilizer together is a sustainable agricultural method that increases crop output, encourages plant growth, and improves soil fertility (Gamage *et al*., 2023). Beneficial microbes, enzymes, growth regulators, and

humic chemicals that enhance soil structure. Furthermore, we believe that phosphorus is an essential nutrient for plant growth, particularly for the development of roots, blooms, and fruit (Fathi and Afra, 2023). Because fixation frequently results in reduced phosphorus availability in soils, using organic fertilizer, such as vermicompost, assists in solving the issue.

Combining organic amendments with phosphorus fertilizer greatly increased soybean production, nodulation, and nutrient uptake as compared to alone, as shown by Debela *et al*.(2021) and Sande *et al*.(2024). Positive reactions were linked by these authors to decreased phosphorus fixation, increased root growth and nutrient absorption, improved soil pH, and microbial activity. In the same way, Bekele *et al*.(2019) suggested that combining vermicompost with mineral phosphorus increased biomass and seed output, especially in acidic soils. Particularly in low-phosphorus soils, synergistic actions with phosphorus fertilizer increase the effectiveness of phosphorus uptake and utilization by soybean plants. It has been demonstrated that applying 2.5 t ha^{-1} of vermicompost and 46 kg of phosphorus ha^{-1} enhances soybean seed production as well as agronomic indicators, including nodulation, plant height, and dry matter accumulation (Asefa and Wegari, 2021).

In order to achieve sustainable soybean production, improve soil health, and ensure long-term productivity, they promote the adoption of integrated nutrient management (INM) techniques, which include organic and inorganic sources. Microorganisms and organic acids included in vermicompost help in the solubilization of phosphorus, producing more accessible to plants (Sande *et al.*, 2024). It also improve soil microbiology, phosphate cycling, and root development. According to previous research, using both phosphorus and vermicompost fertilizers combined increased crop biomass, yield, and nutrient content more than using either fertilizer alone (Bekele *et al.*, 2019).

3. MATERIALS AND METHODS

3.1 Description of the Study Area

The experiment was carried out during the 2025 GC main cropping seasons at Bako Agricultural Research Center (BARC), which is located in Oromia Regional State, West Shoa Zone, about 250 km away from the capital city, Addis Ababa, on the way to Nekemte town. The Bako Agricultural Research Center was Eight (8 km) from Bako town at an altitude of 1650 m.a.s.l. The center is located at about 9.2'N latitude and 37.08'E longitude. The area has received a minimum and maximum annual rainfall of 850 mm and 1680 mm, respectively, mainly from May to October, with maximum precipitation in the months of June to August (Meteorological station of the center). The predominant soil type of the area is Nitosols. The area is known for its mixed crop and livestock farming system in which the cultivation of maize (*Zea mays* L.), hot pepper (*Capsicum annuum* L.), soybean (*Glycine max* L.), common bean (*Phaseolus vulgaris* L.), Mango (*Mangifera indica* L.), banana (*Musa spp*.), and sugarcane (*Saccharum officinarum* L.) are the major cropping activities. As a whole, it has good agricultural potential.

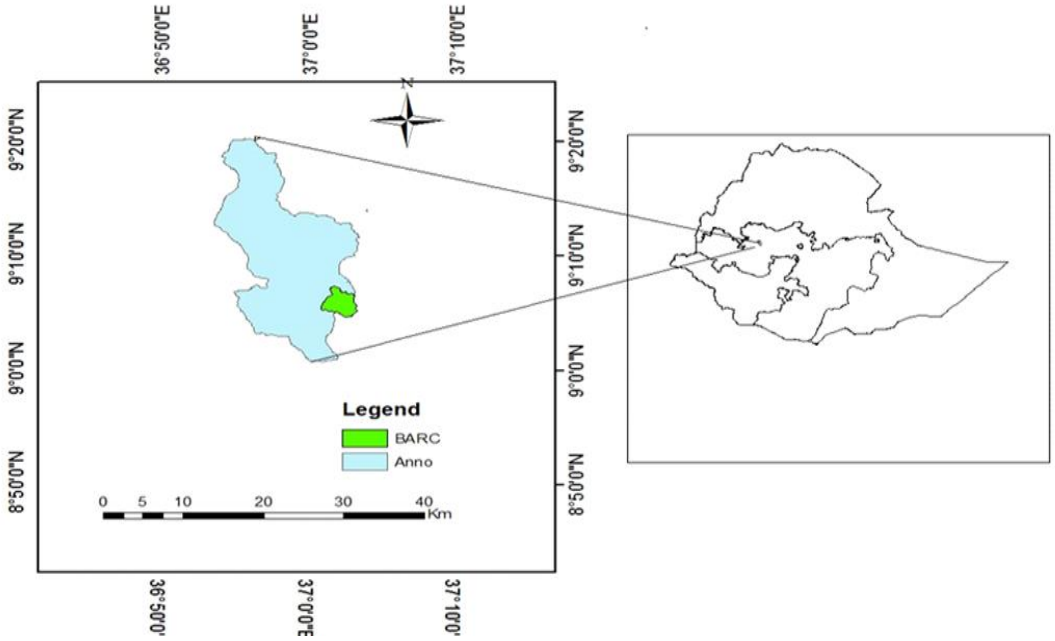


Figure 1. Map of the study area

3.2 Mean monthly weather of the study area

Information obtained from the Bako Research Center Meteorological Observatory through the Ethiopian National Meteorology Agency indicates that the total annual rainfall received in the 2025 cropping season was 951.06 mm, with mean maximum and minimum temperatures of 26.43 and 15.21 °C, respectively .

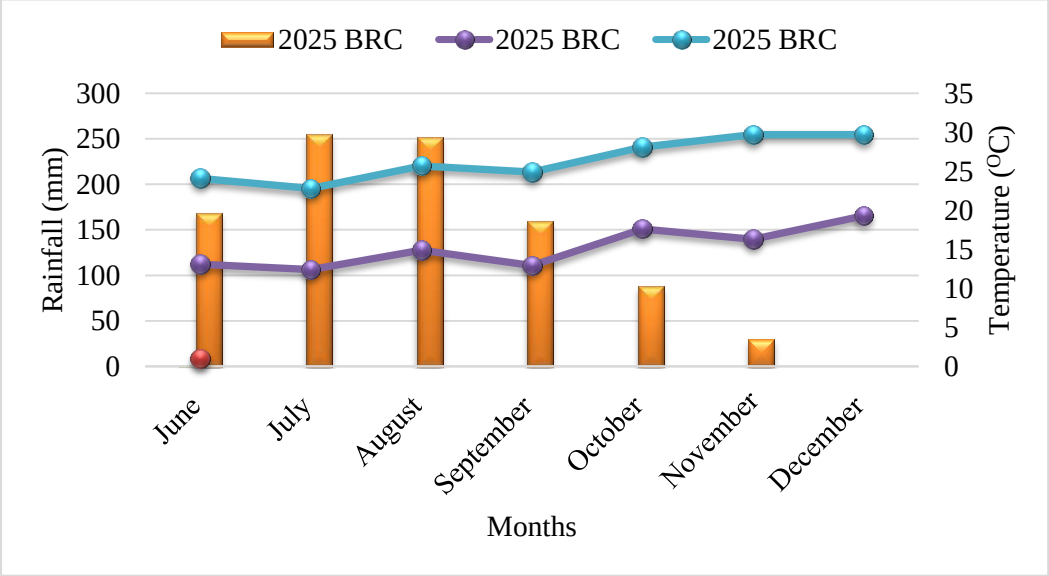


Figure 2. Monthly rainfall (mm) and mean temperatures (°C) of the experimental site during the 2025 cropping season (source: Bako Agricultural Research Center Meteorological Observatory through Ethiopian National Meteorology Agency).

3.3 Description of Experimental Materials

An improved soybean variety (Gute) was used as a test crop (the variety was released by the Bako Agricultural Research Center (BARC) during 2012 E.C). The variety was characterized by the late maturity group (110 to 141) days to maturity, and having a indeterminate growth habit and yellow seed color. this variety is highly adaptable to condition areas of mid and low altitudes. The yield potential of the soybean Gute variety at Farm area 1.5 t ha^{-1} to 2.4 ton ha^{-1} and on station area 1.8 t ha^{-1} to 2.7 t ha^{-1}(Arega and Dabesa, 2020). Triple superphosphate(TSP) contained 46%P_2O_5 was taken from the Bishoftu Agricultural Research Center and was applied in the row as per the treatment and mixed with the soil just at the time of planting. Vermicompost was taken from BARC for the experiment at the recommended rate and incorporated into the specified plot.

3.4 Treatments and experimental design

The experiment comprised four phosphorus rates (0, 23, 46, and 69 kg ha^{-1}) and four vermicompost rates (0, 1.25, 2.5, and 3.75 t ha^{-1}) with a total of 16 treatments. The experiment was laid out as a randomized complete block design (RCBD) in a factorial arrangement with 3 replications. The experiment established on a total gross plot area of 458.2 m^2, measuring 11.6 m width by 39.5 m in length. Individual gross plots were prepared with a size of 2 m length and a width of 3.2 m (6.4 m^2) by keeping 0.5 m and 1m wide paths between plots and blocks, respectively. The treatments were assigned to each plot randomly. Soybean was sown in rows of 10 cm between plants and 40 cm between rows. The outer row from each side was considered a border row with edge effects, and plants in such rows were not considered for collecting data. In addition, one plant at the end of each row was excluded to remove edge effects. Hence, a net plot area spanned 1.9 m x 2.8 m (5.32 m^2), containing six rows with a total of 108 plants per net plot area.

3.5 Soil Sampling and Analysis

Before starting the experiment, surface soil samples were collected randomly in a diagonal pattern from ten(10) different spots of the entire experimental field at depths ranging from 0 to 20 cm using an auger. Soil subsamples were mixed thoroughly to make a single composite before laboratory analysis. The samples were air-dried at room temperature, ground, and passed through a 2 mm diameter sieve for analysis of most soil parameters except organic carbon and total nitrogen, for which the samples were further crushed to pass through a 0.50 mm sieve diameter.

