JIMMA UNIVERSITY COLLEGE OF AGRICULTURE AND VETERINARY MEDICINE

DEPARTMENT OF HORTICULTURE AND PLANT SCIENCES

EFFECTS OF PHOSPHORUS FERTILIZER RATE AND RHIZOBIA INOCULATION ON GROWTH, NODULATION AND YIELD OF SOYBEAN [*Glycine max* (L.) Merrill] VARIETIES UNDER NITISOLS OF SOUTHWESTERN ETHIOPIA

MSc. THESIS

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Effects of Phosphorus Fertilizer Rate and Rhizobia Inoculation on Growth, Nodulation and Yield of Soybean [*Glycine max* (L.) Merrill] Varieties under Nitisols of Southwestern Ethiopia

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Submitted To Jimma University College of Agriculture and Veterinary Medicine Department of Horticulture and Plant Sciences, In Partial Fulfillment of the Requirements for the Degree of Master of Science In Agronomy

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DEDICATION

This paper is dedicated to God Almighty, my wife, Zinash Wedajo, who has given me all strength and fortitude. She instilled in me her interest in my graduate studies and wished me a great lifelong career.

STATEMENT OF THE AUTHOR

First, I declare that this work is my work and that all sources and materials used in this work are duly acknowledged. This work was carried out to realize part of the facilities of the master's program. Submitted degree from the Faculty of Agriculture and Veterinary Medicine, Jimma University, and will be deposited in the university library and provided to borrowers as part of the library sale. I solemnly declare that my thesis will not be submitted to any institution for the award of degrees, diplomas, or certificates. Short quotations from this work are permitted without specific permission, provided the source is accurately cited. If this manuscript is to be reproduced in whole or in part, permission for extended citation may be requested from the Dean or Graduate Studies Coordinator of the Department where the material is intended to be used or the Head of the Department of Horticulture and Plant Sciences. There is for academic purposes. However, in other cases, the author's consent must be obtained.

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BIOGRAPHICAL SKETECH

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ABBREVATIONS AND ACRONMYS

ANOVA	Analysis of Variance
BARC	Bako Agricultural Research Center
BeARC	Bedele Agricultural Research Center
BFN	Biological nitrogen fixation
BNMA	Bedele National Metrology Station
CIMMYT	Centro International de Mejoramiento de maizy Trigo
CSA	Central Statistical Agency
DAP	Diammonium Phosphate
FAO	Food and Agricultural Organization of the United Nations
LSD	Least Significant Difference
MAP	Mono ammonium phosphate
m.a.s.l	Meter above sea level
OARI	Oromia Agricultural Research Institute
TVC	Total Variable Cost
TSP	Triple Super Phosphate
USDA	United State Development Agriculture

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EFFECTS OF PHOSPHORUS FERTILIZER RATE AND RHIZOBIA INOCULATION ON GROWTH, NODULATION AND YIELD OF SOYBEAN [*Glycine max* (L.) Merrill] VARIETIES UNDER NITISOL OF SOUTHWESTERN ETHIOPIA

ABSTRACT

Soybean is high quality protein source for resource poor families and oil crop in Ethiopia, but low phosphorus levels and soil acidity limit yields in the Buno Bedele area. Therefore, the aim of this study is to investigate the effect of phosphorus fertilizer and different rhizobia strains on soybean performance in terms of growth, nodulation, and yield in Nitisol of southwestern Ethiopia. The experiment was conducted at Buno Bedele, Ilke kerero sub site of Bedele Agricultural Research Center in 2023 main cropping season. The experiment included 16 treatment combinations four phosphorus levels (0, 10, 20 and 30 kg P ha^{-1}), with and without inoculation MAR-1495 rhizobia, and two soybean varieties (Ketta and Cheri). The experimental design was Randomized Complete Block Design RCBD) in factorial arrangement with three replications. The Analysis of variance showed Very high significant (P<0.0001) interactions between rhizobia inoculation and phosphor us levels, as well as variety (P<0.0001) effects on growth, nodulation, and yield. The highest yields were achieved (3.45 ton ha^{-1}) with 30 kg P ha^{-1} and Rhizobium inoculation, particularly with the Ketta variety, while the lowest grain yield was observed 0.33 ton ha^{-1} under un-inoculated rhizobia and control plot of P application. The combined application of MAR-1495 rhizobia and 30 kg P ha^{-1} significantly improved nodulation and yield. This approach also resulted in the highest net benefits (113231.2ETB) and marginal rate of return (541.6%), making it a profitable strategy for enhancing soybean production and farmer income in the region. The findings from this research provide several practical recommendations for optimizing soybean cultivation in environments similar to the one studied: Cultivar Selection and Fertilizer Management. By implementing these practical recommendations, farmers in similar environments can optimize their soybean cultivation practices and improve the productivity and profitability of their operations.

Keywords: Glycine max, Inoculation, MAR-1495 strain, phosphorus, symbiotic nitrogen fixation.

1. INTRODUCTION

Soybean (*Glycine max* (L.) Merrill) is one of the most important pulse crops and it belongs to the family (Leguminosae). Soybean is cultivated all over the world, as a major source of oil (20%) and protein (40%). Soybean is one of the most valuable crops in the world, due to its multiple uses as a source of livestock and aquaculture feed, protein and oil for the human diet (Ali *et al.*, 2020). Beside, producing valuable grain, soybean fixes between 50-300 kg N ha^{-1} (Anchal Dass *et al.*, 2015) , which makes a significant N contribution to inter-cropped and rotated cereal crops (Craswell and Vlek, 2013), estimated the improvement of maize crop following soybean crop at between 0.5 and 3.5 tons ha^{-1} or 30-350% relative to maize-maize sequences. The country's current foremost soybean-growing regions are located in the West and Southwest of the country. More than 44% of the country's soybean production is produced in the Oromia region, especially in the western and eastern areas of Wollega and Illu-ababor (Debela Regasa and Wogi, 2020). These regions have vast fertile land and favorable agricultural climate suitable for growing soybeans. In Ethiopia, an area of 75,938.88 hectares of land is planted with soybeans, producing 185,522.23 tons with a yield of 2.44 ton ha^{-1} (CSA, 2021/22), low compared to the world average of 2.74 ton ha^{-1} (USDA, 2021/22). In the Ethiopian region, production and fluctuations in two consecutive years (2021 and 2022) show the area from 83,613.66 ha to 75,938.88 ha, a decrease of 9.18%. Production 208,497.43 tons to 185,522.23 tons, changes 11.02%, and productivity from 2.49 ton ha^{-1} to 2.44 tons ha^{-1}, down 2.04% compared to 2021 production area , output also decreased by 11.02% (CSA, 2021/22).

In Oromia Region an area of 4946.85 hectares of land is planted with soybeans, producing 10941.7 tons with a yield of 2.2 tons ha^{-1} (CSA, 2021/22), low compared to the worldwide and National average of 2.74 and 2.43 ton ha^{-1}. In Buno Bedele an area of 1,663 hectares of land is planted with soybeans, producing 3,448.5 tons with a yield of 2.07 tons ha^{-1} (Zone of Buno Bedele Agricultural office, 2021/22), still low compared to the worldwide, national and regional average of 2.74, 2.44 and 2.2 ton ha^{-1}.

In spite of the great potentials of the crop, soybean production is still inadequate owing to low yields, resulting in a wide gap between what is currently produced and what is needed. As a way of improving production level, one of the major areas to consider is the development of high yielding and improved varieties and development of improved cultural management practices. Soybean yield reduction resulting from soil acidity and other constraints is a significant issue in various regions, particularly in areas with high rainfall and acidic soils (Dabesa and Tana, 2021b). Here are some key points regarding the impact of soil acidity and other constraints on soybean yields: Soil acidity with associated low nutrient availability is a major constraint to soybean production in many regions, including southwestern Ethiopia. Soil pH levels below 5.0 can lead to high Al content, P fixation, and deficiencies in essential nutrients like Mg2+, Ca2+, and K+, which can significantly reduce soybean yields. Lime application can help alleviate these issues by increasing root and shoot yields, but high rates of lime application may not be economically feasible for resource-poor farmers. Other Constraints: Drought and water stress can also significantly impact soybean yields, particularly in areas with limited rainfall. Pests and diseases can further reduce yields if not managed effectively. Limited access to quality inputs, such as improved seeds and fertilizers, can also hinder optimal soybean production. Inadequate post-harvest handling, storage, and marketing infrastructure can lead to losses and reduce farmer income. Many of factors, such as Drought, soil acidity, soil fertility reduction, poor nutrient use, poor agronomic practices, poor accessibility to quality seed, Pests, diseases and climate change affected soybean production (Koskey *et al.*, 2017).

Soil acidity is a prevalent problem in the Ethiopian highlands, affecting soil productivity and crop yields. Acidic soils cover a substantial portion of arable land in Ethiopia, with the western part of the country being particularly affected (Gurmessa, 2021a). Factors contributing to soil acidity in Ethiopia include heavy rainfall, high temperatures, erosion of topsoil, and improper agricultural practices that lead to the degradation of organic matter and leaching of essential nutrients from the soil (Beyene *et al.*, 2023). Acidic soils in Ethiopia are inherently infertile and often exhibit aluminum or manganese toxicity, which hinders plant growth and reduces crop productivity. The low pH of acidic soils affects nutrient availability, especially phosphorus and other macronutrients, essential for plant growth. About 43% of the Ethiopian arable land has affected by soil acidity, of these about 28.1% of soils were dominated by strongly acidic soils (pH 4.1-5.5) (Bekana *et al.*, 2022). Correcting soil acidity through liming can improve soybean yields, but high rates of lime application may not be economically feasible for resource-poor farmers. Selecting soybean varieties tolerant to soil acidity and phosphorus deficiency can help mitigate these constraints. Integrated soil management options, such as micro-dosing lime application, can improve soil physical and chemical properties and enhance crop production. Proper agronomic practices, including row planting and timely fertilizer application, can also enhance soybean yields

The establishment of an effective and efficient BNF depends on optimizing all of the components (i.e. legume rhizobium, management and environment) together (Soumare *et al.*, 2020). An understanding of the effects of these management factors on the symbiosis may assist in the selection of P-efficient soybean genotypes that will enhance symbiotic nitrogen fixation and soybean yield. Phosphorus is an essential ingredient for Rhizobia bacteria to carry out BNF processes. Inadequate P restricts root growth, the process of photosynthesis, translocation of sugars and other such functions, which directly influence N fixation by legume plants. The phosphorus serves as an energy source during the physiological processes taking place in the plant (Karthika *et al.*, 2018). Therefore, this study was aims to investigate the effect of phosphorus fertilizer and rhizobia strains on soybean performance in terms of growth, nodulation, and yield in Nitisols of southwestern Ethiopia. The findings of this research was contribute to the development of sustainable agricultural practices, including optimized phosphorus management and the identification of suitable rhizobia strains, to enhance soybean production in Nitisols of southwestern Ethiopia.

Objective

General objective

- ❖ To assess the combined effect of P fertilizer and rhizobium on the performance of soybean varieties on nitisols

Specific objectives

- ✓ To determine the effect of P fertilizer rates on growth, nodulation and yield of soybean varieties
- ✓ To determine the appropriate of P fertilizer rates, inoculation and soybean varieties for economical yield production of soybeans in the study area

2. LITERATURE REVIEW

2.1. Agro-Ecology and Growth Habit of Soybean

Soybeans (*Glycine max* L.) can be grown in a wide range of agro-ecological zones and soil types, but perform best in warm, moist environments with well-drained soils (Tarar *et al.*, 2022). The crop is adapted to a wide range of soil pH levels between 4.5 and 8.5, but avoids waterlogged or very sandy, gravelly soils (Bania *et al.*, 2023). Soybean varieties differ in their growth habits and maturity periods (Kong *et al.*, 2018). Determinate varieties have a terminal flower and stop growing in height after flowering, while indeterminate varieties continue growing in height after flowering (Wijewardana *et al.*, 2018). Early maturing varieties are suitable for drier environments or late planting, while late maturing varieties produce higher yields but are less suitable for drier areas (Staniak *et al.*, 2023). Soybean growth and yield is influenced by agro-ecological factors like precipitation, temperature, and solar radiation (Guo *et al.*, 2023). Higher soybean seed yields were obtained in the derived savanna agro-ecology compared to the rainforest agro-ecology, likely due to differences in climatic conditions (Jandong *et al.*, 2019). Soybean varieties also respond differently to intercropping with maize and cassava in different agro-ecologies (Le *et al.*, 2018)

2.2. Soybean Production and Productivity in Ethiopia

Soybeans are one of the most important legumes and oilseeds grown around the world and are believed to have been first domesticated in China, between 2500 and 2300 BC. The crop spread to South and Southeast Asia following the migration of local people in that region until the late 18th century, when it was introduced to Europe and grown as an ornamental plant in England and France (Shennan, 2018). Soybeans quickly gained importance in the early 19th century, when they were grown as animal feed in Yugoslavia. From Europe, culture spread to other parts of the world, primarily through British and French imperialism, missionary work, and trade (Nayar, 2015). Soybeans were first grown experimentally in Ethiopia in the 1950s and the experiment was stopped due to very low yields. A trial then continued into the late 1960s and with the introduction of new high-yielding cultivars in the 1970s, renewed interest was generated (Langthaler, 2020).

During the 1970s, Ethiopia produced 6,000 tons of soybeans per year, becoming one of four major soybean producers in Africa. Current national soybean production in the country is estimated at 75938.88 hectares (CSA, 2021/2022). Soybean production and production area are expected to increase due to growing demand from domestic processing and animal feed (cattle, poultry) industries. Ethiopia has suitable agro ecological conditions and large land suitable for investing in soybean cultivation or production. There are many favorable locations, especially in the western, southwestern, and eastern regions of the country, including Jimma, Bedele, Chawaka, Assossa, Pawe, Harar, Shashemene, and Arsi (Desissa, 2019), while the actual harvest yield is 2.49 ton ha^{-1} (CSA, 2021/2022). However, a potential yield of 3,500 kg ha^{-1} can be achieved (Teixeira *et al.*, 2019). Soybeans are important in rotational production, especially with cereals such as corn and sorghum, and counteract the depletion of plant nutrients in the soil caused by continuous grain monocultures (Selim, 2019).

Among the food legumes grown in Ethiopia, soybeans have recently gained importance following extensive efforts to incorporate soybeans as a legume into people's diets, directly in the form of seeds or processed into value-added foods (e.g. soybeans, soymilk, and soybean powder) or added as a mixture in traditional foods, although it was introduced to the country in the 1950s. The recent trend of increasing soybean area is mainly driven by increasing demand from domestic processing industries (Voora *et al.*, 2020). Therefore, large-scale production of this crop can improve the income of small farmers. The country can also earn a significant amount of foreign exchange through soybean exports thanks to its strategic location to global consumers. In Ethiopia, soybean yields are far below the global average, lower than 2.49 ton ha^{-1} (CSA, 2021/2022), mainly due to a lack of appropriate production programs and promotional activities for different cropping systems and agro ecosystems (Khojely *et al.*, 2018).

2.3. Importance of Soybean

Soybeans are the largest oil crop in the world and are known as golden beans or miracle beans due to their diverse nutritional qualities containing 20% oil and 40% protein, with biological value in the form of meat protein (Modgil *et al.*, 2021). Fish and rich in amino acids like lysine, and tryptophan (Kasozi *et al.*, 2019). The edible legumes, which are excellent sources of protein and edible oils, can play an important role in meeting dietary needs during food shortages and widespread malnutrition wide today (Ikhajiagbe *et al.*, 2022). Thus, soybean has been variously described as a "miracle bean" or "golden bean" because it is a relatively cheap grain and has high protein content (Lin *et al.*, 2019). It contains 40% high-quality protein, 20% vegetable oil, and a good balance of amino acids

(Miransari, 2016). There is enormous potential to improve the nutritional status and well-being of the resource. Many legumes provide some protein, but soybeans are the only crop that provides an inexpensive, high-quality protein source comparable to meat, poultry, and eggs. Soy protein has great potential as a major dietary protein source. Oil produced from soybeans is easily digestible and contains no cholesterol. Soybean meal, a byproduct of oil production, is used as a high-protein animal feed in many countries (Guzeler and Yildirim (2016).

Soybeans are important raw materials for the food processing and oil; in crop rotation, as their nitrogen-fixing ability is important for improving soil fertility and the health benefits of its consumption (Bitew and Abera, 2019). It is also considered a strategic crop in the fight against food shortages and malnutrition worldwide due to its high nutritional value (Mathonsi, 2021).

2.4. Soybean Production Constraints in Ethiopia

Soybeans were introduced to Ethiopia in the 1950s (Tesfaye *et al.*, 2018). Even so, several decades after its introduction, wider distribution and production of soybeans was not easy; especially in small farmers. The main limitations are: - local farmers lack knowledge on how to use the crop, lack an attractive market for the products, and lack a systematic approach to popularize the crop through training female farmers on how to prepare meals different from soybeans. As a result, the country's percentage of land planted with soybeans has remained low for several years.

Despite the importance of the crop and efforts to improve production, soybean yields in farmers' fields remain very low, at 920 to 1,410 kg ha^{-1} compared to potential yields of 2,000 to 3,500 kg ha^{-1} (Abebe, 2012). Low productivity is attributed to a number of constraints including:- lack of use of the correct type and quantity of fertilizer, poor soil fertility management, poor crop management practices and lack of suitable rhizobia for planting.

Poor soil fertility management practices, i.e. lack of use of commercial fertilizers and lack of use of improved varieties with high yields and efficient nutrient use are some of the major factors leading to poor productivity. Soybean yield is low, especially on soils with low fertility (Mongare, 2020). Furthermore, most farmers devote fertile land to cereal production, especially corn, while legumes, especially soybeans, are grown on poor soils, often in rotation. This is because the nitrogen fixation ability of legumes improves soil fertility for high yields. Furthermore; Farmers sometimes apply sub-optimal fertilizer levels but generally do not apply commercial fertilizer to legumes in general and soybeans in particular. The main reasons why subsistence farmers rarely use commercial fertilizers are poor financial capacity and fertilizer infrastructure (Abebe, 2012), high commercial fertilizer prices, and poor fertilizer delivery systems. Rural communication and distribution networks are underdeveloped, especially during the rainy season. As a result, subsistence farmers grow most crops, including soybeans, with very low soil nutrients.

In low pH soils, which contain large amounts of Al and Fe oxides, P is deficient in the soil solution because it is precipitated or adsorbed on the surface along with Al and Fe as insoluble compounds (Mwangi, 2021). Several other essential plant nutrients are present in the soil solution in the form of deficient cations. In acidic soils, soybean yields are affected directly or indirectly, which can include plant root damage, reduced water and nutrient uptake, reduced availability of essential plant nutrients, and aluminum and manganese toxicity, (Mn); and microbial survival in soil (Michael, 2021).

Ensuring good agricultural productivity on acidic soils may require the application of a number of amendments to correct nutrient deficiencies, including liming, adding organic matter, and fertilizing with mineral fertilizers (Gurmessa, 2021b). Liming reduces Al^{3+} and H^+ ions because it reacts with water, leading to the production of OH ions, which react with $Al3^+$ and H^+ in acidic soils to form Al $(OH)_3$ and H_2O. Precipitation of Al^{3+} and H^+ by lime increases pH, improving microbial activity and nutrient availability (Johan *et al.*, 2021). Soybeans, as a legume, rely on microbial nitrogen fixation as a nitrogen source. However, in acidic soils, rhizobium population’s decrease and, as a result, nodulation and nitrogen fixation are impaired. This negatively affects crop nutrition and productivity. Therefore, applying lime to acidic soil for soybean production will improve soil conditions for microbial growth. Mineral fertilizers increase the availability of nutrients in the soil solution, as they are readily available and the addition of organic matter will provide food for microorganisms, thereby increasing their population and thus reducing increased mineralization (Fageria, 2012).

The symbiotic relationship between the host plant and its nitrogen-fixing bacteria depends on many environmental factors and can strongly influence the management or agronomic practices of farmers (e Castro *et al.*, 2016). Certain adverse environmental factors, such as salinity, unfavorable soil pH, nutrient deficiency, mineral toxicity, extreme temperatures, low or extremely high soil moisture, insufficient photosynthesis, and diseases, can affect the growth and development of plants. In addition, native rhizobia populations influence root infection and nitrogen fixation by limiting the host plant's ability to function (Bhattacharya, 2022). Heavy rainfall has a profound effect on soybean plants by inhibiting plant growth, nodule formation, and yield (Palta *et al.*, 2010), causing waterlogging during nitrogen fixation (Kaur *et al.*, 2020). Oxygen-limited environments can reduce rhizobia activity. Bacteria are living organisms and require large amounts of oxygen to function. Biological nitrogen fixation in soybeans is very sensitive to soil water stress compared to other physiological processes, such as photosynthesis and transpiration. Water stress can impair nodule function. After exposure to water stress for 14 days, the cell walls of nodules begin to degrade, leading to bacterial senescence (Matamoros and Becana, 2021). Drought can also reduce nodule weight and nitrogenase enzyme activity. Accumulation of Na^+ can reduce plant growth, nodule formation, and symbiotic nitrogen fixation under saline conditions (Wang *et al.*, 2022). High salt concentrations can directly affect the early interaction between rhizobia during nodulation in legumes.

Higher soil moisture is considered one of the major growing problems of legumes due to its effect on nitrogen fixation in tropical and subtropical regions. The ability of rhizobia to live in soil for long periods of time is influenced by soil temperature (Thilakarathna and Raizada (2017). The potency and efficiency of different legumes in nitrogen fixation are different. For example, the critical temperature for nitrogen fixation is between 25 and 30°C for common beans; whereas cowpeas, soybeans, and peanuts are between 35 and 40°C (EL Sabagh *et al.*, 2020). Nodule formation and nitrogen fixation depend on the rhizobium strain and nodule of the legume, as well as the genotype of the plant. Survival of rhizobia in well-cohesive soils exposed to high temperatures was higher than in non-cohesive soils and was better under dry than wet conditions. For example, the sensitivity of R. leguminosarum by, the Trifoliithan bradyrhizobium species is very high to regulated soil temperature in sandy soils (Allito *et al.*, 2020). Bacterial activity and health can also deteriorate during storage. It is important that rhizobium inoculum is stored in a cool, dry place to avoid damage from heat or water.

Rhizobia colonization in a legume rhizosphare was reduced due to high soil pH. Nitrogen fixation results from low soil pH (Bakari *et al.*, 2020). The characteristics of high acidic soil (pH < 4) includes: low level of phosphorus, calcium, molybdenum, along with aluminum and manganese toxicity, which affects both the plant and rhizobia. As a result, under low soil pH conditions, nodulation and N fixation is more affected than plant growth. High alkaline (pH > 8) soils tends to be high in sodium, Chlorine, bicarbonate, Borate, which reduces N fixation.

In addition to environmental factors, agricultural management factors also influence the proportion of nitrogen originating from the atmosphere. Management factors include:- preparations, phosphate and nitrogen fertilization, variety selection, and tree density affect tree growth and development (Naji *et al.*, 2015). The symbiotic relationship between legumes and soil bacteria is established when nodules form, due to soil rhizobia bacteria infecting legume roots (Peix *et al.*, 2015). Potential soybean production areas in Africa with low nitrogen fixation activity may not produce optimal soybean yields unless inorganic fertilizers or rhizobium inoculants are used (Thuita *et al.*, 2018). Legume transplantation depends on the presence of compatible rhizobia in the soil and its effectiveness.

Phosphorus supply has a direct influence on processes such as specific nodule activity and nitrogen fixation (Martins *et al.*, 2017). Phosphorus (P) is an essential nutrient for plants that participates as a structural component of nucleic acids, phospholipids, and adenosine triphosphate (ATP), which is a key element of metabolic and biochemical processes , especially biological nitrogen fixation and photosynthesis (Mitran *et al.*, 2018). Plants absorb P in two soluble forms: monobasic (H_2PO_4) and dibasic (HPO_4^2). However, a large proportion of P is present in insoluble form and is therefore unavailable for plant nutrition. Low P levels reflect the reactivity of phosphate with other soluble constituents, such as aluminum in acidic soils (pH < 5) and calcium in alkaline soils (pH > 7) (Abawari *et al.*, 2020). Phosphorus can be added naturally to the soil, and released from clay minerals, which is important over time. However, for agricultural uses, P levels are often artificially mineralized through the use of fertilizers. Phosphate fertilizers come in many forms, such as livestock manure, diammonium phosphate (DAP), triple superphosphate (TSP), and mono-ammonium phosphate (MAP). Phosphorus is immobilized in the soil profile. Therefore, some growers incorporate P into the soil when tillage, or apply it directly to the soil when planting to make it easier for the plant root system to absorb and use. In the absence of attention, P stratifies in the soil layer due to a lack of incorporation (Blanco & Lal, 2023).

Nitrogen availability in the soil may also reduce the rhizobia-soybean symbiotic relationship. Plants may not initially need bacteria due to excess nitrogen in the soil. In such cases, soybeans will not recognize the bacterial response and will therefore not trigger nodule tissue formation. Nitrogen fixation capacity decreased due to the addition of 200 to 300 kg N ha^{-1} (Mohammadi *et al.*, 2012).