The soil samples were analyzed at the Bako research center soil laboratory for selected physical and chemical properties (pH, texture, organic carbon (OC), total Nitrogen (N), available Phosphorus (P), exchangeable bases (Mg, Ca,) and cation exchange capacity (CEC). Soil pH was determined in a 1:2.5 soil-to-water suspension using a glass electrode pH meter (Van Reeuwijk, 1992). Soil textural class was determined by the Bouyoucous hydrometer method (Hazelton & Murphy, 2007). Soil OC was determined by the chromic acid oxidation method (Walkley, 1994). Soil total nitrogen was analyzed using the macro-Kjeldahl digestion method followed by the ammonium distillation and titration method (Jones, 2003). Soil available phosphorus was analyzed calorimetrically using the Bray II method (Bray and Kurtz, 1945). Soil CEC was assessed using a 1M ammonium acetate

(NH4OAc) saturated sample at pH 7(Chapman, 1965). Soil exchangeable bases were determined following the atomic absorption spectrophotometer method(Okalebo *et al*., 2002).

Similarly, from the bulk of vermicompost, representative composite samples were collected before sowing, while post application soil samples were obtained after harvest by collecting soil from different randomly selected spots within vermicompost-treated plots at a depth of 0 to 20 cm to capture treatment induced changes. All collected subsamples were thoroughly mixed to form composite samples, air dried at room temperature, gently crushed, and passed through a 2 mm sieve before laboratory analysis. Selected physicochemical properties (pH, OC, total N, available P, and CEC) were determined for both pre sowing vermicompost and post-application soil samples using the same methodology followed above and analyzed at the Bako Research Center Soil Laboratory.

3.6 Experimental Procedures and Field Management

To create fine soil particles, the experimental field was tilled three times using a tractor. According to the prescribed rates indicated in the treatments and experimental design above, vermicompost was applied 3 weeks before sowing to each plot. A 60 kg ha^{-1} recommended seed rate was used, and two seeds were planted per hill in June 2025. At the two to three leaf stage, the plants were thinned to maintain the optimum plant population by considering the weak, insect-damaged, and diseased plants. The full recommended (18 kg N ha^{-1}) rate of nitrogen in the form of urea was applied to all the experimental plots in rows at the time of sowing as a starter and covered with soil. All recommended soybean husbandry practices were followed as required throughout the growth period. At harvesting maturity (when the pods dried and the seeds inside the pods made a sound on shaking), harvesting was done following cultural practice.

3.7 Data Collected and Measurements

3.7.1 Phenological Parameters of soybean

Days to 50% emergence were recorded as the number of days from the date of sowing to the time when 50% of the seeds in each plot emerged from the ground by visual observations.

Days to 50% flowering were determined by counting the number of days from the date of planting to the time when 50% of plants in each plot had shown flowers.

Days to 90% physiological maturity were determined as the number of days from planting to the time when 90% of the plants started senescence of leaves (light yellowing of the foliage), and pods started to lose their pigmentation.

3.7.2 Nodule Parameter

Total number of nodules per plant was determined at 50% flowering by carefully uprooting bulk roots from 10 randomly selected plants taken from the destructive rows of each plot. The roots were gently washed under running tap water using a sieve to remove adhering soil without dislodging nodules, after which all nodules were carefully separated and counted to obtain the total nodule number per plant.

Number of effective and non-effective nodules per plant were determined by carefully slicing each nodule with a sharp blade and visually examining the internal color. Nodules with a white or green color occurred inside were categorized as non-effective, whereas those with a pink or reddish color were considered inside successful, signifying active nitrogen fixing.

Nodule fresh weight per plant was determined by pooling all nodules collected from 10 randomly sampled plants in each plot, including those dissected for effectiveness assessment, and immediately weighing them using a sensitive analytical balance to obtain fresh weight, which was then expressed on a per-plant basis.

Nodule dry weight per plant was determined by oven-drying nodules collected from the roots of 10 randomly sampled plants at 70 °C for 48 hours. The dried nodules were then weighed using a sensitive analytical balance, and the mean value was calculated and expressed in grams per plant.

3.7.3 Growth Parameters

Plant height was measured at physiological maturity from the base of the plant to the tip of the main stem for 10 randomly pre-tagged plants from the harvestable rows using a meter tape, and the values were averaged and expressed on a per-plant basis.

Number of branches per plant was determined at physiological maturity by counting all branches produced by the main stem on 10 randomly pre-tagged plants from the net plot, and the values were averaged and expressed on a per-plant basis.

Number of leaves per plant was determined by manually counting the total number of leaves at 50% flowering and again at 90% physiological maturity from 10 randomly pre-tagged plants per plot, and the mean value was calculated and expressed on a per-plant basis.

3.7.4 Yield and Yield Components

Number of pods per plant was recorded at physiological maturity by manually counting all pods from 10 randomly pre-tagged plants within each net plot, and the mean value was calculated and expressed on a per-plant basis.

Number of seeds per plant was determined by counting the total number of seeds obtained from 10 sampled plants and dividing all seeds by 10 plants, and the result was expressed as the average number of seeds per plant.

Hundred-seed weight was determined by counting 100 grains from the bulk of shelled grains of each net plot using a grain counter, weighing them with by sensitive balance at 10 % moisture content, and expressing the average weight in grams per 100 grains.

Aboveground dry biomass yield was determined by cutting all plants in the net plot at ground level, bundling them, and sun-drying in a standing position until a constant weight was achieved (approximately seven days), after which the dry biomass was weighed and recorded using electronic balance.

Grain yield was determined by manually harvesting soybeans from each net plot using the plucking method, followed by sun-drying. Grains were separated from pods by hand threshing, and the moisture content of the grains was immediately measured using oven-drying method.

The grain weight was then adjusted to a standard moisture content of 10 % and multiplied by the plot area to calculate the adjusted grain yield per hectare using the following formula.

$$\text{Grain yield kg ha}^{-1} = \text{grain yield kg per net plot}^{-1} \times \frac{10000\ \text{m}^2}{\text{Net plot size m}^2}$$

Harvest Index (HI) was calculated as the ratio of grain yield per plot (adjusted to 10 % moisture content) to the total sun-dried aboveground biomass yield per plot, and expressed as a proportion or percentage.

$$\text{HI}\ (\%) = \left(\frac{\text{Grain Yield}}{\text{Aboveground dry biomass}}\right) * 100$$ (Pinto *et al.*, 2018)

3.8 Data Analysis

The collected Agronomic Data were subjected to Analysis of Variance (ANOVA) following standard procedure applicable to factorial experiment in RCBD given by Gomez and Gomez(1984) using Statistical analysis Soft ware (SAS Version 9.0) (SAS Institute, 2004). The Mean separation was Done using Least Significance Difference (LSD) test at 5% probability level and simple correlation were made in determining association of yield components and yield parameters.

3.9 Economic Analysis

According to CIMMYT (1988), economic analysis was used to compare the treatments' economic feasibility. The main purpose of this analysis was to assess the economic feasibility at a minimum rate of return of 50 to 100% (CIMMYT, 1988). To control the difference between the experimental yield and the yield that farmers might expect from the same treatment, soybean seed yields from experimental plots were adjusted downward by 10% for management and plot size variations.

Phosphorus fertilizer application cost (200 ETB per 100 $kgha^{-1}$), vermicompost application cost (400 ETB ton ha^{-1}), phosphorus fertilizer cost (185 ETB kg^{-1}), and vermicompost cost (2000 ETB ton^{-1}) were used to obtain variable cost for this analysis. The current soybean seed local price (140 ETB kg^{-1}) was used for the economic analysis. Gross field benefit was determined by multiplying the field price that farmer receive for the crop when they sell it adjusted yield. GFB = AGY × field price for the crop. Total variable cost (TVC) was the cost of Vermicompost, and phosphorous cost included in the application. Net benefit (NB) was determined by subtracting the total variable costs (TVC) from gross field benefits (GFB) for each treatment as NB = GFB – TVC.

Dominance Analysis (identification and elimination of inferior treatments): Before proceeding with the evaluating of Marginal Rates of Return, an initial testing of the costs

and benefits of each treatment, called dominance analysis, is important. The dominance analysis was carried out by first listing all the treatments in their order of increasing costs that vary (TVC), and their net benefits (NB) were then put aside. Any treatment that has a higher TVC but net benefits that are less than or equal to the previous treatment (with lower TVC but higher net benefits) is dominated (marked as “D”).The dominance analysis showed that to improve farmers' income, it is important to pay attention to net benefits rather than yields, because higher yields do not necessarily mean higher net benefits. Marginal rate of return (MRR) (%) was determined by dividing the change in net benefit (ΔNB) by the change in total variable cost (ΔTVC).

$$MR = \frac{\Delta NB}{\Delta TVC} \times 100$$

4. RESULTS AND DISCUSSIONS

4.1 Physico-chemical properties of the soils of the experimental site

The soil analysis results (Table 1) indicated that the experimental soil is classified as sandy clay loam, consisting of 60.5% sand, 15.3% silt, and 24.2% clay, a texture that is generally favorable for crop growth but highly responsive to management. The soil response was very strongly acidic (pH 4.97), which can severely limit nutrient availability and crop performance (Jones, 2003). According to ratings of Tekalign *et al*. (1991), organic carbon (1.3%) and organic matter (2.24%) were low, reflecting poor soil structural stability and limited nutrient reserves. Similarly, according to Olsen *et al.* (1954) and Jones (2003), ratings, available phosphorus (9.7 mg kg^{-1}), and total nitrogen (0.09%) were low, indicating major constraints to crop productivity. Furthermore, according to FAO (2008) classification, the cation exchange capacity (23 meq 100 g^{-1}) was medium, and exchangeable Ca (10.8 meq 100 g^{-1}) is high. According to Hazelton and Murphy (2007) classification, Mg (7.78 meq 100 g^{-1}) was high; the overall fertility status of the soil was inadequate to sustain optimal crop yields. In general, the results clearly demonstrate that the study area is nutrient deficient, a condition likely resulting from continuous cropping, limited organic matter resources, and minimal fertilizer application, which have collectively contributed to progressive soil fertility decline and reduced productive potential.