2.5. Economic benefits of Rhizobia Inoculation and Phosphorus Fertilizer in Soybean

The production of cereal legumes is increasing significantly due to their widespread use in various situations, including food and feed as well as industrial needs. Due to the growing human consumption of plant products and the economic constraints associated with fertilizing legumes, legumes are playing a more important role in cropping systems, especially in areas where access to fertilizer is difficult (Vanlauwe *et al.*, 2019). Legumes such as soybean, cowpea, and common bean have many potential uses and are grown in different agro ecological zones (Vanlauwe *et al*., 2019). They are economically important crops used in a variety of products (Maphosa and Jideani, 2017). They play a very important role in the sustainability of agricultural systems. Biological nitrogen fixation is becoming a more attractive and economically viable source of nitrogen, replacing inorganic fertilizers for resource-poor farmers and providing environmentally friendly agricultural inputs (Adegbeye *et al.*, 2020). For economic efficiency and environmentally friendly agricultural practices, nitrogen inputs must be properly managed through symbiotic nitrogen fixation (Hungria and Mendes, 2015).

Nutrient supply in agricultural production is one of the key factors to achieve higher productivity (Jat *et al.*, 2015). Increased agricultural productivity due to mineral nutrient supplementation in developed countries has been widely documented (Tairo and Ndakidemi, 2013a). However, Africa will be the place that uses the least fertilizer in the world. Per capita fertilizer consumption in Tanzania is 8 kg ha^{-1}, compared to 52 kg ha^{-1} in South Africa and Zimbabwe and 27 kg ha^{-1} in Malawi (Tairo and Ndakidemi, 2013b). In Ethiopia, per capita fertilizer consumption is 8.95 kg N ha^{-1} (Snethlage *et al.*, 2021). Nitrogen (N) is the most limiting nutrient for crop productivity and nitrogen fertilizer is a very expensive input in agriculture, costing more than $45 billion per year globally (Ladha *et al.*, 2005). Biological nitrogen fixation can reduce the need for nitrogen fertilizer, saving an estimated $3 billion per agricultural crop (Pimentel *et al.*, 1997).

2.6. Response of Soybean to Rhizobia Inoculation

The goal of legume inoculation is to ensure that large numbers of rhizobia are viable and effective in the root zone to allow a selected inoculant strain to colonize, nodulate, and rapidly fix nitrogen to maximize the yield potential of legumes (Sindhu *et al.*, 2020). To achieve optimal growth of plants, the nutrients required for their development must be available in adequate and balanced quantities. The main constraint limiting crop productivity in developing countries, especially for resource-poor farmers, is reduced soil fertility. Sustainable agriculture based on the use of microbial products is an effective option to overcome the problem of soil fertility. Commercial microbial products contain live cells of various microorganisms that, when applied to seeds, plant surfaces, or soil, colonize the rhizosphere inside the plant and promote growth (Backer *et al.*, 2018).

For decades, it was thought that soybeans could only form nodules when combined with Bradyrhizobium japonicum (Szpunar-Krok *et al.*, 2023). However, over time, it has been reported that soybeans can also be nodulated by different Brady rhizobium species, as well as Rhizobium, Mesorhizobium, and Sinorhizobiumfredii (Han *et al.*, 2020). The success of the introduced inoculant depends on the quality of the inoculant (Thilakarathna & Raizada, 2017), and the number of viable rhizobia per unit of inoculum as well as the number of introduced rhizobia leading to infection (Abera *et al.*, 2015). Roots are critically importance for successful nodulation. Because the mobility of rhizobia in the soil is limited under practical conditions, inoculation methods must ensure that there are enough rhizobia around the seeds for successful nodulation (Thilakarathna and Raizada, 2017). However, a crop's N requirement is determined by the yield potential of the crop in a given environment. If native rhizobia populations can meet soybean N requirements, then inoculation with even effective rhizobia strains may not show yield improvements. The existence and survival of rhizobia are influenced by soil and environmental factors (Ji *et al.*, 2017). The survival of rhizobium in soil has been shown to be affected by extreme soil pH, drought conditions, nutrient deficiencies, salinity, alkalinity, temperature extremes, toxicity (Sindhu *et al.*, 2020).

2.7. Soybean Response to Phosphorus Fertilizer

Phosphorus is an essential element for the growth, development, and yield of soybeans and has a beneficial effect on the nodulation and nitrogen fixation ability of soybeans. Phosphorus is important for optimal formation of nodules, flowers, and seeds and promotes plant maturation (Kumar *et al.*, 2013). Phosphorus application significantly increases soybean dry matter production, yield, and yield-contributing traits.

Agri-fax reported that applying 60 kg P_2O_5 ha^{-1} increased seed yield, accelerated flowering, and reduced plant height compared to the unfertilized control and 30 kg P_2O_5 ha^{-1}. Adequate P enhances basic photosynthesis, N fixation, flowering, seed production (quality and quantity), and root maturation and development (Malhotra *et al.*, 2018). The different answers given by the authors may be because the availability of inorganic phosphorus is determined by many different factors, such as soil pH, dissolved iron, aluminum, and manganese, the presence of minerals containing iron, aluminum, and manganese, calcium, and calcium mineral availability, the degree of decomposition of organic matter and microbial activity. The number of branches per plant is significantly affected by different phosphorus utilization rates, which may be due to the cumulative effect of phosphorus on cell division and nutritional balance (Mubarik *et al.*, 2021). Phosphorus fertilization also significantly increased plant height compared to the control group. Accordingly, maximum plant height may be due to biological activities stimulated when there is a balanced nutrient supply.

Today, people are concerned about the scarcity of P sources for agriculture in the future because phosphate rocks may be depleted within the next 50 to 100 years (Cooper *et al.*, 2011). Phosphorus is an essential nutrient for soybean yields, but rock phosphate used as fertilizer is a non-renewable resource and an important limiting factor in achieving optimal yields in agriculture. (van de Wiel *et al.*, 2016). Phosphorus fertilization has a direct effect on processes such as nitrogen fixation, specific nodules, and nodule activity (Divito and Sadras, 2014). For legumes, it is very important to develop mechanisms for better P absorption and utilization due to the high P requirement for legume symbiosis. There are several mechanisms that help legumes adapt to acquire P under P poor soil conditions (Stevens *et al.*, 2019).

These adaptive mechanisms include changes in root morphology, increased P acquisition through mycorrhizal symbiosis, acidification of the rhizosphere through the release of H^+ ions, and production and release of acid phosphatase. High phosphorus inputs in agriculture have led to environmental problems. Phosphorus present in soil is also not absorbed by plants due to the ability of most soils to fix phosphorus (Syers *et al.*, 2008). The amount of P in soil is very low, ranging from 100 to 200 mg P per kg of soil, corresponding to about 350 to 7,000 kg P ha^{-1} per 25 cm of soil, although only a small portion of P is available for use immediately available for cultivation (Gaskell and Smith, 2007). About 30% of the world's soils have high phosphate binding capacity, e.g. in southern China, Brazil, and sub-Saharan Africa (Dimkpa *et al.*, 2023). To improve the utilization of phosphorus nutrients, fertilization containing Pi is very important, however, this phosphorus mainly comes from non-renewable resources (van de Wiel et al., 2016).

3. MATERIAL AND METHODS

3.1. Description of the Study Area

The experiment was conducted in the Bedele district, of Oromia regional state, Southwestern Ethiopia in the 2023 main cropping season. The district is located between $8^{o}14'30''$N and $8^{o}37'53''$N latitude and $36^{o}13'17''$E to $36^{o}35'05''$E longitude (Fig. 1).The area is situated at about 480 km Southwest of Addis Ababa, Ethiopia, and the elevation of the study area ranges from 1013 to 2390 m a.s.l. The experimental site has a sub- humid climate of 13.1°C and 26.5°C, minimum and maximum annual temperatures, respectively. The area receives an annual rainfall of 2097.6 mm with maximum precipitation from April to October (Bedele National Metrology Station, 2022/2023) (Fig. 2). The area is characterized by a rugged topography dominated by gentle slopes and localized steep slopes ranging from 2 to 45%. The predominant soil types are Nitisols, Luvisols and Cambisols in the plateau and side slopes and Vertisols in low land (Regassa *et al.*, 2023). The soil acidity of the study area ranged from slightly acidic to very strongly acidic with pH values of 4.5 to 6.8 and the available P (ppm) content of nearly 80.23% of the soils was in the very low (< 5) and low (5-10) categories (Gedefa *et al.*, 2021). Mixed farming is the main agricultural activity carried out in the area. The main livelihood strategies in the district include crop production, livestock rearing, and off-farm activities. The major crops grown in the district includes maize (*Zea-maize*), wheat (*Tritium aestivum*), sorghum (*Sorghum bicolor*), finger millet (*Eleusine coracana*), coffee (*Coffee arabica* L.), and teff (*Eragrotis abyssinica*). Pulse crops such as faba bean (*Vicia faba*) and field peas (*Pisum sativum*) are also grown in selected areas. Generally, the study area covered a total area of 74468.50 hectares of land (Huluka *et al.*, 2018).

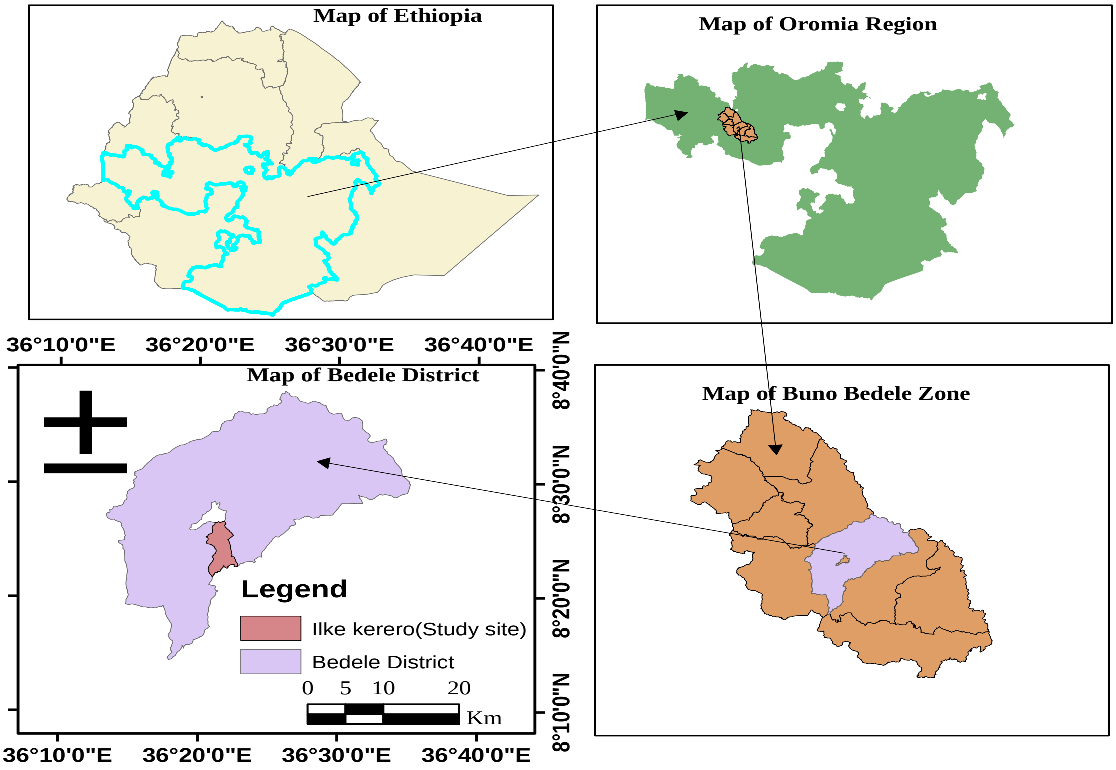


Figure 1. Location map of the study area

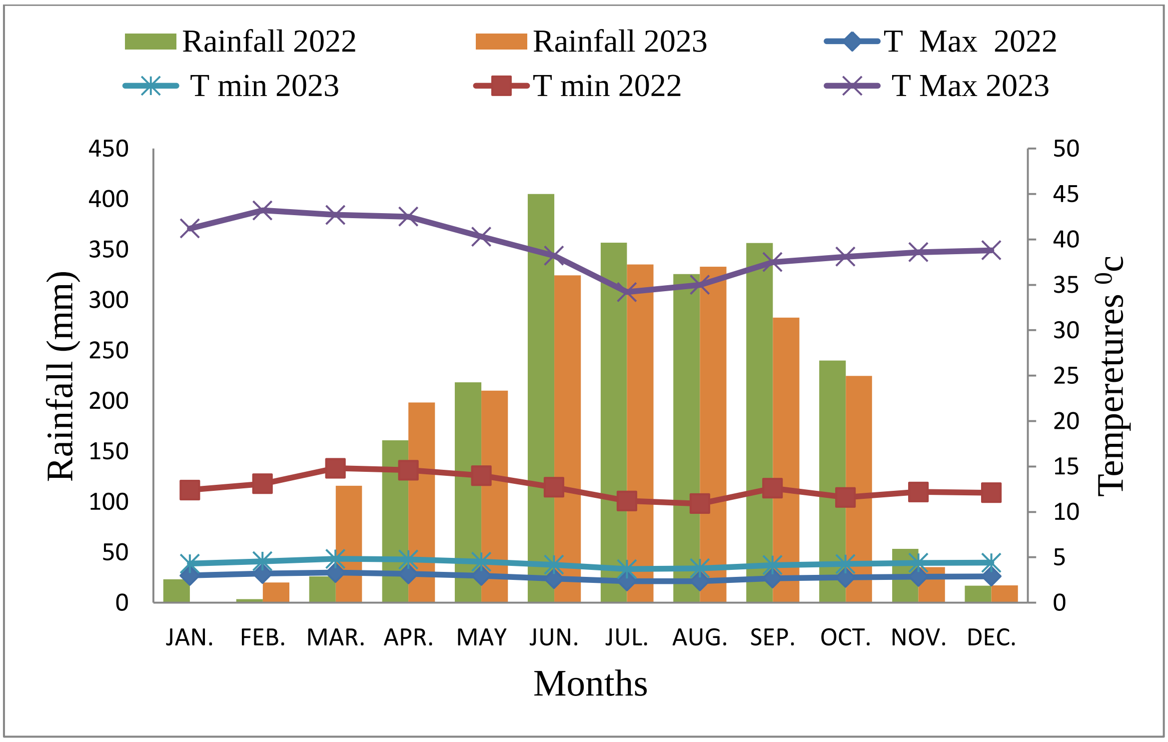


Figure 2. Monthly rainfall (mm), minimum and maximum temperature (°C)

Source: - Ethiopia Agrometeology institute Bedele metrology first class station in 2022 and 2023

3.2. Experimental Materials

The study has used soybean Varieties named as: Ketta and Cheri obtained from BeARC. Table 1 shows brief description of the varieties.

Table 1. Varieties characteristics

Varity	Maturity Type	Altitude (m.a.s.l.)	Rainfall (mm)	Breeder/ Maintainer	Year of Release	Oil Content	Protein Content	Yield t ha^{-1}
Ketta (PR-145-2)	Medium	1200-1900	1000-1200	BARC/OARI	2011	18.82	38.73	1.4-3.2
Cheri (IPB-81-EP7)	Medium	1300-1850	900-1300	BARC/OARI	2003	21.30	35.90	2.2

Source: (Tesfaye *et al.*, 2018)

3.3. Experimental Design and Procedure

The field experiment was laid out in factorial randomized complete block design (RCBD) with three replications (Table 2). The treatments were consists of two cultivars, four different P rates (0, 10, 20, and 30 kg ha^{-1}) and two levels of Bradyrhizobium (un-inoculated and inoculated with MAR-149). Therefore, this experiment consists of 16 treatments and replicated 3 times. A total of 48 plots. The size of each experimental plot was 4.2 m × 2 m (8.4 m^2), with distances between plants, rows, plots, and blocks of 5 cm, 60 cm, 0.5 m, and 1 m, respectively, for a total area of 576.7 m^2. The seeds were weighed on an electronic scale and soaked in a sugar solution. Bradyrhizobium strain (MAR-1495) was applied to the moistened seeds at a rate of 10 g kg^{-1} seeds. The Bradyrhizobium inoculum was thoroughly mixed with the seeds. Seeds were air-dried in the shade for 30 min to maintain cell viability and then sown within 1 hour at the required rate and spacing.

Table 2 Treatments combination arrangement

Varieties	Rhizobium	Phosphorus level (kg P ha^{-1})			
		0 kg P ha^{-1}	10 kg ha^{-1}	20 kg ha^{-1}	30 kg ha^{-1}
		P_0	P_1	P_2	P_3
V_1	R_0	$V_1R_0P_0$	$V_1R_0P_1$	$V_1R_0P_2$	$V_1R_0P_3$
	R_1	$V_1R_1P_0$	$V_1R_1P_1$	$V_1R_1P_2$	$V_1R_1P_3$
V_2	R_0	$V_2R_0P_0$	$V_2R_0P_1$	$V_2R_0P_2$	$V_2R_0P_3$
	R_1	$V_2R_1P_0$	$V_2R_1P_1$	$V_2R_1P_2$	$V_2R_1P_3$

V_1=katta, V_2=Cheri, R_0 =No Rhizobium, R_1=inoculated with Rhizobium, P_0 = No P applied, P_1= 10 kg P ha^{-1}, P_2 =20 kg P ha^{-1} and P_3 =30 kg P ha^{-1}

3.4. Soil Sampling and Analysis

Before planting, representative soil samples were randomly collected from eight test plots at depths of 0-20 cm using an auger. Finally, composite samples were prepared for analysis to determine the physicochemical properties of the soil experimental site. A 1 kg composite sample was prepared and brought to the soil laboratory of the Bedele Agricultural Research Center in labeled polythene bags. The soil samples were air-dried, ground, and sieved through a 2-mm sieve to analyze soil texture, pH, available phosphorus, and cation exchange capacity (CEC), and the soil samples were ground to a sieve size of 0.5 mm. Soil organic carbon content was determined by the Walkley and Black (1934) as described in the FAO (2006) Laboratory Guide for Plant Nutrient Analysis (Pineiro *et al.,* 2008). Soil texture was measured using the hydrometer method (Bouyoucos, 1951).

Soil pH was measured in water using a potentiometric pH meter and a glass electrode connected to a digital pH meter at a soil-to-water ratio of 1:2.5 (Pineiro *et al*., 2008) .Total nitrogen was measured using the Kjeldahl method (Jackson, 1967). Available soil phosphorus was extracted and measured by spectrometer using the Olsen method Holford and Cullis (1985). Cation exchange capacity (CEC) was determined by using ammonium acetate method (Miller and Wolin, 1982). After soybean harvest, representative soil samples were randomly collected in a V-shape at two to three locations in each experimental plot using an auger at a depth of 0 to 20 cm. Finally, plot-based samples were prepared for analysis to determine the effects of treatments on selected soil chemical properties at the experimental sites. The collected soil samples were air-dried, ground, and sieved with a mesh size of 2 mm. Samples were prepared, placed in polyethylene bags, labeled, and sent for analysis of available phosphorus, total nitrogen, organic carbon, and soil pH using the same procedures described above.

3.5. Land Preparation and Planting

The site was cleared using a tractor in April 2023. A field which was cropped to finger millet in the previous season plowed to a depth of 0-20 cm to create fine seedbeds and leveled by hand before field layout. A fine seedbed is prepared according to the design, the field layout is prepared, and each treatment is randomly assigned to experimental units within a block. The soybean was planted on June 26, 2023; with a 60 cm inter row spacing and a 5 cm between intra row spacing. As a precaution to avoid cross-contamination; the non-inoculated treatment was planted first followed by the inoculated treatment. This experiment was conducted under rain-fed conditions.

3.6. Management of the Experiment

The inoculated seeds of each treatment were sown by one individual, Ridges were made to prevent the spread of bacteria due to rainwater on the site and within the city block, weed managements, followed, and data recorded was carried out during the growing season. In the experimental field, weeding was performed during the growing season.

3.7. Data Collected

3.7.1. Phenological parameters.

Days to 50% flowering: - Record the number of days from emergence until 50% of the plants in the plot have at least one flower.

Days to 90% physiological maturity*:* - Number of days from emergence until 95% of plants in each net plot show yellow color and pods turn yellow before senescence is recorded.

3.7.2. Nodulation parameters.

Total number of nodules: - Nodule and root characteristics were measured by carefully uprooting five randomly selected plants from each plot along with the soil during the time of flowering.

Root volume: the root samples of five plants were collected and immersed carefully in 1000 ml capacity plastic cylinder, which is filled up with water to a volume of 100ml. The volume of water displaced by the roots was recorded as root volume per plant.

Tap root length: the tap root length of five randomly selected plants was measured and the average of the root lengths was recorded.

Total Number of effective nodule: - Deep dark red, slightly dark red and pink nodules were considered effective for nitrogen fixation. On the other hand, green or white ones may be considered ineffective. The percentage of effective nodules (%) was then calculated.

Nodule fresh weight (g per plant):- Root nodules were collected from five plants, and weighed, and the average fresh weight of the nodules was recorded.

Nodule dry weight (gm. per plant*):-* The nodules were dried in an oven at 70 °C for 48 h to constant weight. The dry nodule weight was then measured and the average nodule dry weight was recorded.

3.7.3. Growth parameter

Leaf area: This is measured at physiological maturity in five randomly selected marked plants. Five plants were randomly sampled from each plant to represent the lower, middle, and upper parts. Then measure the length and width with a ruler in centimeters, multiply the width by the length and the correction factor to get the area of each leaf, and applying the equation LA = a × (L × W), where LA is the leaf area (cm^2), L is the leaf length (cm), W is the largest leaf width (cm), and a is the angular coefficient (2.0185) (Turek *et al.*, 2023).

Leaf Area Index: The leaf area index was calculated using the relation:

$$\text{Leaf area index} = \frac{\text{Leaf area}}{\text{Ground cover}} ----------------------- (1)$$

The plant height: Plant height was measured from the ground to the highest tip of the stem for five randomly selected plants per plot at physiological maturity before harvest. Average plant height (cm) was calculated for each treatment.

Number of primary branches: This was measured during the sampling period and at physiological maturity when all plants stopped growing. We counted the branches of the five plants sampled from each plot and calculated the average.

3.7.4. Yield and yield components

Number of pods per plant (count):- Counts were made from five randomly selected plants from the middle three rows at maturity and expressed as the average for each plant.

Number of seeds per plant (count):- Counts were made from five randomly selected plants from the central row at maturity and expressed as the average of the five plants.

Hundred seed weight (g*)*:- The harvested seeds per net plot were randomly counted and weighed (g) using an electronic balance at a seed moisture (GT PRO) content of 12.5% standard moisture content for soybean crops.

Grain yield: It was measured by harvesting the crop from the three central rows of the net plot area.

Above ground biomass: The total aboveground biomass of the net plot area in the middle three rows was determined by harvesting at physiological maturity near the soil surface and drying in the sun to constant weight. Finally, the net plant plot area biomass yield was converted to per hectare and expressed in tons ha^{-1}.

Harvest index (%):-The harvest index per plot was recorded as the ratio of grain yield to soil biomass yield of or more per plot. Calculated using flow equation:

$$\mathrm{HI}(\%) = \frac{\mathrm{GY}}{\mathrm{BY}} * 100 ----------------------------(2)$$

Where HI = harvest Index, GY = Grain Yield (kg), BY = Biological Yield (kg)

3.8. Phosphorus uptake Efficiency

Phosphorous is essential to crop production; it stimulates early root formation and growth, gives a rapid and vigorous start to plants, and promotes flower and seed production. Phosphorous is needed in the genetic coding material, which controls cell division. The P content in plants is usually between 0.1 to 0.5% of the dry matter. Total P in plant material can be attained either by wet-digestion procedure or by dry-ashing procedure (Mader *et al.*, 1998). Both methods are satisfactory. However, dry-ashing is a simpler, easier, non-hazardous and economical option. Later, P content in the digests or dissolved ash aliquots is measured spectrometer. Dry ashing is appropriate for analyzing P, but only in plant tissues containing low silica contents (like legumes). The procedure is slight modifications (Pratt & Chapman, 1961).

Dry-ashing Procedure

1. Weigh 0.5-1.0 g dry and ground plant material in a 30-50 mL porcelain crucibles or Pyrex glass beakers.

2. Place porcelain crucibles into a cool muffle furnace, and increase temperature gradually to 550 °C.

3. Continue ashing for 5 hours after attaining 550 °C.

4. Shut off the muffle furnace and open the door cautiously for rapid cooling.

5. When cool, take out the porcelain crucibles carefully.

6. Dissolve the cooled ash in 5-mL portions 2 N HCl and mix with a plastic rod.

7. After 15-20 minutes, bring to the volume (usually to 50-mL) using DI water.

8. Mix thoroughly, allow standing for about 30 minutes, and use the supernatant or filter

through Whatman No. 42 filter paper, discarding the first portions of the filtrates.

9. Analyze the aliquots for P by spectrometer (by Ammonium Vanadate-Ammonium Molybdate yellow color method).

Phosphorus uptake efficiency (PUE) was calculated using the formula of (Fituma, 2015).

$$\text{PUE} = \text{P concentration} * \text{dry biomass yield} ------------------(3)$$

Agronomic efficiency (AE) is defined as the grain yield per unit of fertilization.

$$\text{AE}\left(\frac{\text{kg}}{\text{kg}}\right) = \frac{\text{Gf} - \text{Gu}}{\text{Na}} --------------------------------(4)$$

Where, Gf is the grain yield (kg) in the fertilized area, and GU is the grain yield in the fertilized area. Unfertilized area (kg), **Na** is the amount of P applied (kg).