Table 1. Soil physico-chemical properties of the experimental field before sowing

Soil characteristics	Values	Category	References
A.Particlesize Distribution(%)			
Sand (%)	60.5		
Clay (%)	24.2		
Silt (%)	15.3		
Textural class		Sand Clay loam	Hazelton and Murphy (2007)
B. Chemical properties			
pH (1:2.5)	4.97	Very Strongly Acidic	Jones (2003)
Org. Carbon%	1.3	Low	Tekalign *et al*.(1991)
Total N%	0.09	Very Low	Jones (2003)
Avail. P(mg/kg)	9.7	Low	Olsen *et al.* (1954)
CEC (meq 100 g^{-1})	23	Medium	FAO (2008)
Ca (meq 100 g^{-1})	10.8	High	FAO (2008)
Mg (meq 100 g^{-1})	7.78	VeryHigh	Hazelton and Murphy (2007)

4.2 Physico-chemical properties of vermicompost used for the experiment

Laboratory evaluation of the vermicompost used in this study indicated that it was a chemically stable and biologically mature product (Table 2), suitable for agricultural application.

The measured moisture content was 39.2% which falls within the optimal range for sustaining microbial activity, which is essential for nutrient transformation and gradual release in soil nutrients (Edwards, 2010). The vermicompost exhibited a slightly alkaline reaction (pH 8.2) suggesting that the vermicompost can serve as an effective ameliorant for acidic soils, enhancing nutrient availability and reducing aluminum toxicity. The maturity of vermicompost was clearly demonstrated by a C: N ratio of 16.27, well below the critical threshold of 20, indicating that nitrogen mineralization rather than immobilization would occur following soil application (Bernal *et al*., 2009). This maturity

and stability were further supported by a high cation exchange capacity (CEC) of 52.47 cmol(+) kg^{-1}, exceeding the standard benchmark for well-humified organic amendments and reflecting the abundance of functional organic surfaces capable of retaining and supplying nutrients (Harada and Inoko, 1980). In terms of fertility, the vermicompost exhibited a high nutrient density, with substantial organic matter content (55.5%), which is critical for improving soil structure, water-holding capacity, and long-term carbon sequestration (Lal, 2004). Moreover, the relatively high concentrations of total nitrogen (1.98%) and Avail.P(1.39%) highlight the vermicompost's strong potential as a sustainable nutrient source (Hazelton and Murphy(2007). Overall, these results indicated that the produced vermicompost possesses both the stability and fertility attributes required to enhance soil quality and support crop growth when applied to agricultural fields.

Table 2. Chemical properties of vermicompost before sowing

Chemical properties	Values	Rating/Category	References
Moisture content%	39.2	Acceptable	Edwards (2010)
pH (H_2O)	8.2	Slightly alkaline	Hazelton and Murphy(2007)
Organic matter%	55.50%	Very High	Lal(2004)
Organic Carbon %	32.22	Very High	Hazelton and Murphy(2007)
C: N ratio	16.27	Very high	Bernal *et al.*, (2009).
Total %N	1.98	High	Hazelton and Murphy(2007)
Avail. %P	1.39	High	Hazelton and Murphy(2007)
CEC of cmol(+)/kg	52.47	very high	Harada and Inoko (1980).

4.3 Post-harvest soil physico-chemical properties

4.3.1 Soil Physical Properties (Texture)

The interaction between Phosphorus (P) fertilizer and Vermicompost had no significant effect ($p>0.05$) on post-harvest soil texture (Appendix Table 6).

The soil textural class remained sandy clay loam. This result is consistent with the findings of Tadesse *et al.*(2022), who noted that soil texture is a fundamental physical property that cannot change through short-term organic or inorganic amendments.

4.3.2 Soil Reaction (pH)

The main effects of rates of vermicompost and the interaction between Phosphorus (P) fertilizer and vermicompost had a significant effect ($P<0.05$) on soil pH, while rates of phosphorus did not affect this parameter(Appendix Table 6).

Soil pH responded significantly to the combined application of phosphorus and vermicompost, increasing from 4.95 in the control treatment to a maximum of 5.02 under the highest treatment level (69 kg P ha^{-1} and 3.75 t ha^{-1} vermicompost). The increase is agronomically significant for a very acidic soil, as even minor pH changes can have significant effects on nutrient availability and aluminum toxicity. Proton consumption during decarboxylation of organic anions and vermicompost mineralization releases basic cations (Ca^{2+} and Mg^{2+}) that displace H^{+} ions from exchange sites, driving the observed pH increase. These approaches improve crop growth by decreasing exchangeable aluminum, minimizing acidity stress, and boosting soil buffering capacity (Yuan *et al.*, 2023).

4.3.3 Soil Organic Carbon (OC) and Total Nitrogen (TN)

The main effects of rates of vermicompost and the interaction between phosphorus (P) fertilizer and vermicompost had a significant effect ($P<0.05$) on OC and TN. However this parameters were not significantly ($p\geq0.05$) affected by the rates of phosphorus (Appendix Table 6).

Soil OC and TN responded consistently and well to the combined application of phosphorus and vermicompost. Organic carbon increased from 1.30% in the control to 1.394% under the highest treatment level (69 kg P ha^{-1} and 3.75 t ha^{-1}vermicompost), while total nitrogen increased from 0.09% to 0.0966% across the same treatment gradient.

Although the absolute increases were minor, they are statistically and agronomically significant in the context of highly weathered, low-fertility soils, where incremental gains in carbon and nitrogen stocks can have a significant impact on soil function.The enrichment of OC reflects the contribution of vermicompost as a chemically stable carbon pool, which enhances soil aggregation, improves structural resilience, and supports long-term carbon sequestration. Concurrently, the observed increase in TN indicates that vermicompost functions as a slow-release nitrogen source, while also stimulating microbial activity that accelerates the mineralization of native soil nitrogen and improves nitrogen cycling efficiency. These combined effects highlight the importance of vermicompost not only as a nutrient amendment but also as a significant driver of soil biological processes and nutrient stabilization, ultimately contributing to soil fertility restoration in intensive cropping systems (Raza *et al*., 2023).

4.3.4 Available Phosphorus

The results of the analysis of variance showed that rates of vermicompost and the interaction between rates of phosphorus (P) fertilizer and vermicompost had a significant ($p \leq 0.05$) effects on available phosphorus, whereas rates of phosphorus did not affect on this variable (Appendix Table 6).

Among the observed soil chemical characteristics, available phosphorus showed the most significant and responsive change, rising from 9.70 mg kg^{-1} in the control treatment to 9.804 mg kg^{-1} under the highest combined application rate (69 kg P ha^{-1} and 3.75 t ha^{-1} vermicompost). Although the absolute increase was small, it is statistically significant and agronomically meaningful in strongly acidic, P-fixing soils, where minor increases in accessible phosphorus can result in major gains in crop absorption and yield. This response is primarily due to the biochemical processes associated with vermicompost decomposition, specifically the release of low-molecular weight organic acids that compete with phosphate ions for sorption sites on soil colloids, as well as the chelation of aluminum and iron ions, which are responsible for phosphorus fixation.

These mechanisms effectively reduce P sorption intensity, enhance phosphorus solubility, and sustain a higher concentration of plant-available phosphorus in the soil solution. The results underscore the critical role of vermicompost in improving phosphorus bioavailability and high light the synergistic benefits of integrating organic amendments

with mineral phosphorus fertilization for managing P constraints in acidic soils (Yang *et al*., 2024).

4.3.5 Cation Exchange Capacity (CEC) and Exchangeable Bases

The analysis of variance revealed that CEC and exchangeable bases were significantly ($p \leq 0.05$) affected by the main effects of vermicompost rates and the interaction between vermicompost and Phosphorus (P) fertilizer rates (Appendix Table 6).

Cation exchange capacity (CEC) increased progressively from 23.00 cmol(+) kg^{-1} in the control treatment to 23.84 cmol(+) kg^{-1} under the highest combined application rate (69 kg P ha^{-1} and 3.75 t ha^{-1} vermicompost), indicating an improvement in the soil's capacity to retain and supply nutrients. In parallel, exchangeable calcium rose from 10.80 to 10.904 cmol(+) kg^{-1}, while exchangeable magnesium increased from 7.80 to 7.93 cmol(+) kg^{-1}, reflecting enhanced base saturation and nutrient availability. Although these increases were moderate, they are agronomically meaningful in highly weathered soils where cation retention is inherently limited. The observed improvements are attributed to the incorporation of vermicompost-derived organic matter rich in carboxylic, phenolic, and hydroxyl functional groups, which generate a high density of negative surface charges capable of adsorbing and stabilizing essential base cations against leaching losses. This enhancement of exchange sites strengthens soil buffering capacity, improves nutrient-use efficiency, and contributes to the long-term resilience of the soil chemical environment, underscoring the value of integrating vermicompost with mineral fertilization for sustainable soil fertility management (Kumar *et al*., 2024).

Table 3. Post- harvest soil physico-chemical properties of the experimental site as affected by the interaction effects of rates of P fertilizer and Vermicompost in Bako district during the 2025 cropping season.