3.9. Partial Budget Analysis

Economically acceptable treatments were determined through a partial budget analysis that estimated total grain yield using adjusted yield to grain market value (Bezabeh *et al.*, 2021) and growing season inputs. Only the total variable cost (TCV) was used to calculate costs. The current prices of soybeans, inoculants, and P, as well as the costs of applying inoculation and P, were considered to vary according to their costs. To estimate the economic parameters, soybean yield was valued at an average market price of birr kg^{-1}. To compare soybean yields with the yields farmers receive, the achieved yields have been revised downward by 10%. Both costs and benefits were converted to Ethiopian Birr (ETB) amounts and reported per hectare. Net treatment benefits (NB) and TCV were compared using a two-step superiority analysis described below. The first step was to calculate NB as shown in the following formula suggested by CMMITY (Program, 1988)

NB = (GYxP)-TCV, (1) where GY x P is the total field benefit (GFB), GY is adjusted profit. Grain yield per hectare, P is the field price per unit of harvest. Second, beneficial TCVs were listed in ascending order according to dominance analysis. All treatments with NB below the low TCV treatment were marked with the letter “D” for being dominant and excluded from further analysis. Non-dominant treatments were subjected to marginal return (MRR) analysis.

$$\text{MRR (\%)} = \frac{\text{Change in (NBb} - \text{NBa)}}{\text{Cahnge in TCV (TCVB} - \text{TCVa)}} * 100 ---------------(5)$$

Where NBa = NB is the immediately lower TCV, NBb = NB is the next higher TCV, TCVa = immediately lower TCV, TCVb = next TCV highest TCV. MRR of 100% implies a return of one Birr on every Birr of expenditure in the given input. Finally, a treatment having marginal rate of return (MRR) greater than 100% and with the highest net benefit was considered to be economically the best

3.10. Statistical Analysis

All data were examined for normal distribution and analysis of variance (ANOVA) was performed using the statistical analysis system "SAS, 2012". Software version 9.0, using the Proc- GLM method. Treatment differences were separated using the least significant difference (LSD) method with a probability of 5%. Correlation analysis between parameters was performed to determine the magnitude and extent of their relationships.

4. RESULTS AND DISCUSION

4.1. Soil Physico-chemical Properties before Soybean Planting

The results of the analysis of selected physicochemical properties indicate that the particle size distribution of the soil is dominated by clay (58%) followed by sand (32%), and silt (10%) (Table 3). Accordingly, the textural class of soil of experimental site was clay. Soybean produced a high yield in loamy textured soil, but it can also grow well in clay soils (Butcher *et al.*, 2018). The soil pH of experimental site was 4.6, which is strongly acidic according to (Bruce and Rayment, 1982).

Soybean has been found to grow well in pH values of 5.5-7.0 and any pH below and above these values will affect its growth and thus such soil needs amendment to neutralize the extreme soil reactions (Gordon *et al.*, 2022). Chemical reaction like total N, available P, OC, and CEC of the soil before planting were 0.12%, 0.5 mg kg^{-1}, 1.14%, and 9.64 $cmol_{(+)}$ kg^{-1}, respectively (Table 3). The soil had low total N content based on the classification of total N content (%) (Joint, 2006). Moreover, the study site had very low available P content (Table 3) according to classification of (Holford and Cullis (1985). The organic carbon content of the soil before planting was 1.14% indicating as very low (Table 3) according to (Joint, 2006) rating. The cation exchange capacity (CEC) of the soil was 9.64 $cmol_{(+)}$ kg^{-1} which is in the low range (Table 3) according to (USDA, 2007).

Generally, the soil analysis revealed that the soil sample is predominantly clay with a strong acidic pH, very low organic carbon content, low total nitrogen content, very low available phosphorus, and a low in cation exchange capacity (CEC) level. This result was in line with the findings of (Gedefa *et al.*, 2021), who mapped the spatial distribution of soil properties in the study area and found that 62.61%) of the soils had strongly acidic (pH < 5.5), 73.39% had low OC content (2-4%), and 80.23% of the available P (ppm) content was categorized between low (5-10) and very low (< 5). Understanding these soil properties is crucial for making informed decisions regarding soil management practices, nutrient amendments, and crop selection to optimize agricultural productivity in this specific soil type.

Table 3. Effect of P fertilizer Rate, Rhizobium Inoculation and varieties on selected soil Chemical Properties before Soybean Planting.

Soil properties	Value	Rating	Range	Reference
1. Particle size distribution				
Clay (%)	58			
Silt (%)	10			
Sand (%)	32			
Soil structural class	Clay			
2.Chemical Properties				
pH (1:2.5 H_2O) Suspension	4.6	Strongly acid	4.5-5.5	Bruce and Rayment (1982)
Organic carbon (%)	1.14	Very low	< 2	(Joint, 2006)
Total nitrogen (%)	0.12	Low	0.01-0.2	(Joint, 2006)
Available phosphorus mgkg^{-1} soil)	0.5	Very low	< 5	Holford and Cullis (1985)
CEC cmol $_{(+)}$ kg^{-1}	9.64	Low	6-12	(Miller and Wolin, 1982)

4.2. Effect of P fertilizer Rate, Rhizobium inoculation and Soybean Varieties on Selected Soil Chemical Properties after Harvest

4.2.1. Soil pH

The interaction of variety*fertilizer*rhizobium inoculation showed non-significant effect on soil pH (Appendix Table 1).The main effect of P fertilizer, rhizobium inoculation and soybean varieties had very highly significant (P<0.001) influence on soil pH . On the other hand, the soil pH value of the experimental site increased by 5.13% over initial soil pH value of the experimental site increased by 5.13% over initial soil pH of 4.6%. The increment in soil pH by 5.13% over initial pH because of application of phosphorus at 30 kg ha^{-1} with Rhizobium inoculation might be ascribed to the impact of organic matter on soil pH through formation of complexes with acid forming cation such as Al and Fe. The highest soil pH value 4.82 was recorded at T_4 received 30 kg P ha^{-1} with rhizobium inoculation, while the lowest soil pH 4.64 was recorded T_1 received control plot of P appli cation and un-inoculated (Table 4). Even though a slight increment was observed in strong ly acidic (Bruce and Rayment, 1982).

4.2.2. Soil organic carbon

Analysis of variance indicated very highly significant (P<0.0001) main effect of P application, Rhizobium inoculation and Varieties on soil organic carbon (Appendix Table 1). However, the three factor interactions effect of P*V*Rh also had non-significant influences on soil organic carbon content of the experimental site (Appendix Table 1). The average organic carbon content of soil of each plot after harvesting was about 66.67% higher than the initial organic carbon content 3.51% (Table 4). The increased of organic carbon by 66.67% over initial soil organic carbon 3.51% content of the experimental site might be associated with the improvement of soil conditions, which might be enhanced biomass production, proliferation of soil microbial and their activity in the soil. An average organic carbon content of each treatment after harvesting was 8.4% higher than the initial organic carbon content of the soil at Bako (Dabesa and Tana, 2021a). This result is in agreement with the findings that the attributed increase in soil organic carbon to the dropping of leaves, which added organic carbon to the soil (Tisdall, 2020).

4.2.3. Total nitrogen

Analysis of variance indicated very highly significant ($P < 0.0001$) main effects of Rhizobium inoculation, P application rate and Varieties on total nitrogen content of the soil after harvesting of the soybean (Appendix Table 1). Also, the three factor interactions of P*V*Rh had non-significant ($P > 0.05$) effect on total nitrogen of the experimental site. The highest total nitrogen content 0.28% was recorded from plots that received Phosphorus application at 30 kg ha^{-1} and rhizobium inoculation, while the lowest total nitrogen 0.18% was recorded for plots that received control plot of P application and un-inoculated plot (Table 4). The increment in total nitrogen content of the soil due to phosphorus application with rhizobium inoculation might be due to increase of the organic matter content of the soil and still found in medium class according to (Joint, 2006). The total nitrogen content of the soil increased from 13.48% by Phosphorus application at 30 kg ha^{-1} and rhizobium inoculation over the control at Alicho Wuriro Highland Ethiopia (Woldekiros *et al.*, 2018). Furthermore, the release of N from the applied phosphorus with rhizobium might have contributed to the increase in total nitrogen, and soybean leaf dropped may also increase the Nitrogen.

4.3.4. Available phosphorus

The main effect of P fertilizer, varieties and Rhizobium inoculation had significant ($P<0.05$) effect on available soil phosphorous. However, the three factor interactions of P*V*Rh showed non-significant effect on soil available P (Appendix Table 1).

The highest soil available P content was recorded 0.82 mg ka^{-1} from the plots treated with 30 kg P ha^{-1} inoculated with Rhizobium with MAR-1495 strain followed by 20 kg P ha^{-1} with rhizobium inoculated, while the lowest soil available P content was recorded 0.41 mg kg^{-1}. From the control plot of P application rate and un-inoculated rhizobium (Table 4). Available phosphorus recorded at 30 kg P ha^{-1} with Rhizobium inoculated and control plot of P application and without Rhizobium inoculated are still in very low rating according to (Holford and Cullis, 1985). This result indicated integrated use of high rate of P fertilizer with Rhizobium inoculated significantly increased available phosphorus even if it was in medium rate according to (Holford and Cullis, 1985). In general, at low P fertilizer rate and its combination with Rhizobium inoculation increased the available P content of the soil after harvest of soybean from the initial soil available P content (0.82 mg kg^{-1} of soil) (Table 4). This could be due to the fact that P is a key requirement for ATP production during the process of biological nitrogen fixation (Dabessa *et al.*, 2018).

Table 4. Effect of P fertilizer rate, Rhizobium inoculation and varieties on selected soil chemical properties after soybean harvest**.**

Treatment Rhizobium inoculation	Soil pH (H_2O)	Rating	OC (%)	Rating	TN (%)	Rating	Av.P (mg kg^{-1})	Rating	CEC (mg kg^{-1})	Rating
Un-inoculated	4.70^{b}	Strongly acidic	2.53^{b}	Low	0.22^{b}	Medium	0.55^{b}	Very low	26.46^{b}	high
Inoculated	4.74^{a}		2.82^{a}		0.24^{a}	Medium	0.65^{a}		27.80^{a}	
LSD (0.05)	0.0066		0.1004		0.0084		0.0459		0.173	
P rate kg ha^{-1}										
T_1 (0)	4.64^{d}		2.03^{d}	Low	0.18^{d}	Medium	0.41^{d}	Very low	21.4^{d}	Medium
T_2 (10)	4.70^{c}		2.44^{c}		0.21^{c}		0.48^{c}		27.5^{c}	
T_3 (20)	4.74^{b}		2.97^{b}		0.25b		0.69^{b}		27.75^{b}	
T_4 (30)	4.82^{a}	Strongly acidic	3.29^{a}	Low	0.28^{a}	Medium	0.82^{a}	Very low	32.00^{a}	high
LSD (0.05)	0.0093		0.14		0.012		0.065		0.244	
Varieties										
Ketta	4.74^{a}	Strongly acidic	3.17^{a}	Low	0.27^{a}	Medium	0.63a	Very low	20.87b	Medium
Cheri	4.70^{b}		2.19^{b}		0.19^{b}		0.57^{b}		33.45a	high
LSD (0.05)	0.0066		0.10		0.00^{8}		0.05		0.17	
CV (0.05)	0.24		6.35		6.21		12.96		1.08	
Reference	Bruce and Rayment (1982)		(Joint, 2006)		(Joint, 2006)		Holford and Cullis (1985)		(Miller and Wolin, 1982)	

4.3 Effect of Bradyrhizobium Inoculation and P application Rate on Phenology of Soybean Varieties

4.3.1. Flowering days

For the variety Ketta, the number of days to 50% flowering decreased with increasing phosphorus application rates for inoculated conditions. The lowest number of days to 50% flowering was observed 68 days at 30 kg ha^{-1} P for both inoculated and un-inoculated treatments. For the variety Cheri, a similar trend was observed with an increase in the number of days to 50% flowering with increasing phosphorus application rates for inoculated conditions. The highest number of days to 50% flowering was observed 80 days at 30 kg ha^{-1} P for both inoculated and un-inoculated treatments (Table 5).

The study revealed that rhizobia inoculation delayed the number of days to flowering which suggests that inoculation, had influence on days to 50% flowering. The prolonged days to flowering could be due to the rhizobia inoculation that facilitated nitrogen fixation and enhanced vegetative growth, which in turn extended the flowering date. Nitrogen produced by biological nitrogen fixation, as part of the protein compound, enzyme and effective compound in energy transfer takes part in the structure of DNA, in the structure of chlorophyll, and direct impact on vegetative growth (Bhatla and Lal, 2023). Soybean inoculation increased the leaf chlorophyll content and plant biomass, and the leaf chlorophyll content of the plant remained at high levels until, the pod filling stage, as a result of delays in days to flowering (Grassini *et al.*, 2021). This result is in agreement that inoculation induced late flowering in soybean in both glasshouse and field experiments (Adeyemi *et al.*, 2020). This might be due to sufficient nitrogen produced by N_2 fixation promoted vegetative growth, which in turn extended days to flowering.

Phosphorus application was significantly (P=0.022) affected days to flowering. This could be due to the presence of adequate P applied to enhance shoot, root growth, and promote early flowering. Similarly, reported though the effect of P was significant, P application has slightly reduced the days to 50% flowering on soybean bean as P rate increased (Adjei-Nsiah *et al.*, 2019). The three ways of interaction were significantly influenced on days 50% flowering. The significant effect of inoculation of Bradyrhizobium japonicum and Phosphate Solubilizing Pseudomonas spp on days to 50% flowering (Irankhah *et al.*, 2021).

4.3.2. Days to 90% physiological maturity

For both varieties, the number of days to reach 90% physiological maturity varied with phosphorus application rates and inoculation status. In general, there was no consistent trend across all treatments for both varieties. Comparison between Inoculated and Un-inoculated Treatments: In general, there were differences in the number of days to reach 50% flowering and 90% physiological maturity between inoculated and un-inoculated treatments for both varieties across different phosphorus application rates. Cheri variety at 30 kg ha^{-1} P application and with the inoculation of Rhizobium bacteria was the latest matured with 165 days to maturity; while the earliest matured (124 days to maturity) variety was Ketta, with Rhizobia un-inoculation and control plot of P application (Table 5).

The result revealed that days to maturity delayed in response to phosphate fertilizer application relative to control plot (Table 5). This might be due to the important role of phosphorus, as the vital component of adenosine triphosphate (ATP). Soybean needs phosphorus for adequate growth and nitrogen fixation. Sufficient phosphorus levels are also required to enhance different plant organs growth and promote nodulation and early maturity (Malhotra *et al.,* 2018). Phosphorus is a very important nutrient for plant cell division, growth and root lengthening, seed and fruit development, and early ripening, as well. In line the observed the phosphorus is known for its effect to promote maturity (Liu *et al.*, 2022). The other reason for hastening maturity could be due to the mobilization of leaf nitrogen to the reproductive organs for development (Snider *et al.*, 2021).

Soybean maturity was delayed by a result of inoculation rhizobia. The delay in maturity of soybean might be because the N_2 fixed by inoculation promoted vegetative growth the crop. Similarly, inoculation enabled soybean to display better growth and increase in days to maturity (Kumawat *et al.*, 2019). The interaction between the varieties, inoculation and p application did not significantly (P=0.0602) influenced days to physiological maturity.

Table 5. Responses of two soybean varieties to rhizobia inoculation and rate of phosphorus application for flowering date and 90% days to physiological maturity

Varieties	Inoculation Status	Number of days 50% Flowering (days) Phosphorus application (kg ha^{-1})				Number of days 90% Physiological maturity (days) Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	75^{d}	72^{e}	70^{f}	68^{h}	130de	132^{d}	132^{d}	132^{d}
	Un-inoculated	64^{j}	65^{j}	65^{j}	66^{i}	124^{g}	128^{f}	125^{g}	129^{ef}
Cheri	Inoculated	79^{ab}	78^{b}	78^{b}	80^{a}	161^{bc}	162^{b}	161^{ab}	165^{a}
	Un-inoculated	69^{g}	70^{bc}	77^{c}	77^{c}	160^{c}	160^{c}	162^{bc}	162^{bc}
LSD (0.05)		1.17				2.17			
CV (%)		0.96				0.895			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

4.4. Effect of Bradyrhizobium Inoculation and P application rate on Growth of Soybean Varieties

4.4.1. Leaf area

For the variety Ketta, in the inoculated condition, the leaf area increased with increasing phosphorus application rates up to 20 kg ha^{-1} P and then slightly decreased at 30 kg ha^{-1} P. The highest leaf area was observed 96.44 cm^{2} at 20 kg ha^{-1} P. In the un-inoculated condition, a similar trend was observed, with the highest leaf area 95.06 cm^{2} at 10 kg ha^{-1} phosphorus. For the variety Cheri, in both inoculated and un-inoculated conditions, the leaf area increased with increasing phosphorus application rates. The highest leaf area was observed 112.79 cm^{2} at 20 kg ha^{-1} P for both inoculated and un-inoculated treatments (Table 6).The lowest leaf area was produced by the variety Ketta (75.25 cm^{2}) under the control plot of P application and no rhizobia inoculation. The top variety showed 33.35% leaf area increases over the genotype that produced the lowest leaf area.

This finding is in agreements the early maturing soybean genotypes achieve minimum leaf area values required for maximum potential yield at the early reproductive growth stage (Lopez *et al.*, 2021). Phosphate is also very important for leaf expansion, increase in leaf surface area and higher number of leaves. Phosphate application has been reported to increase shoot growth and leaf growth of soybean and other leguminous crops (Akpalu *et al.*, 2014). Reduction in phosphate supplementation resulted in decrease in shoot growth, specifically in leaf size. A reduction in leaf area with decrease phosphate fertilizer implied changes in leaf initiation rates and activity of shoot apical meristem. Decreased size of individual leaves could be related to changes in either cell division or cell expansion of both (Chiera *et al.*, 2002).

4.4.2. Leaf area index

For the Ketta variety: Inoculated plants had higher leaf area index values compared to un-inoculated plants across all phosphorus application levels. The highest leaf area index for the Ketta variety was observed (0.29) at a phosphorus application level of 10 kg ha^{-1} for both inoculated and un-inoculated plants. The differences in leaf area index between phosphorus applications levels were more pronounced in inoculated plants compared to un-inoculated plants.

For the Cheri variety: Inoculated plants generally exhibited higher leaf area index values compared to un-inoculated plants. The highest leaf area index for the Cheri variety was observed 0.37 at a phosphorus application level of 20 kg ha^{-1} for inoculated plants. The differences in leaf area index between phosphorus application levels were more consistent compared to the Ketta variety.

Generally, the results suggest that phosphorus application has a significant effect on leaf area index, with variations depending on the variety and inoculation status. Inoculated plants generally showed higher leaf area index values, indicating a positive impact of inoculation on plant growth in response to phosphorus application.

This findings is in agreements that inoculation and phosphorus application levels play a significant role in influencing leaf area index (Adeyemi *et al.*, 2021), with differences observed between inoculated and un-inoculated plants as well as variations in response to different phosphorus levels.

Table 6. Responses of two soybean varieties to rhizobia inoculation and phosphorus application rate for leaf area and Leaf Area Index

Varieties	Inoculation Status	Leaf Area (cm^2)				Leaf area index			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	83.34^{de}	91.03^{b-e}	96.44^{a-e}	90.03^{b-e}	0.26^{de}	0.29^{bcd}	0.26^{de}	0.28^{cde}
	Un-inoculated	75.25^{e}	95.06^{bcd}	83.29^{de}	87.57^{cde}	0.23^{e}	0.24^{e}	0.26^{de}	0.27^{de}
Cheri	Inoculated	96.01^{a-d}	104.76^{ab}	112.79^{a}	103.38^{abc}	0.28^{cde}	0.35^{ab}	0.37^{a}	0.34^{ab}
	Un-inoculated	83.07^{de}	97.45^{a-d}	94.93^{bcd}	98.5^{a-d}	0.27^{cde}	0.32^{abc}	0.31^{bcd}	0.33^{abc}
LSD (0.05)		16.65				0.055	0.05		
CV (%)		10.94				10.92	10.94		

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

4.4.3. Plant height

For the variety Ketta, inoculated plants generally had higher plant heights compared to un-inoculated plants at all levels of phosphorus application. The difference in plant height between inoculated and un-inoculated plants was statistically significant (indicated by different letters) at most phosphorus application levels. The highest plant height for Ketta was observed in the inoculated group 95.80 cm at 30 kg ha^{-1} phosphorus application. For the variety Cheri, inoculated plants also showed higher plant heights compared to un-inoculated plants at most levels of phosphorus application. There were statistically significant differences in plant height between inoculated and un-inoculated plants at some phosphorus application levels. The highest plant height for Cheri was observed in the inoculated group 100.40 cm at 30 kg ha^{-1} phosphorus application. The shortest plant height of 70.33 cm was found with Ketta variety under no Rhizobia inoculation and control plot of P application (Table 7). Therefore, it can be concluded that inoculation and appropriate phosphorus application can positively influence plant growth in these varieties.

A linear increase in plant height was observed with the advancement in age of all the soybean varieties. The plant height became slow till maturity stage, which might be due to the fact that the plant converted from the vegetative to reproductive phase of growth and development. Thus, it was also observed from the data that the increase in plant height continued up to maturity stage.

Phosphorus application affected the height of soybean. It was found that P application at the rate of 10, 20 and 30 kg P ha^{-1} significantly increased plant height of rhizobia inoculated soybean by 29.37, 30.48 and 29.17 % with inoculated respectively over the control plot of P application. Also, phosphate solubilizing fungi inoculated soybean plants scored significantly higher plant heights, which was 81% over the un-inoculated treatment (Argaw, 2012).This finding is in agreement phosphorus application of 60, 120 and 180 mg P kg^{-1} significantly influenced soybean height (Imenu *et al.*, 2022). The increase in plant height, due to increase phosphorus application, might be attributed to pronounced vegetati ve growth in response to the applied P (Amanullah *et al.*, 2019).

4.4.4. Number of primary branches

For the variety Ketta, in both inoculated and un-inoculated conditions, the number of primary branches increased with increasing phosphorus application rates. The highest number of primary branches was observed six at 30 kg ha^{-1} P for both inoculated and un-inoculated treatments. For the variety Cheri, a similar trend was observed with an increase in the number of primary branches with increasing phosphorus application rates for both inoculated and un-inoculated conditions (Table 7).

The lowest number of primary branch was recorded by the variety Cheri (2.8) under the control plot of P application and no rhizobia inoculation. The variety that produced the highest number of primary branch showed more than 53.3% increases over the lowest variety. There was significant effect on number of primary branches because of Bradyrhizobium inoculation or phosphorus application and their interaction (P=0.05). Similarly, The number of primary branches was significantly influenced by the application of Bradyrhizobium inoculation, phosphorus, and their combined effect (Dabesa and Tana, 2021a). The number of branches per plant was significantly affected by different rates of phosphorus application and this might probably be due to the cumulative effect of phosphorus on the process of cell division and balanced nutrition. Dissimilar report: The effect of Bradyrhizobium inoculation and phosphorus application on the number of primary branches was not statistically significant (Musa *et al.*, 2018).

Table 7. Responses of two soybean varieties to rhizobia inoculation and rate of phosphorus application for plant height and Number of Primary Branches

Varieties	Inoculation Status	Plant Height (cm)				Number of Primary Branches (count)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	79.26^{de}	88.47^{bcd}	90.13^{abc}	95.80^{ab}	4.6^{c-f}	5.2^{abc}	4.8^{bcd}	6.0^{a}
	Un-inoculated	70.33^{e}	92.93^{abc}	87.80^{bcd}	92.46^{abc}	4.1^{d-g}	5.7^{ab}	4.6^{cde}	4.8^{bcd}
Cheri	Inoculated	94.66^{ab}	96.0^{ab}	97.53^{ab}	100.40^{a}	3.2^{hi}	3.8^{e-h}	4.1^{d-g}	4.7^{cde}
	Un-inoculated	82.80^{cd}	91.80^{abc}	93.86^{ab}	91.66^{abc}	2.8^{i}	3.7^{f-i}	4.2^{def}	3.2^{ghi}
LSD (0.05)		10.97				0.93			
CV (%)		7.28				12.78			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

4.5. Effect of Bradyrhizobium Inoculation and P application rate on Nodulation of Soybean Varieties

4.5.1. Number of nodule plant^{-1}

For the variety Ketta, inoculated plants generally had a higher number of nodules per plant compared to un-inoculated plants across all levels of phosphorus application. The difference in the number of nodules between inoculated and un-inoculated plants was statistically significant at most phosphorus application levels. The highest number of nodules for Ketta was observed in the inoculated group 31.80 at 30 kg ha^{-1} phosphorus application (Fig.3), which is due to rhizobia inoculation and phosphorus application increases the number of nodule per plants by attributing nodule formation and nitrogen fixation of basic energy transfer of phosphorus. For the variety Cheri, a similar trend was observed with inoculated plants having a higher number of nodules compared to un-inoculated plants at most phosphorus application levels. The difference in the number of nodules between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The highest number of nodules for Cheri was observed in the inoculated group 25. 6 at 20 kg ha^{-1} phosphorus application.

The lowest number of nodules per plant (16.33) was recorded on the variety Cheri with no inoculation of rhizobia, and the control plot of P application (no application of P) (Fig.3), which showed about 94.73% decrease over the variety that produced the highest number of nodules.

Likewise the application of P fertilizer at the rates of 0, 50, 100 and 150 kg P_2O_5 ha^{-1} significantly increased number of nodules (Houngnandan *et al.*, 2020). Also an increased number of nodules per plant under the highest rate of phosphorus (30 kg P ha^{-1}) Rhizobium inoculation (Singh *et al.*, 2018). Phosphate application increased the activity of rhizobia, which might have intern increased the formation of root nodule. Plant tissue develops around the infected area, forming the nodule and site for the bacterial growth, which creates environment for the fixation of elemental nitrogen from the soil.