P Rate (kg ha^{-1})	VC(t ha^{-1})	Sand (%)	Clay (%)	Silt (%)	pH (H_2O)	Org.C (%)	Org.M (%)	Total N (%)	Avail.P (mg/kg)	CEC (cmol+/kg)	Ca (cmol+/kg)	Mg (cmol/ kg)
0	0	62.92	22.07	15.01	4.95 ^{h}	1.30 ^{g}	2.24 ^{f}	0.090 ^{h}	9.70 ^{g}	23.00 ^{i}	10.80 ^{f}	7.80 ^{i}
0	1.25	62.90	21.97	15.13	4.96 ^{gh}	1.31 ^{fg}	2.25 ^{f}	0.091 ^{gh}	9.72 ^{f}	23.21 ^{h}	10.82 ^{de}	7.83 ^{gh}
0	2.5	62.85	21.94	15.21	4.97 ^{fg}	1.32 ^{ef}	2.27 ^{f}	0.092 ^{fg}	9.74 ^{ef}	23.32 ^{g}	10.84 ^{cd}	7.85 ^{ef}
0	3.75	62.74	21.99	15.27	4.98 ^{ef}	1.33 ^{de}	2.29 ^{f}	0.093 ^{de}	9.76 ^{de}	23.43 ^{f}	10.86 ^{abc}	7.87 ^{cd}
23	0	62.95	22.02	15.03	4.96 ^{gh}	1.32 ^{ef}	2.27 ^{f}	0.091 ^{gh}	9.71 ^{fg}	23.13 ^{h}	10.81 ^{ef}	7.82 ^{h}
23	1.25	62.36	22.46	15.18	4.97 ^{fg}	1.33 ^{de}	2.24 ^{f}	0.092 ^{fg}	9.74 ^{ef}	23.36 ^{fg}	10.84 ^{cd}	7.85 ^{ef}
23	2.5	62.31	22.49	15.20	4.98 ^{ef}	1.34 ^{d}	2.29 ^{f}	0.093 ^{de}	9.75 ^{ef}	23.41 f	10.85 ^{bc}	7.86 ^{d}
23	3.75	62.29	22.49	15.22	4.98 ^{ef}	1.34 ^{d}	2.29 ^{f}	0.093 ^{de}	9.75 ^{ef}	23.45 ^{ef}	10.85 ^{bc}	7.87 ^{cd}
46	0	62.93	22.04	15.03	4.98 ^{ef}	1.34 ^{d}	2.29 ^{f}	0.092 ^{fg}	9.65 ^{h}	23.40 ^{f}	10.79 ^{f}	7.79 ^{i}
46	1.25	61.13	23.61	15.18	4.99 ^{de}	1.35 ^{cd}	2.32 ^{e}	0.094 ^{cd}	9.76 ^{de}	23.55 ^{d}	10.86 ^{abc}	7.89 ^{bc}
46	2.5	61.11	23.62	15.20	4.99 ^{de}	1.36 ^{c}	2.34 ^{de}	0.094 ^{cd}	9.77 ^{cd}	23.60 ^{d}	10.87 ^{ab}	7.89 ^{bc}
46	3.75	61.10	23.61	15.22	5.00 ^{cd}	1.37 ^{bc}	2.36 ^{cde}	0.095 ^{bc}	9.78 ^{bc}	23.65 ^{c}	10.88 ^{ab}	7.90 ^{b}
69	0	62.93	22.05	15.03	4.99 ^{de}	1.36 ^{c}	2.34 ^{f}	0.094 ^{cd}	9.77 ^{cd}	23.59 ^{d}	10.78 ^{f}	7.88 ^{bc}
69	1.25	60.46	24.21	15.26	5.00 ^{cd}	1.38 ^{b}	2.379 ^{bcd}	0.095 ^{bc}	9.79 ^{ab}	23.74 ^{b}	10.89 ^{ab}	7.92 ^{a}
69	2.5	60.29	24.37	15.27	5.01 ^{b}	1.38 ^{b}	2.379 ^{abc}	0.096 ^{ab}	9.79 ^{ab}	23.79 ^{ab}	10.89 ^{ab}	7.93 ^{a}
69	3.75	60.11	24.53	15.29	5.02 ^{a}	1.39 ^{a}	2.396 ^{ab}	0.096 ^{a}	9.80 ^{a}	23.84 ^{a}	10.90 ^{a}	7.93 ^{a}
LSD(0.05)		NS	NS	NS	0.01	0.01	0.006	0.001	0.01	0.07	0.02	0.01
CV (%)		0.32	0.42	0.45	0.25	1.21	0.54	1.45	0.38	0.56	0.31	0.4

VC = vermicompost; LSD = least significant difference; CV = coefficient of variation , Org.C = Organic carbon, Org.M = Organic matter, Total N = Total Nitrogen, Avail.P = Available Phosphorus, CEC = Cation exchange capacity, Ca = calcium, Mg = magnesium. *Mean values followed by the same letter (s) within the column are not significantly different at a 0.05 probability level.*

4.4. Phenological Parameters of Soybean

4.4.1 Days to 50 % Emergence

The analysis of variance showed that the main effects of phosphorus (P) fertilizer rates, vermicompost rates, and their interaction did not have significant ($p \geq 0.05$) effects on the days to 50% emergence (Appendix Table 1).

Soybean seed emergence was not affected by the two factors application, indicating that early emergence is largely independent of external nutrient inputs. Seed emergence at this stage is mostly determined by seed viability, soil moisture, temperature, and endogenous nutrition reserves inside the cotyledons, as emerging seedlings require a well-developed root system to obtain nutrients. As a result, neither phosphorus nor vermicompost changed emergence dynamics, which is similar with previous study showed that nutrient supplements typically affect crop performance only after root establishment and during subsequent development phases (Demise *et al.*, 2017).

4.4.2 Days to 50 % Flowering

The main effects of phosphorus fertilizer rates and vermicompost rates was significantly ($p \leq 0.05$) influenced on days to 50% flowering, but their interactions did not have a significant ($p \geq 0.05$) effect on days to 50% flowering (Appendix Table 1).

Days to flowering were significantly affected by vermicompost application, with the highest rate (3.75 t ha^{-1}) resulting in the longest time to flowering (71.5 days), while the control treatment recorded the earliest flowering (65.2 days) (Table 4). The observed delay in flowering at higher vermicompost rates is likely attributable to the gradual release of nitrogen and micronutrients, which enhances vegetative growth and prolongs the vegetative phase, thereby postponding the transition to reproductive development. Such nutrient-mediated extension of vegetative growth reflects improved nutrient availability rather than physiological stress. This response aligns with previous findings indicating that organic amendments sustain nutrient supply and extend vegetative growth duration before flowering (Tesfaye and Balcha, 2023).

Phosphorus application also significantly influenced the duration to 50% flowering, with the longest period (75.8 days) recorded at the highest rate of 69 kg P ha^{-1}, whereas the shortest duration (62.1 days) occurred in the control treatment (Table 4). Similar results were reported by Alemayehu *et al.*(2017), who found that phosphorus fertilizer

significantly affected days to 50% flowering of soybean, their study indicated that soybean plants fertilized with 60 kg P ha^{-1} required 74.6 days to reach 50% flowering, whereas the control treatment reached flowering significantly earlier at 63.4 days. Adequate phosphorus supply enhances root development, canopy expansion, photosynthetic capacity, and when available in sufficient amounts together with nitrogen derived from soil reserves or biological fixation, it prolongs the maintenance of active green leaf area. This sustained vegetative growth delays senescence and subsequently postpones the onset of flowering. The present findings are similar with those of Tarekegn *et al*. (2021), who reported a significant delay in soybean flowering with increasing phosphorus application due to extended vegetative growth duration.

4.4.3 Days to 90% Physiological Maturity

The analysis of variance showed that phosphorus fertilizer rates and vermicompost rates had a significant ($p \leq 0.05$) effect on days to 90% physiological maturity, but their interactions did not have a significant ($p \geq 0.05$) effect on days to 90% physiological maturity (Appendix Table 1).

Physiological maturity was significantly influenced by vermicompost application, with plots receiving 3.75 t ha^{-1} requiring the longest time to mature (143.4 days), whereas the control treatment reached maturity earliest (134.5 days) (Table 4). Similar results were obtained by Hazzori (2023), who showed that soybeans treated with high vermicompost rates needed 132 to 139 days as compared to 118 to 122 days in the control. According to Dugassa *et al*.(2025), a high rate of vermicompost resulted in delayed maturity, which increased from 129.6 (control) to 141.8 days(treated soil). The observed delay in maturity under higher vermicompost rates may be primarily attributed to a pronounced stay-green effect, driven by the sustained availability of nitrogen and other essential nutrients that prolong photosynthetic activity and delay senescence. In addition, vermicompost improves soil moisture retention and nutrient buffering capacity, creating a more favorable growth environment that extends the functional life cycle of the crop. These findings are consistent with Gichangi *et al*.(2020), who reported that organic fertilizers delay crop maturity by enhancing soil moisture status and ensuring a continuous nutrient supply throughout the growing season.

Regarding phosphorus application, the longest duration maturity (146.3 days) was observed at the highest phosphorus rate (69 kg ha^{-1}), while the control treatment reached maturity earlier (133.5 days) (Table 4). Adequate phosphorus supply migth enables plants to fully satisfy vegetative growth requirements before progressing to reproductive development and supports efficient assimilate translocation during grain filling, thereby extending the reproductive phase. In contrast, phosphorus-deficient plants tend to senescence prematurely due to constrained metabolic activity and limited assimilate availability. This pattern aligns with findings by Wondimu and Tana (2022), who reported prolonged maturity periods in legumes under increased mineral fertilization.

Table 4. Soybean phenological parameters as affected by the main effects of rates of Phosphorus fertilizer and vermicompost in Bako district during the 2025 cropping season

Treatments	Days to 50% Emergency	Days to 50% Flowering	Days to 90% physiological Maturity
Rates of VC (t ha^{-1})			
0	6.26	65.2^{c}	134.5 ^{c}
1.25	6.26	68.4^{b}	138.2 ^{b}
2.5	6.26	70.1^{a}	141.0 ^{a}
3.75	6.26	71.5^{a}	143.4 ^{a}
LSD($p \leq 0.05$)	NS	2.14	3.05
P (kg ha^{-1})			
0	6.17	62.1^{d}	133.5^{c}
23	6.17	66.8^{c}	136.2^{c}
46	6.17	70.5^{b}	141.1^{b}
69	6.17	75.8^{a}	146.3^{a}
LSD ($p \leq 0.05$)	NS	2.14	*3.05*
CV (%)	9.5	5.6	4.1

LSD = Least significant difference, CV = Coefficient of variation, Mean Values followed by the same letter(s) within the column are not significantly different at a 0.05 probability level.

4.5 Nodule Parameter of soybean

4.5.1 Number of Total Nodules Per Plant

The main effect of phosphorus fertilizer rates and vermicompost rates, and their interaction, had a highly significant ($p \leq 0.001$) effect on the total number of nodules per plant (Appendix Table 2).

The total number of nodules per plant was strongly influenced by the integrated application of vermicompost and phosphorus fertilizer, with the highest nodule count (32.77) recorded under 3.75 t ha^{-1} vermicompost combined with 69 kg ha^{-1} phosphorus, whereas the lowest number (12.93) occurred in the control treatment (Table 5). These findings are consistent with those of Abeje *et al.* (2022), who reported that the maximum number of nodules (43.67) was recorded with the interaction of both organic and inorganic fertilizer, and gave the minimum number of nodules (4.3) occurred in the control treatment.

Phosphorus is important in Rhizobium legume symbiosis, especially during the energy intensive processes of root hair infection, nodule primordia start, and early nodule development. This could explain the significant increase in nodulation under combined nutrient delivery. Furthermore, vermicompost likely improved the physical structure, microbial activity, and aeration of the soil, making the rhizosphere more conducive to Rhizobium infection and survival. The findings of this investigation on the complementing effects of mineral and organic nutrient inputs are similar with previous studies by Bayu *et al.* (2022) and Gure (2023). Moreover, the findings corroborate those of Bekele *et al*. (2020), who demonstrated that integrated nutrient management not only increases nodule abundance but also improves nodulation efficiency, a critical factor in meeting the high nitrogen demand of soybean through biological nitrogen fixation.

4.5.2 Number of Effective Nodules Per Plant

The analysis of variance indicated that the number of effective nodules per plant was highly significantly ($p \leq 0.001$) affected by the main effect of rates of phosphorus fertilizer and vermicompost, and their interaction effects (Appendix Table 2).

The number of effective nodules per plant responded markedly to the integrated application of vermicompost and phosphorus fertilizer, with the highest effective nodule count (32.34) recorded under the combined treatment of 3.75 t ha^{-1} vermicompost and 69 kg ha^{-1} phosphorus, while the lowest value (11.95) was observed in the control treatment (Table 5). These current findings are consistent with those of Abeje *et al.(*2022) who recorded the highest effective nodules from the interaction of organic and NPSB (52.67) at Assosa and (52.33) in Bambassi.

This pronounced enhancement reflects the synergistic effects of phosphorus and vermicompost on the Bradyrhizobium soybean symbiosis. Phosphorus plays a central role in energy transfer and ATP synthesis, processes that are critical for nodule initiation and sustained biological nitrogen fixation, whereas vermicompost improves soil pH, aeration, organic carbon availability, and microbial activity, thereby creating a more favorable rhizosphere environment for effective nodulation. Beyond increasing total nodule formation, this integrated nutrient supply ensured that a greater proportion of nodules were physiologically active and functional, as evidenced by their effectiveness. These findings are in strong agreement with those of Bayu *et al*. (2022) and Alemu and Bayu (2022), who reported that combined applications of phosphorus (energy source) and vermicompost (soil quality enhancer) create optimal conditions for efficient Bradyrhizobium symbiosis. Similarly, Bekele *et al*. (2020) demonstrated that integrated nutrient management enhances not only nodule abundance but also nodulation effectiveness, a critical requirement for meeting the high nitrogen demand of soybean through biological nitrogen fixation.

4.5.3 Number of Ineffective Nodules Per Plant

The main effects of rates of phosphorus fertilizer and vermicompost, and their interaction, had a significant ($p \leq 0.05$) effect on the number of ineffective nodules per plant (Appendix Table 2).

The number of ineffective nodules was significantly reduced by the combined application of phosphorus fertilizer and vermicompost, with the lowest value (0.43) recorded at the highest treatment level (69 kg ha^{-1} phosphorus and 3.75 t ha^{-1} vermicompost).

In contrast, the highest number of ineffective nodules (0.98) was observed in the control treatment, a response that was statistically comparable to treatments receiving vermicompost alone at 1.25 and 2.50 t ha^{-1} without phosphorus (Table 5). The marked decline in ineffective nodules under integrated nutrient management suggests that adequate phosphorus supply and improved soil conditions provided by vermicompost corrected nutrient limitations, thereby enabling the host plant to favor the formation and maintenance of metabolically active nodules while suppressing non-functional ones. This reflects an improved efficiency of the symbiotic relationship, where plant carbon

investment is preferentially allocated to productive nitrogen-fixing structures. The present findings are consistent with Bejiga (2021) and further supported by Bekele *et al*. (2020), who reported that combined phosphorus fertilization and organic amendments enhance nodule functionality by promoting optimal nodule development and reducing the proportion of ineffective nodules.

Table 5. Soybean Nodule parameters as affected by the interaction effects of rates of vermicompost and phosphorus fertilizer in Bako District during the 2025 cropping season

Rates of VC (t ha^{-1})	P fertilizer rates (kg ha^{-1})	TNPP	ENPP	IENPP
0	0	12.93 ^{k}	11.95 ^{l}	0.98 ^{a}
	23	17.98 ^{h}	17.15 ^{i}	0.83 ^{b}
	46	23.19 ^{e}	22.51 ^{f}	0.68 ^{d}
	69	28.41 ^{c}	27.87 ^{c}	0.54 ^{f}
1.25	0	14.77 ^{j}	13.84 ^{k}	0.93 ^{a}
	23	19.28 ^{g}	18.49 ^{h}	0.79 ^{b}
	46	24.5 ^{d}	23.85 ^{e}	0.65 ^{d}
	69	29.71^{b}	29.21 ^{b}	0.50 ^{g}
2.5	0	16.16 ^{i}	15.26 ^{j}	0.90 ^{a}
	23	19.72 ^{g}	18.94 ^{h}	0.78 ^{b}
	46	26.28 ^{c}	25.64 ^{d}	0.62 ^{e}
	69	31.47 ^{b}	31.00 ^{b}	0.47 ^{g}
3.75	0	16.81 ^{i}	15.93 ^{j}	0.88 ^{b}
	23	22.34 ^{f}	21.17 ^{g}	0.74 ^{c}
	46	27.12 ^{c}	26.53 ^{d}	0.59 ^{e}
	69	32.77 ^{a}	32.34 ^{a}	0.43 ^{h}
LSD ($p \leq 0.05$)		1.24	1.15	0.05
CV (%)		4.8	5.1	8.2

VC = vermicompost; CV = Coefficient of variation; LSD = Least significant difference; TNPP = Total Nodule per plant; ENPP = Effective Nodule per plant; IENPP = Ineffective Nodule per plant. Means followed by the same letters within each column are not significantly different at $p \leq 0.05$.

4.5.4 Nodule Fresh Weight and Dry Weight

The main effects of phosphorus fertilizer rates and vermicompost rates were highly significant ($p \leq 0.01$) on both nodule fresh weight and nodule dry weight. However, the interaction effect of phosphorus and vermicompost was non-significant($p>0.05$) for both nodule fresh weight and dry weight (Appendix Table 3).

Vermicompost application significantly enhanced both nodule fresh and dry weights, with the highest values (0.31 g plant^{-1} fresh weight and 0.16 g plant^{-1} dry weight) recorded at 3.75 t ha^{-1} vermicompost; these were statistically comparable to treatments receiving 1.25 and 2.50 t ha^{-1} (Table 6). In contrast, the control treatment exhibited the lowest nodule fresh and dry weights (0.25 and 0.12 g plant^{-1}, respectively), reflecting suboptimal conditions for nodule development. the increase in nodule biomass following vermicompost application is most likely due to enhanced micronutrient availability, particularly molybdenum, a key cofactor for the nitrogenase enzyme involved in biological nitrogen fixation(Tesfaye *et al.,*2022). Furthermore, vermicompost provides readily available organic carbon, which stimulates microbial activity in the rhizosphere and promotes nodule formation and functionality. Gichangi *et al*.(2020), found that vermicompost promotes the accumulation of leghemoglobin and beneficial bacterial populations within nodules, resulting in greater nodule mass and better symbiotic function.

Phosphorus application markedly affected nodule biomass, with the highest rate (69 kg P ha^{-1}) producing the maximum nodule fresh (0.33 g plant^{-1}) and dry weights (0.17 g plant^{-1}), whereas the control treatment recorded the lowest corresponding values (0.20 and 0.10 g plant^{-1}, respectively) (Table 6). The enhancement of nodule mass under higher phosphorus supply reflects the central role of phosphorus in energy transfer and ATP synthesis processes essential for nitrogenase activity and sustained nodule growth. Adequate phosphorus availability supports both nodule initiation and subsequent enlargement, leading to heavier and more physiologically active nodules.These results are similar with reports by Tolera *et al*. (2023), who demonstrated that phosphorus deficiency restricts nodulation, and significant increases in nodule fresh and dry weights in response to phosphorus fertilization.

Table 6. Nodule fresh and dry weight as affected by the main effects of vermicompost and P fertilizer rates in Bako district during the 2025 cropping season.

Treatments	Nodule Fresh Weight (g)	Nodule Dry Weight (g)
Rates of VC (t ha⁻¹)		
0.00	0.25[b]	0.12[a]
1.25	0.28[ab]	0.14[a]
2.50	0.30[a]	0.15[ab]
3.75	0.31[a]	0.16[a]
Phosphorus (kg ha⁻¹)		
0	0.20[c]	0.10[c]
23	0.29[b]	0.11[c]
46	0.30[b]	0.15[a]
69	0.33[a]	0.17[a]
LSD($p \leq 0.05$)	0.03	0.02
CV (%)	10.5	9.5

LSD = Least significant difference, CV = Coefficient of variation, Mean Values followed by the same letter(s) within the column are not significantly different at a 0.05 probability level.

4.6. Growth Parameter of soybean

4.6.1 Plant Height (cm)

The main factor, phosphorus fertilizer rates, and vermicompost fertilizer rates had a highly significant effect ($P \leq 0.001$) on plant height, while the main factor interaction had a significant effect ($P < 0.05$) (Appendix Table 3).

The maximum plant height (121.5 cm) was attained with the combined application of 69 kg P ha⁻¹ and 3.75 t VC ha⁻¹, whereas the minimum (95.8 cm) was recorded in the control (Table 7). These findings are consistent with those of Alemu *et al*.(2022), who reported that an increase in plant height of soybean using vermicompost and phosphorus fertilizer together greatly boosted the height of soybean plants from 94.3 cm (control) to 120.7 cm of treated soil. The increase in plant height is likely due to the combined effect of the fertilizers, which is important for root development and cell division at the meristematic tissues. Increased plant height under combined nutrient management shows improved nutrient availability and vegetative growth. However, taller plants do not necessarily

result in high grain yield; rather,plant height is an indicator of overall growth performance under favorable nutrient conditions.

Moreover, Vermicompost not only provides essential macro-and micronutrients but also contains plant growth-promoting substances such as auxins and cytokinins and significantly enhances soil aeration, porosity, and biological activity, thereby improving crop growth and soil fertility (Mulatu and Bayata, 2024; Desta *et al*., 2025). This result corresponds with Gedamu *et al*. (2021) and Chaudhary *et al*.(2022), who indicated that combined nutrient management significantly improved the height of leguminous crops.

Table 7. Main effects of Phosphorus fertilizer and vermicompost rates on plant height per plant in Bako district during the 2025 cropping season.