Correspondingly, the application of 46 kg ha^{-1} P_2O_5 and inoculation of Rhizobium japonicum significantly increased the number of nodules per plant by 240.7% and 123%, respectively (Tarekegn and Kibret, 2017). This result was in collaborate with the application of Bradyrhizobium japonicum strain USDA110 and 60 kg of P_2O_5 enhanced the number of nodule per plant (Houngnandan *et al.*, 2020).

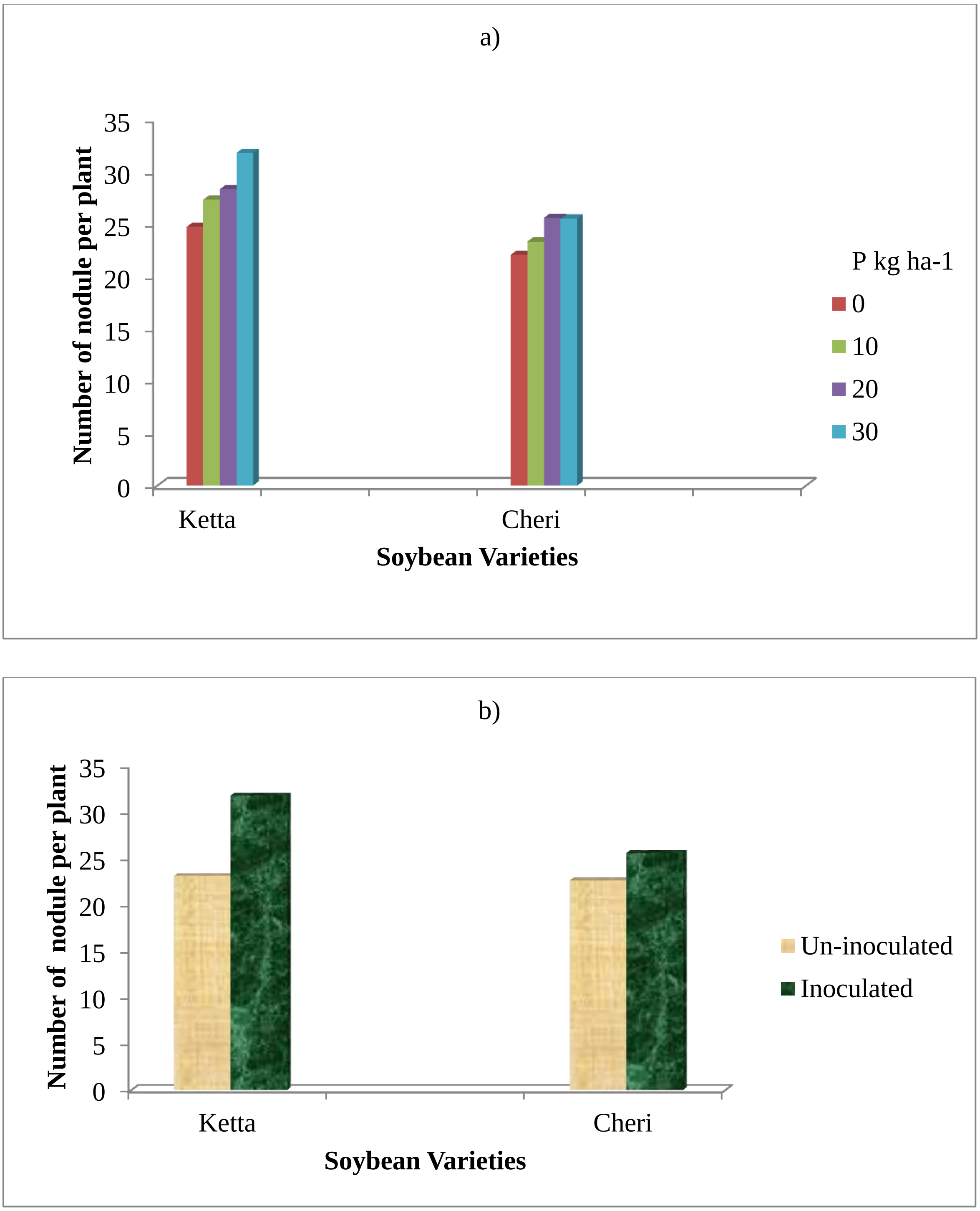
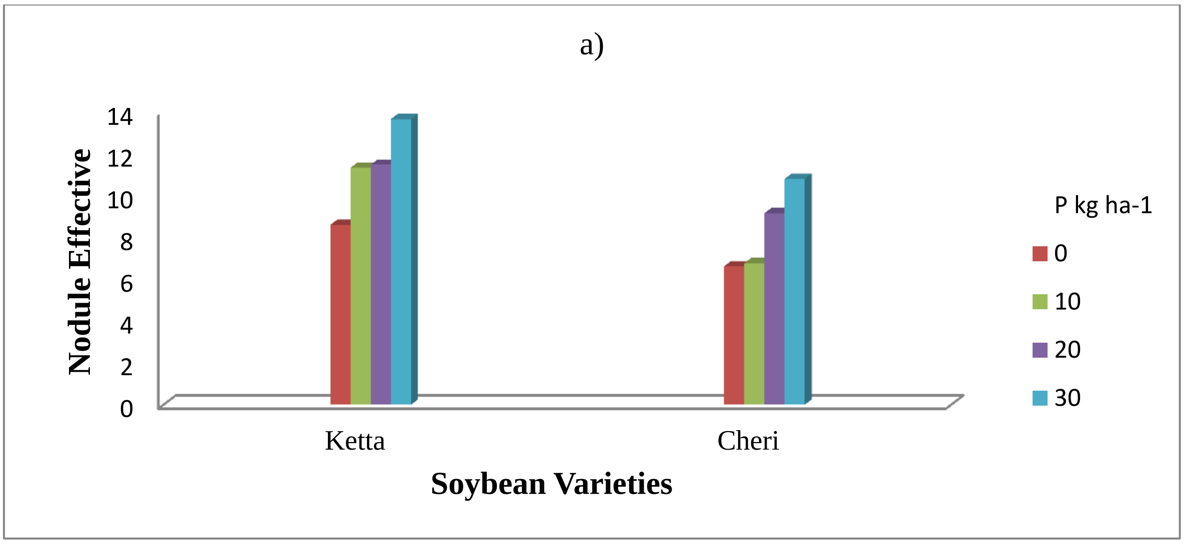


Figure 3. Interaction effects of; a) variety × phosphorus and b) variety × Bradyrhizobium inoculation on Number of nodule per plant.

4.5.2. Effective nodule

Nodule effectiveness refers to the efficiency of nodules in fixing nitrogen. Higher values indicate better nitrogen fixation. For both varieties, inoculated plants generally showed higher nodule effectiveness compared to un-inoculated plants at most levels of phosphorus application. The difference in nodule effectiveness between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The highest nodule effectiveness for both varieties was observed in the inoculated group 13.66 and 10.80 at 30 kg ha^{-1} phosphorus application respectively. Phosphorus application affected the effective nodule of soybean. It was found that P application at the rate of 30 kg P ha^{-1} significantly increased effective nodule of rhizobia inoculated soybean by 90.26, and 87.69% with inoculated respectively over the control plot of P application. The lowest number of effective nodules was produced by the variety Cheri (1.33) under un-inoculated and the control plot of P application conditions (Fig. 4). Nodules with deep dark red, slightly dark red and pink were considered effective and fixing nitrogen and typically of healthy and effective was due to presence of leghemoglobin protein responsible for oxygen binding (Kasper, 2019). In addition, other reported legume nodules having dark pink or red centers (due to leg hemoglobin presence) are an indication for effectiveness of the strain used and positively correlated with higher N_2 fixation (Meleta and Abera, 2019). This is due to compatibility between rhizobia inoculation and host plant. This is due to the deficiency of phosphorus and fixation of availability of P in the soil condition of the acidity (Billah *et al.*, 2019). Larger response to inoculation and higher number of nodules per plant in comparison to un-inoculated treatments in a field that has no soybean cropping history was reported by (Rahim *et al.*, 2016). This indicates suggested that inoculation does not always enhance nodulation. Improved soybean varieties (TGx 1448-2E) did not respond to inoculation in terms of nodule production in the Nigeria's moist savanna zone (Adjei-Nsiah *et al.,* 2019).

However, P rates and their interaction with inoculation did not significantly (P=0.25) affect the number of effective nodules. The non-responsiveness of the number of effective nodules due to P application might be described to the high P fixation of the soil. Besides, iron, which is deficient in alkaline soils, plays vital role in leghemoglobin formations, which render pink or red color to nodules.



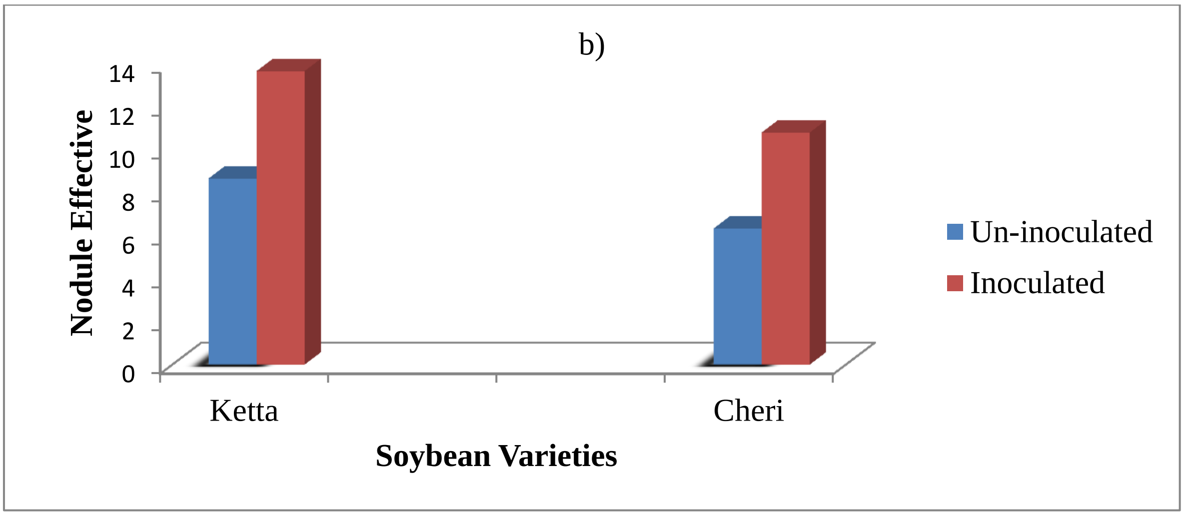


Figure 4. Interaction effects of; a) variety × phosphorus and b) variety × Bradyrhizobium inoculation on Effective nodule per plant.

4.5.3. Nodule fresh weight

For the variety Ketta, inoculated plants generally had higher nodule fresh weights compared to un-inoculated plants across different levels of phosphorus application. The difference in nodule fresh weight between inoculated and un-inoculated plants was statistically significant at most phosphorus application levels. The highest nodule fresh weight for Ketta was observed in the inoculated group 12.45 g at 10 kg ha^{-1} phosphorus application.

For the variety Cheri, a similar trend was observed with inoculated plants showing higher nodule fresh weights compared to un-inoculated plants at most phosphorus application levels. The difference in nodule fresh weight between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The highest nodule fresh weight for Cheri was observed in the inoculated group 12.35 g at 20 kg ha^{-1} phosphorus application, whereas the lowest nodule fresh weight of 5.54 g $plant^{-1}$ were found on variety Cheri under no inoculated and control plot of P application conditions. The variety that produced the highest nodule fresh weight showed more than 55.5% increase over the variety that produced the lowest nodule fresh weight (Table 8).

In line the number and fresh weight of nodules are commonly used as the criteria of effective complementary between macro and micro with the rate of atmospheric nitrogen fixation (Tarekegn and Kibret, 2017). Similarly, reported that a simple relationship a rises between nodule number and nodule fresh weight and they are indices of nitrogen fixation (Sanyal *et al.,* 2020).