Treatments	Rates of Phosphorus Fertilizer (kg ha^{-1})				Mean
Rates of VC (t ha^{-1})	0	23	46	69	
0	95.8 ^{g}	100.2 ^{g}	105.1 ^{e}	108.4 ^{d}	102.4
1.25	97.6 ^{g}	104.3 ^{e}	108.1 ^{d}	108.5 ^{d}	104.6
2.5	99.7 ^{f}	103.8 ^{f}	109.4 ^{c}	113.0 ^{b}	106.5
3.75	101.5 ^{f}	105.9 ^{e}	112.0 ^{b}	121.5 ^{a}	110.2
Mean	98.6	103.6	108.7	112.9	
LSD ($p \leq 0.05$)	1.85				
CV (%)	1.5				

LSD = Least significant difference, CV = Coefficient of variation, Mean values followed by the same letter(s) within the column are not significantly different at a 0.05 probability level.

4.6.2 Number of Branches Per Plant

The main factors of phosphorus and vermicompost fertilizer rates had a highly significant ($P \leq 0.001$) effect on the number of branches per plant, but their interaction had no significant ($P \geq 0.05$) effect on this parameter (Appendix Table 3).

The application of the highest vermicompost fertilizer rates (3.75 t ha^{-1}) produced the highest number of branches (10.9), while the least number of branches (8.4) was obtained from soybean plants sown without vermicompost (control treatment) (Table 8). This might be due to vermicompost activating plant hormones that are responsible for promoting the number of branches. The current study is in line with the study result of

Arora *et al.* (2018), who declared that the increased amount of humus in soil through the application of vermicompost and the decomposition of organic mulches by earthworms would certainly help a favorable change in the physical, chemical, and biological properties of soil, and enhancing the water-holding capacity would increase plant growth.

Regarding phosphorus application, the greatest number of branches per plant (11.5) was recorded at 69 kg P ha^{-1} of fertilizer. Conversely, the lowest number of branches per plant (8.30) was observed in the absence of P fertilizer rates (Table 8).These findings are corroborated with those of Dabasa and Tana (2021), who recorded the greatest number of branches per plant(10.6) at the rate of 69 kg P ha^{-1} of fertilizer. while the lowest number of branches per plant (6.8) was recorded at 0 kg P ha^{-1} of fertilizer. This suggests that adequate growth resources, such as nutrients leading to increased cell division, meristematic activity, and improved root growth and plant height. Additionally, phosphorus fertilizer contributes to lateral branch formation. The current study is in line with Kaysha *et al*. (2020), who further demonstrated that elevated P rates led to an increase in branch proliferation, facilitated by the sufficient availability of nitrogen, phosphorus, and sulfur nutrients, thus fostering greater canopy development.

4.6.3 Number of Leaves Per Plant

The analysis of variances showed that the main factor of Phosphorus and vermicompost fertilizer rates had a highly significant ($P \leq 0.001$) effect on the number of leaves per plant, but the interaction of the two factors were non-significant effect ($P > 0.05$) (Appendix Table 3).

The Application of the highest vermicompost fertilizer rates (3.75 t ha^{-1}) produced the highest number of leaves per plant (38.50), while the lowest number of leaves per plant (29.50) was obtained from soybean plants sown without vermicompost (Table 8). The highest values of leaves obtained at the highest rate of vermicompost might be attributed to nitrogen mineralized from vermicompost, which promotes vegetative growth and leaf production. Worku and Astatkie (2019) stated that organic amendments significantly increased Number of leaf and leaf area in pulses. Similar findings were reported by Kumar *et al*. (2021) and Tegbaru *et al*.(2020) in their respective studies on soybean nutrition.

The maximum number of leaves per plant (40.20) was recorded under application of 69 kg P ha^{-1}, while the minimum number of leaves per plant (29.05) was recorded under control treatment (Table 8). This might be due to the fact that phosphorus contributes to photosynthesis and assimilate partitioning; P supply ensures vigorous growth and retention of leaves. This result is consistent with Amare *et al.* (2023), who found that P levels positively influenced the leaf number of soybean.

Table 8.Main effects of vermicompost and phosphorus fertilizer rates on growth parameters of soybean in Bako district during the 2025 cropping season.

Treatments	Number of Branches	Number of Leaves
Rates of VC (t ha^{-1})		
0	8.40[d]	29.50[d]
1.25	8.90[c]	31.20[c]
2.5	9.80[b]	33.40[b]
3.75	10.90[a]	38.50[a]
Rates of Phosphorus Fertilizer (kg ha^{-1})		
0	8.30[d]	29.05[d]
23	9.10[c]	31.85[c]
46	10.20[b]	36.05[b]
69	11.50[a]	40.20[a]
LSD($p \leq 0.05$)	0.65	2.8
CV (%)	9.4	7.1

LSD = Least significant difference; CV = Coefficient of variation; Mean Values followed by the same letter(s) within the column are not significantly different at a 0.05 probability level.

4.7. Yield Components and Yield of Soybean

4.7. 1 Number of pod per plant

The analysis of variance showed that the main effect of phosphorus fertilizer rates and vermicompost, as well as their interaction, had a highly significant ($P \leq 0.001$) effect on the number of pods per plant (Appendix Table 4).

The highest number of pods per plant (75.27) was recorded at the rate of 69 kg P ha^{-1} combined with 3.75 t VC ha^{-1}, and the lowest number of pods per plant (65.27) was obtained from the control treatment (Table 9).These findings are corroborates with

Amanula and Yasir (2025), who found that vermicompost and high phosphorus rates produced 68.3 number of pods of plant^{-1}, demonstrating the strong synergistic effect of both organic and mineral nutrition sources. The lowest pod numbers obtained at the control treatment might be due to phosphorus deficiency, which often leads to flower abortion; therefore, adequate phosphorus supply improves pod retention. Additionally, vermicompost supplies micronutrients like boron and zinc, which are essential for pollen tube germination and successful fertilization. The combination ensures that the flowers produced are retained as pods. These results are consistent with the recent findings of Adugna (2021) and Ebisa *et al.* (2021). Dereje *et al*. (2020) highlighted that available P is the main driver for pod setting and retention in legumes.

4.7.2 Number of Seeds Per Plant

The analysis of variance demonstrated that the main effect of phosphorus fertilizer rates and vermicompost had a highly significant effect ($P<0.001$) on the number of seeds per plant. Moreover, their interaction had a significant ($P\leq0.05$) effect on this variable (Appendix Table 4).

The number of seeds per plant responded strongly to the integrated application of vermicompost and phosphorus fertilizer, with the highest value (173.37) recorded under the combined treatment of 3.75 t VC ha^{-1} and 69 kg P ha^{-1}, while the lowest number (52.20) occurred in the unfertilized plot (Table 9). This significant rise reflects the combined effects of organic and inorganic nutrient inputs on crop reproductive performance.Vermicompost promotes soil physical structure, moisture retention, and microbial activity, resulting in a more favorable rhizosphere environment for nutrient uptake and use, whereas mineral phosphorus directly boosts energy metabolism and reproductive growth. Together, these benefits improve nutrient use, encourage better pod development, and result in a greater number of seeds produced per plant. The current findings are consistent with those of Belay *et al.*(2022), who reported significant improvements in pods per plant and seeds per pod with combined vermicompost and inorganic fertilizer application, as well as Bekele *et al.* (2022), who demonstrated that integrating vermicompost with phosphorus fertilization significantly increases seed number per plant in soybean.

4.7.3 Above-Ground Dry Biomass Yield (kg ha^{-1})

The main effect of vermicompost, phosphorus fertilizer rates, and their interactions was highly significant ($P<0.001$ and $P<0.01$) on above ground biomass yield, respectively (Appendix Table 5).

The highest biomass yield (8146.43 kg ha^{-1}) was obtained from the combined application of 69 kg P ha^{-1} and 3.75 t VC ha^{-1}, whereas the lowest yield (6780.93 kg ha^{-1}) was recorded in the unfertilized treatment (Table 9). The current findings are consistent with Dugassa and Worku (2025), who recorded the highest biomass was obtained from the combined use of 10 kg ha^{-1} of phosphorus with 7.5 t ha^{-1}vermicompost, resulting in 10300 kg ha^{-1} of biomass yields. The superior biomass accumulation under integrated nutrient management can be attributed to synergistic effects on plant growth and yield components, including enhanced plant height, seed yield, and number of seeds per pod.

Phosphorus is important for energy transfer, root growth, and shoot development, all of which support rapid plant growth. Vermicompost simultaneously improves the physical structure of the soil, increases microbial activity, and makes nutrients more accessible, all of which contribute to effective nutrient uptake. Increased assimilate production and biomass accumulation were probably the outcomes of the combined application's optimization of soil-plant interactions. These results support earlier research by Ebbisa *et al.*(2021), who found that applying organic amendments and mineral phosphorus together greatly enhanced the yield of soybean biomass. In the same way, Gure (2023) found increased biomass production when phosphorus fertilizer and vermicompost were applied together, highlighting the complementary role of organic and inorganic nutrient sources in increasing crop productivity.

Table 9. Soybean yield components and grain yield as affected by the interaction effects of rates of vermicompost and phosphorus fertilizer at Bako District during the 2025 cropping season.

Rates of VC (t ha^{-1})	P fertilizer rates (kg ha^{-1})	NPPP	NSPP	DBMY (kg ha^{-1})	GY (kg ha^{-1})	HI (%)	HSW (g)
0.0	0.0	65.27 ^{h}	52.20 ^{j}	6780.93 ^{k}	1901.00 ^{l}	28.03 ^{h}	18.13 ^{h}
	23	67.63 ^{f}	71.63 ^{h}	6726.5 ^{k}	2072.00 ^{i}	30.80 ^{e}	18.14 ^{h}
	46	68.10 ^{ef}	87.83 ^{f}	7661.5 ^{f}	2168.2 ^{i}	28.2 ^{g}	18.40 ^{g}
	69	69.87 ^{d}	96.83 ^{e}	7457.4 ^{h}	2204.7 ^{i}	29.5 ^{e}	18.50 ^{fg}
1.25	0.0	66.00 ^{h}	72.37 ^{h}	6882.3 ^{j}	1943.6 ^{k}	28.24 ^{gh}	18.17 ^{h}
	23	67.83 ^{f}	77.00 ^{g}	7563.4 ^{g}	2172.2 ^{g}	28.7 ^{g}	18.70 ^{f}
	46	69.50 ^{d}	102.77 ^{e}	7728.3 ^{e}	2326.8 ^{e}	30.12 ^{e}	19.20 ^{d}
	69	68.37 ^{e}	89.60 ^{f}	7533.3 ^{g}	2379.2 ^{d}	31.58 ^{b}	19.00 ^{e}
2.5	0.0	67.80 ^{f}	68.20 ^{i}	7017.8 ^{i}	2059.3 ^{j}	29.34 ^{e}	18.27 ^{gh}
	23	68.33 ^{e}	80.47 ^{g}	7542.4 ^{g}	2167.3 ^{g}	29.59 ^{f}	18.80 ^{f}
	46	71.20 ^{c}	114.37 ^{d}	7809.8 ^{d}	2450.2 ^{c}	31.38^{b}	19.60 ^{c}
	69	72.40 ^{b}	146.47 ^{b}	7815.6 ^{d}	2649.0 ^{b}	33.89 ^{a}	19.60 ^{c}
3.75	0.0	66.43^{g}	69.30 ^{i}	7079.1 ^{i}	2137.3 ^{h}	30.19 ^{e}	18.57 ^{fg}
	23	68.13 ^{ef}	90.27 ^{f}	7527.8 ^{h}	2234.6 ^{f}	29.68 ^{g}	19.40 ^{cd}
	46	70.83 ^{c}	130.63 ^{c}	7849.81 ^{c}	2526.5 ^{b}	32.18 ^{b}	20.00 ^{a}
	69	75.27 ^{a}	173.37 ^{a}	8146.43 ^{a}	2713.53 ^{a}	33.31 ^{a}	20.300 ^{a}
LSD ($p \leq 0.05$)		0.95	8.42	62.4	45.6	1.02	0.85
CV (%)		1.2	5.8	2.9	3.2	3.4	2.4

VC = vermicompost; CV = Coefficient of variation; LSD = Least significant difference; NPPP = number of pods per plant; NSPP = number of seeds per plant; HSW = hundred seed weight; HI = harvest index; DBMY=dry biomass yield; GY = grain yield. Means followed by the same letters within each column are not significantly different at $p \leq 0.05$.

4.7.4. Grain Yield

The analysis of variance (ANOVA) revealed that Grain yield was highly significantly influenced ($p \leq 0.001$) by the main effects of vermicompost rates and phosphorus fertilizer rates. In addition, the interaction between vermicompost and phosphorus fertilizer also had a highly significant ($p \leq 0.001$) effect on grain yield (Appendix Table 5).

The highest Grain yield (2713.53 kg ha⁻¹) was achieved with the combined application of 69 kg P ha⁻¹ and 3.75 t VC ha⁻¹, whereas the lowest yield (1901.00 kg ha⁻¹) was recorded in the unfertilized control (Table 9). This result is in line with the findings of Abeje *et al.*(2020), who reported that the maximum grain yield (2621.67 kg ha^{-1}) was obtained from the interaction of both organic and NPSB, whereas the lowest grain yield (1527 kg ha^{-1}) was recorded in the unfertilized treatment(control).

The marked yield improvement under integrated nutrient application can be attributed to enhanced nutrient availability and improved soil biological activity.Vermicompost contains organic matter that improves soil structure, microbial growth, and nutrient retention, whereas mineral phosphorus directly supports critical physiological processes such as energy transmission, flowering, and seed production. Vermicompost, a slow-release fertilizer, most likely matched crop demand with nutrient supply, increasing phosphorus utilization efficiency and encouraging greater root growth and nodulation. These combined activities raised grain yield by improving assimilate production and partitioning toward reproductive structures. The current findings correspond with those of Belay *et al*. (2022), who found that combining high rates of phosphorus fertilizer with vermicompost significantly improved soybean seed yield.Similarly, Fekadu *et al.*(2020) observed superior yield performance under integrated phosphorus and vermicompost treatments compared with sole applications. Comparable results were also documented by Sande *et al.*(2024), highlighting the agronomic advantage of integrated nutrient management.

4.7.5 Harvest Index (HI)

The main effect of phosphorus fertilizer rates and vermicompost, as well as their interaction, had a significant effect ($P \leq 0.05$) on the harvest index (Appendix Table 4).

The harvest index was significantly influenced by the integrated application of vermicompost and phosphorus fertilizer, with the highest value (33.31%) recorded under the combined treatment of 3.75 t VC ha⁻¹ and 69 kg P ha⁻¹. This result was statistically comparable to the treatment receiving 2.50 t VC ha⁻¹ combined with 69 kg P ha⁻¹, while the lowest harvest index (28.03%) was observed in the control treatment (Table 9). The current findings are consistent with Dabesa and Tana (2021), who recorded the highest

Harvest index (43%) at the rate of 69 kg P ha^{-1} with organic fertilizer ,whereas the lowest harvest index (29%) was recorded at the rate of 0 kg P ha^{-1} with no organic fertilizer.The enhanced harvest index under integrated nutrient management indicates improved assimilate partitioning efficiency toward grain production, driven by balanced nutrient availability and sustained nutrient release from vermicompost coupled with readily available phosphorus. This synergistic effect promotes efficient biomass conversion into economic yield rather than excessive vegetative growth. The present findings align with those of Zeleke *et al*. (2021), who reported increased harvest index with combined vermicompost and phosphorus application, and are further supported by Ebbisa *et al*. (2021), who similarly observed the highest harvest index under integrated organic and inorganic phosphorus fertilization and the lowest values in unfertilized control plots.

4.7.6 Hundred Seed Weight (g)

The main effect of vermicompost and phosphorus fertilizer rates, as well as their interaction had a highly significant ($p \leq 0.001$) effect on hundred seed weight(Appendix Table 4).

The 100-seed weight was significantly influenced by the integrated application of phosphorus fertilizer and vermicompost, with the highest value (20.30 g) recorded under the combined treatment of 69 kg P ha^{-1} and 3.75 t VC ha^{-1}, whereas the lowest 100-seed weight (18.13 g) occurred in the unfertilized treatment (Table 9). The improvement in seed weight under integrated nutrient management reflects enhanced photosynthetic efficiency and assimilate partitioning during the grain filling period, supported by adequate phosphorus supply and the sustained nutrient release from vermicompost. In addition, vermicompost improves soil moisture retention and buffering capacity, reducing moisture stress at critical reproductive stages and thereby favoring effective grain filling. These findings are consistent with Getachew *et al.*(2021), who reported increased 100-seed weight in soybean under combined vermicompost and phosphorus application, and are further supported by Mekonen *et al.*(2023), who demonstrated that improvements in pod and seed formation under integrated nutrient management indirectly contribute to increased seed weight.

4.8 Correlation Analysis

Correlation analysis showed that significant positive connections ($P \leq 0.05$ and $P < 0.01$) between phenological traits, growth parameters, yield components, and soybean yield (Table 10), demonstrated strong functional inter- relationships among variables.

Days to 50% flowering (r = 0.93**) and 90% physiological maturity (r = 0.88**) exhibited strong positive correlations with grain yield, suggesting that extended crop duration enhanced cumulative photosynthate production and effective assimilate translocation to developing seeds.This supports the concept that prolonged vegetative and reproductive phases improve biomass partitioning efficiency toward reproductive sinks, as similarly reported by Kumar *et al.*(2022) in pulse crops.

Dry biomass indicated the strongest positive association with grain yield (r = 0.95**), underscoring the fundamental source-sink relationship in yield formation. High biological yield provides the assimilatory foundation necessary for maximizing economic yield, consistent with the framework described by Zhang *et al*.(2022). Structural growth attributes, including plant height (r = 0.87**) and number of branches (r = 0.82**), were strongly correlated with grain yield and positively associated with number of pods per plant (r = 0.80**). These findings highlight the importance of canopy architecture in enhancing reproductive capacity, in agreement with Jaiswal *et al.* (2021).

Notably, root symbiotic efficiency emerged as a critical determinant of yield performance. The number of effective nodules revealed a strong positive correlation with grain yield (r = 0.93**), reinforcing evidence that phosphorus availability increased nodulation efficiency and nitrogenase activity (Li *et al.*, 023). In contrast, ineffective nodules showed a significant negative correlation with grain yield (r = −0.89**), indicating that non-functional nodulation may impose a metabolic cost on the plant. Ferguson *et al.* (2019) noticed that under adequate nutrient supply, legumes regulate symbiotic investment to reduce energy expenditure on non-beneficial nodules, thereby allocating more assimilates toward grain filling.

Overall, the correlation matrix approves that soybean yield is a function of integrated phenological duration, structural development, biomass accumulation, and symbiotic efficiency, reflecting a tightly coordinated physiological system governing productivity.

Table 10. Correlation coefficient among parameters of Phenological, Growth, Yield, and Yield Components of soybean in Bako district during the 2025 cropping season.

Parameter	50% Flowering	90% Maturity	Height	Branch	Pods	NSPP	100 Seed Weight	Biomass yield	Yield	Eff. Nodule	Inef.Nodul
50% Flowering	1.00										
90% Maturity	0.95**	1.00									
Height	0.89**	0.84**	1.00								
Branch	0.81**	0.80**	0.76**	1.00							
Pods	0.75**	0.72**	0.79**	0.68**	1.00						
NSPP	0.85**	0.82**	0.82**	0.78**	0.79**	1.00					
100 Seed Weight	0.86**	0.84**	0.85**	0.76**	0.71**	0.86**	1.00				
Biomass	0.91**	0.90**	0.88**	0.81**	0.80**	0.89**	0.91**	1.00			
Yield	0.93	0.88	0.87	0.82	0.80	0.91	0.92	0.95	1.00		
Eff. Nodule	0.91**	0.88**	0.84**	0.78**	0.76**	0.88**	0.87**	0.91**	0.93	1.00	
Ineff. Nodule	-0.82**	-0.79**	-0.80**	-0.75**	-0.68**	-0.81**	-0.79**	-0.84**	-0.89**	-0.94	1.00

4.9 Economic Analysis

Among the evaluated treatments, the combined application of 46 kg P $ha^{-1}$and 3.75 t VC ha^{-1} resulted the highest net benefit (316,285.4 ETB ha^{-1}) with an acceptable marginal rate of return (MRR) of 1220% (Table 11). In contrast, the unfertilized control treatment recorded the lowest net benefit (239,526 ETB ha^{-1}). The high MRR showed that for every one Ethiopian Birr invested in the integrated nutrient treatment, producers could obtain an additional return of 12.20 ETB. These results indicated that soybean profitability is strongly influenced by the optimal combination of mineral phosphorus and vermicompost, balancing input costs with yield gains. The findings align with the principle that economically optimal fertilizer rates may differ from agronomic maxima, emphasizing the importance of integrated nutrient management strategies that maximize financial returns while sustaining soil fertility (Gigaw *et al*., 2014).

Table 11. Partial budget analysis of the effect of vermicompost and P fertilizer rates on soybean in Bako district during the 2025 cropping season.

Treatments		Vermicompost cost	Phosphorus fertilizer cost	fertilizer application cost	Grain yield	Adjusted Grain yield	Gross Return (Birr ha^{-1})	TVC (Birr $ha^{-1)}$	Net benefit (Birr $ha^{-1)}$	MRR (%)
P	VC									
0	0	0	0	0	1901	1710.9	239526	0	239526	
0	1.25	2500	0	500	1956.4	1760.76	246506.4	3000	243506.4	133
0	2.5	5000	0	1000	2037	1833.3	256662	6000	250662	239
0	3.75	7500	0	1500	2123.9	1911.51	267611.4	9000	258611.4	132
23	0	0	4255	46	2053	1847.7	258678	4301	254377	90
23	1.25	2500	4255	546	2143.4	1929.06	270068.4	7301	262767.4	280
23	2.5	5000	4255	1046	2230	2007	280980	10301	270679	264
23	3.75	7500	4255	1546	2220	1998	279720	13301	266419	D
46	0	0	8510	92	2243	2018.7	282618	8602	274016	D
46	1.25	2500	8510	592	2309	2078.1	290934	11602	279332	177
46	2.5	5000	8510	1092	2335.6	2102.04	294285.6	14602	279683.6	12
46	3.75	7500	8510	1592	2649.9	2384.91	333887.4	17602	316285.4	1220
69	0	0	12765	138	2254.2	2028.78	284029.2	12903	271126.2	961
69	1.25	2500	12765	638	2376.7	2139.03	299464.2	15903	283561.2	D
69	2.5	5000	12765	1138	2411	2169.9	303786	18903	284883	44
69	3.75	11250	12765	1776	2713	2441.7	341838	25791	316047	795

Where MRR (%): Marginal Rate of Return; P: phosphorus fertilizer, Fertilizer application cost =200 Birr/100kg ha^{-1}; vermicompost application cost =400 Birr ha^{-1}; phosphorus cost =185 Birr kg ha^{-1}; vermicompost cost =2000 Birr ton^{-1}, soybean grain local selling price = 140 Birr kg^{-1}; TVC: total variable cost; D: Dominated treatment.

5. CONCLUSIONS AND RECOMMENDATIONS

5.1. Conclusions

The highest agronomic performance, including the number of pods per plant (75.27), number of seeds per plant (173.37), 100-seed weight (20.30 g), harvest index (33.31%), above-ground biomass (8146.43 kg ha^{-1}), and Grain yield (2713.53 kg ha^{-1}), was observed under the combined application of 69 kg P ha^{-1} and 3.75 t VC ha^{-1}. However, economic analysis revealed that 46 kg P ha^{-1} with 3.75 t VC ha^{-1} provided the highest net benefit (316,285.4 ETB ha^{-1}) with an acceptable marginal rate of return (1220%), indicating the treatment's superior cost-effectiveness. Therefore, for sustainable soil fertility management, mitigation of nutrient depletion, and optimization of soybean productivity while minimizing the negative impacts of inorganic phosphorus fertilizer, the combined application of 46 kg P ha^{-1} and 3.75 t VC ha^{-1} is recommended for the study area and similar agro-ecologies.

5.2. Recommendation

To enhance soybean production and productivity in the study area, the integrated application of phosphorus and vermicompost fertilizers is recommended. Based on the current findings, the combined application of 46 kg P ha^{-1} with 3.75 t VC ha^{-1} produced 2649 kg ha^{-1} of seed yield, with a net benefit of 316,285.4 ETB ha^{-1} and the highest marginal rate of return of 1220%. Therefore, this nutrient management strategy can be recommended for soybean cultivation in Bako and similar agro-ecological zones. However, as the present study was conducted at a single location for one cropping season, further multi-location and multi-season research is necessary to validate these results and develop comprehensive recommendations for broader agro-ecological applicability.

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7. APPENDICES

Appendix 1 . Mean Squares of ANOVA for Phenological Parameters of soybean

Source of variation	Df	Mean squares		
		50% DE	50% DF	90 % DPM
Replication	2	0.316	7.15	8.77
Phosphorus	3	0.6833	38.30**	157.69**
Vermicompost	3	0.9111	21.63**	170.30**
Interaction(pxv)	9	0.05	1.632	2.15
Error	30	0.5272	0.94	6.53
CV(%)		9.5	5.6	4.1

Where, *, **, ***, : significant at 0.05,0.01, and 0.001, respectively, LSD - Least significant differences, CV: coefficient of variation, DE: days to % 50% emergence, DF: days to 50 % flowering, DPM: Days to 90% physiological maturity.

Appendix 2.Mean Square of ANOVA for the Nodule Parameters of soybean

Source of variation	Df	Mean squares				
		TNNPP	ENPP	IENPP	NFWPP	NDWPP
Replication	2	13.15	13.62	0.0153	0.0025	0.0008
Phosphorus	3	460.39***	455.08***	0.3139**	0.0134***	0.0039***
Vermicompost	3	258.07***	253.05***	0.1790**	0.0083***	0.0025***
Interaction(pxv)	9	2.68***	2.60***	0.0060**	0.748	0.0002
Error	30	1.16	1.22	0.0141	0.0007	0.0003
CV(%)		4.8	5.1	8.2	10.5	9.5

Where, *, **, ***,: significant at 0.05,0.01, and 0.001, respectively, LSD: Least significance differences, CV:coeffecient of variation, Df- Degree of freedom, TNNPP- Total number of nodule per plant(number), ENPP- effective nodule per plant(number), IENPP- Ineffective nodule per plant(number), NFWPP- Nodule fresh weight per plant(gm plant $^{-1}$), NDWPP- Nodule dry weight per plant (gm plant $^{-1}$).

Appendix 3.Mean Squares of ANOVA for Growth Parameters of soybean

		Mean squares		
Source of variation	Df	PH	NB	NLPP
Replication	2	2.67	0.08	0.38
Phosphorus	3	380.42***	8.59***	105.44***
Vermicompost	3	274.39***	7.61***	96.25***
Interaction(pxv)	9	2.70**	0.1	1.941
Error	30	5.93	0.31	2.14
CV(%)		1.5	2.84	2.84

Where, *, **, ***, significant at 0.05,0.01, and 0.001, respectively, LSD: Least Significant Differences, CV: coefficient of variation, Df- Degree of freedom, PH: plant height, NB;- Number Of branch per plant, NLPP: Number of leaves per plant.

Appendix 4.Mean Squares of ANOVA for the Yield Component parameters of soybean

		Mean squares			
Source of variation	Df	NPOPP	NSPPL	HSW	HI (%)
Replication	2	3.86	742.71	0.17	2.43
Phosphorus	3	55.25***	8235.58***	3.34***	24.78**
Vermicompost	3	52.82***	4374.56***	2.28***	15.99**
Interaction (PXV)	9	0.94***	403.54**	0.08***	0.49**
Error	30	2.05	269.49	0.12	0.87
CV(%)		1.2	5.8	2.4	3.4

Where, *, **, ***,: significant at 0.05,0.01, and 0.001, respectively, LSD: Least significant differences, CV: coefficient of variation, Df- Degree of freedom, NPOPP: Number of Pod per plant(number), NSPPL: Number Of seed per plant(number),HSW- Hundred seed weight (gm), HI- harvest index(%).

Appendix 5.Mean Squares of ANOVA For above ground dry biomass and Grain yield of soybean

Source of variation	Df	Mean squares	
		AGBM(Kg ha^{-1})	Grain yield(kg ha^{-1})
Replication	2	158493	11962
Phosphorus	3	1374997.2***	473899***
Vermicompost	3	1129567.1***	399781***
Interaction(pxv)	9	14106.2***	2893***
Error	30	13036.8	2150
CV(%)		2.9	3.2

Where, *, **, ***,: significant at 0.05,0.01, and 0.001, respectively, CV:coefficient of variation, Df- Degree of freedom), AGBM-Above ground dry biomass(kg ha^{-1}), seed yield weight(kg ha^{-1}).

Appendix 6a.Mean Square of ANOVA for Soil Physical and Chemical Properties

Source of variation	Df	Sand (%)	Clay (%)	Silt (%)	pH (1:2.5)	Org. Carbon (%)
Replication	2	0.0452	0.0012	0.0155	0.00012	0.00001
Phosphorus (P)	3	11.2415	0.0482	8.2144	0.00845	0.000215*
Vermicompost (V)	3	0.8142	0.0215	0.4431	0.00268*	0.000251*
Interaction (P x V)	9	0.0854	0.0042	0.0612	0.00022*	0.000024*
Error	30	0.021	0.0009	0.012	0.00008	0.000007
CV(%)		0.32	0.45	0.42	0.25	1.21

Where, *, **, ***,: significant at 0.05,0.01, and 0.001, respectively, CV:coefficient of variation. Df- Degree of freedom.

Appendix 7. Mean Square of ANOVA for Soil Chemical Properties.

Source of variation	Df	Org. Matter (%)	Total N (%)	Avail. P (mg/kg)	CEC (cmol+/kg)	Ca (cmol+/kg)	Mg (cmol+/kg)
Replication	2	0.000017	0.000002	0.00021	0.0024	0.00014	0.00011
Phosphorus (P)	3	0.000370	0.000038	0.01632	0.6125*	0.01242*	0.02541*
Vermicompost (V)	3	0.000432*	0.000042*	0.02425*	0.4482*	0.00915*	0.01822*
Interaction (P x V)	9	0.0000413*	0.000004*	0.00184*	0.0122*	0.00045*	0.00034*
Error	30	0.00001206	0.000001	0.00015	0.0041	0.0001	0.00008
CV(%)		0.54	1.45	0.38	0.56	0.31	0.4

Where, *, **, ***,: significant at 0.05,0.01, and 0.001, respectively, CV:coefficient of variation, Df- Degree of freedom



Appendix Figure 1. Soybean field conditions during the land preparation stage



Appendix Figure . Soybean crop during field observation and management practices



Appendix Figure 3. Photograph taken during agronomic data collection



Appendix Figure 5. Photograph of soybean roots during nodulation counting



Appendix Figure 5. Soybean at harvest: photograph showing threshing and grain yield recording for each plot.