4.5.4. Nodule dry weight

Similar to nodule fresh weight, inoculated plants generally exhibited higher nodule dry weights compared to un-inoculated plants for both varieties across different levels of phosphorus application. The difference in nodule dry weight between inoculated and un-inoculated plants was statistically significant at most phosphorus application levels. The highest nodule dry weight for both Ketta and Cheri was observed in the inoculated group 8.85 and 8.65 g at 30 kg ha^{-1} phosphorus application respectively, while, the lowest nodule dry weight per plant (3.17 g) was produced by the variety Cheri under no rhizobia inoculation and under control plot of P application (Table 8), which was about 179.17% of nodule dry weight reduction over the variety that produced the highest nodule dry weight. The reason might be due to the overall improvement in the performance of the plant in response to phosphorus fertilizer and inoculation, leading to better nodulation underlines phosphorus has on nodule development through its basic function of as an energy source. In soybean production, phosphorus and inoculation with the appropriate rhizobia strain have quite prominent effects on nodule number, dry weight and yield components. Similarly, a combination of 50 kg P_2O_5 ha^{-1} and STM3043 rhizobia strain gave the best nodule dry weight of 4.97 g $plant^{-1}$ (Zoundji *et al.*, 2015). In the present study, however, nodule dry weight ranged between 3.17-8.85 g; where Ketta variety produced the highest nodule dry weight with the application of 30 kg P ha^{-1} and inoculation of Rhizobia bacteria, which is high relative to what is reported by (Zoundji *et al.*, 2015). In agreement the phosphorus application levels with inoculation influence nodule dry weight (Tarekegn and Kibret, 2017). B. japonicum strains with P fertilizer increased the nodule dry weight

(Htwe *et al.*, 2018). Phosphorus application levels, without inoculation, did not influence nodule dry weight (Bekere and Hailemariam, 2012).

Table 8. Responses of two soybean varieties to rhizobia inoculation and rate of phosphorus application for nodule fresh and dry weight

Varieties	Inoculation Status	Nodule fresh weight (g)				Nodule dry weight (g)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	11.6^{cd}	12.45^{a}	11.88^{bc}	12.31^{ab}	8.70^{ab}	8.81^{ab}	8.67^{ab}	8.85^{a}
	Un-inoculated	6.1^{e}	11.71^{cd}	11.68^{cd}	11.65^{cd}	4.68^{c}	8.57^{b}	8.77^{ab}	8.63^{ab}
Cheri	Inoculated	11.3^{d}	11.37^{abc}	12.35^{ab}	12.31^{ab}	8.63^{ab}	8.63^{ab}	8.60^{ab}	8.65^{ab}
	Un-inoculated	5.54^{f}	11.97^{abc}	12.02^{abc}	11.23^{d}	3.17^{d}	8.60^{ab}	8.61^{ab}	8.60^{ab}
LSD (0.05)		0.53				0.25			
CV (%)		2.87				1.88			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

4.5.5. Taproot length

For the variety Ketta, inoculated plants generally had longer taproots compared to un-inoculated plants across different levels of phosphorus application. The difference in taproot length between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The longest taproot length for Ketta was observed in the inoculated group 25.66 cm at 30 kg ha^{-1} phosphorus application. For the variety Cheri, a similar trend was observed with inoculated plants, showing longer taproots compared to un-inoculated plants at most phosphorus application levels. The difference in taproot length between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The longest taproot length for Cheri was observed in the inoculated group 23.36 cm at 30 kg ha^{-1} phosphorus application, while the shortest taproot length of 19.66 cm was produced by the variety Cheri with the control of P application (Table 9). Increasing Phosphate fertilizer could be due to P treatment, which causes root cells to grow.

The highest taproot length of Cheri (23.36 cm) was recorded on un-inoculated rhizobia and 20 kg P ha^{-1} and the shortest taproot length (19.66 cm) of the same variety without inoculated rhizobia and control plot of P ha^{-1}. This is due to un-inoculated rhizobia strain around the infected roots hairs which is not nutrient availability for plants is deep taproot length for nutrient absorption and the inoculated rhizobia and phosphorus application is fixation of nitrogen and nutrient availability which is used for vegetative growth and developments rather than taproot length. There was a significant difference level of phosphate rate for taproot length in this study, and other studies reported that systems with large root surface length and density ensures P uptake efficiency, on soils of low P availability (Battini *et al.*, 2017). The average increase in root length by 41% as compared to un-inoculated control, due to rhizobia inoculation and phosphorus application (Dabesa and Tana, 2021a). Similarly, phosphate stimulates root growth, and it is associated with early crop maturity (Fathi and MEHDINIYA AFRA (2023).

4.5.6. Root volume

In terms of root volume, inoculated plants generally had higher root volumes compared to un-inoculated plants for both varieties across different levels of phosphorus application. The difference in root volume between inoculated and un-inoculated plants was statistically significant at most phosphorus application levels. The highest root volume for Ketta was observed in the inoculated group 61.0 cm^3 at 30 kg ha^{-1} phosphorus application.

Similarly, the highest root volume for Cheri was observed in the inoculated group 52.3 cm^3 at 30 kg ha^{-1} phosphorus application, while the lowest root volume of 22.33 cm^3 was produced by the variety Cheri with the inoculation of Rhizobium bacteria and at the control plot of P application. The variety that produced the highest root volume showed 63.39% increase over the variety that produced the lowest root volume. Phosphate application and inoculation of soybean increased root volume and root biomass, due to the increased rate of nitrogen fixation. Similarly, increasing P_2O_5 application up to 150 kg ha^{-1} increases root volume (Masood *et al.*, 2011). The application of 30 kg P_2O_5 ha^{-1} has increased the root volume by 63.39 and 36.79% under inoculated and un-inoculated conditions, respectively; while the application of 20 kg P_2O_5 ha^{-1} has increased root volume by 55.4 and 53.14 %, respectively and the application of 10 kg P_2O_5 ha^{-1} has increased root volume by 61.71% and 46.83% over the control plot of P application (Table 9).

Table 9. Responses of two soybean varieties to rhizobia inoculation and rate of phosphorus application for root volume and taproot length

Varieties	Inoculation Status	Tap root length (cm)				Root volume (cm^3)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	21.33^{def}	24.60^{ab}	24.20^{b}	25.66^{a}	41.66^{def}	58.3^{ab}	55.0^{abc}	61.0^{a}
	Un-inoculated	20.46^{efg}	21.80^{de}	20.43^{efg}	21.10^{def}	39.33^{ef}	40.0^{ef}	40.0^{ef}	35.3^{f}
Cheri	Inoculated	21.06^{defg}	21.40^{def}	21.73^{de}	23.36^{bc}	33.60^{fg}	50.0^{bcd}	52.0^{bc}	52.3^{bc}
	Un-inoculated	19.66^{g}	20.40^{efg}	22.16^{dc}	20.27^{fg}	22.33^{h}	42.0^{edf}	47.7^{cde}	25.7^{gh}
LSD (0.05)		1.41				8.48			
CV (%)		3.87				11.68			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

4.6. Effect of Bradyrhizobium Inoculation and P application rate on yield and yield components of Soybean Varieties

4.6.1. Number of pods plant^{-1}

For the variety Ketta, plants that were inoculated generally had a higher number of pods per plant compared to un-inoculated plants across different levels of phosphorus application. The number of pods per plant increased with increasing levels of phosphorus application for both inoculated and un-inoculated plants of variety Ketta. The difference in the number of pods per plant between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The highest number of pods per plant for Ketta was observed in the inoculated group 99.38 at 30 kg ha^{-1} phosphorus application. For the variety Cheri, a similar trend was observed with inoculated plants showing a higher number of pods per plant compared to un-inoculated plants at most phosphorus application levels. The number of pods per plant also increased with increasing levels of phosphorus application for both inoculated and un-inoculated plants of variety Cheri. The difference in the number of pods per plant between inoculated and un-inoculated plants was statistically significant at most P application levels. The highest number of pods per plant for Cheri was observed in the inoculated group 88.75 at 30 kg ha^{-1} phosphorus application, while the lowest number of pods per plant (38.63) was produced by the variety Cheri with un- inoculated and the control plot of P application, which showed about 157.26% of pod number decrease over the variety and amendment that produced the highest pod number (Table 10).

Phosphorus applications at the rate of 10, 20 and 30 kg P ha^{-1} increased number of pods per plant by 54.46, 60.36 and 61.12% respectively, over the unfertilized control. This result support with that the higher numbers of pods per plant were produced in response to higher doses of phosphorus (Aryal *et al.*, 2021). This result revealed increased number of pods per plant with increased rate of phosphorus application. This result is similar reported increased number of pods per plant in soybean following the application of P at the rate of 0, 10, 20 and 30 kg P ha^{-1} (Ikeogu and Nwofia, 2013).

One study that reported a similar result is effect of phosphorus application on soybean yield and quality. In this study, they found that increasing phosphorus application rates led to a higher number of pods per plant in soybean (Ferreira *et al.*, 2018). Similarly, significant increase in the number of pods $plant^{-1}$, due to the interaction effect of rhizobia strain IRJ 2180A with the application of 50 kg of P_2O_5 ha^{-1} over the control (Zoundji *et al*., 2015). In general, mean pod number $plant^{-1}$ enhanced due to the combined effect of rhizobia inoculation and phosphorus application.

4.6.2. Number of seeds pod^{-1}

For the variety Ketta, when inoculated, there is a clear trend of increasing number of pods per plant with increasing phosphorus application rates (0 kg P ha^{-1} to 30 kg P ha^{-1}). Similarly, the number of seeds per pod also increases with higher phosphorus application rates. The highest values are observed (2.98) at the highest phosphorus application rate of 30 kg P ha^{-1} For the variety Cheri, similar trends was observed with increasing phosphorus application rates leading to higher number of pods per plant and seeds per pod, especially when the plants was inoculated. Comparing the inoculated and un-inoculated plants, it is evident that inoculation generally results in higher numbers of pods per plant and seeds per pod across both varieties and phosphorus application rates. In terms of the number of seeds per pod, plants that were inoculated generally had a higher number of seeds per pod compared to un-inoculated plants for both varieties across different levels of phosphorus application. The number of seeds per pod increased with increasing levels of phosphorus application for both inoculated and un-inoculated plants of both varieties.

The difference in the number of seeds per pod between inoculated and un-inoculated plants was statistically significant at some phosphorus application levels. The lowest number of seeds per pod (1.95) under un-inoculated rhizobia and control plot of P application of Cheri variety (Table 10). The number of seeds per pods perceived as a significant constituent that directly contributes to the recovery of potential yield in leguminous crops, like soybean (Devi *et al.*, 2013). The number of seeds pod^{-1} significantly varied between genotypes. In agreement reported significant difference in number of seeds per pods after varying p rates (Alemu *et al.*, 2018).

Table 10. Responses of two soybean varieties to rhizobia inoculation and rate of phosphorus application for number of pods per plant and number of seed per pods

Varieties	Inoculation Status	Number of pods plant^{-1} (count)				Number of seeds pod^{-1} (count)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	59.00^{g}	88.73^{b}	97.47^{a}	99.38^{a}	2.45^{f}	2.84^{b}	2.93^{a}	2.98^{a}
	Un-inoculated	57.80^{g}	73.86^{e}	82.46^{cd}	86.60^{bc}	2.10^{i}	2.77^{cd}	2.83^{bc}	2.79^{bc}
Cheri	Inoculated	56.94^{g}	78.12^{de}	83.40^{c}	88.75^{b}	2.17^{h}	2.63^{e}	2.73^{d}	2.85^{b}
	Un-inoculated	38.63^{i}	46.70^{h}	50.12^{h}	63.60^{f}	1.95^{j}	2.20^{gh}	2.20^{gh}	2.24^{g}
LSD (0.05)		4.518				0.059			
CV (%)		3.76				1.4			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

4.6.3 .Grain yield

The data indicates that for the variety Ketta, the highest grain yield was observed 3.45 ton ha^{-1} at 30 kg ha^{-1} of phosphorus application for both inoculated and un-inoculated conditions. In general, inoculated plants tended to have higher grain yields compared to un-inoculated plants across different levels of phosphorus application. Variety Cheri also showed higher grain yields with increasing levels of phosphorus application, especially for the inoculated plants. The lowest grain yield was observed 0.33 ton ha^{-1} under un-inoculated rhizobia and control plot of P application of Cheri variety (Table 11). The grain yield had very highly significantly ($P<0.001$) affected by the three way interaction.

The highest grain yield was obtained by Ketta variety (3.45 ton ha^{-1}) and Cheri variety (2.57 ton ha^{-1}) under both rhizobia inoculation and application of 30 kg P ha^{-1} (Table 11). At the rate of 30 kg P ha^{-1} application, the yield of the highest yielding variety Ketta with rhizobia inoculation showed 64.35% increase over the un-inoculated control. Though, the difference in percentage increase was high, this finding supports grain yield can increase by 40-70%, when the proper rhizobia bacteria is inoculated (Gebremariam and Tesfay, 2021). The highest grain yield (3.45 ton ha^{-1}) obtained from study was moderate relative to the national average 2.43 ton ha^{-1} (CSA 2021/2022) and the productivity in the study area i.e., in Bedele zone, which is 2.07 ton ha^{-1} (2021/2022), which indicates that the production and productivity of soybean can be increased significantly through rhizobia inoculation and application of phosphorus.

The result is also in agreements the varietal difference in rice and soybean with rhizobia inoculation and phosphorus application, respectively (ADEDIRAN, 2019). Ketta variety showed grain yield increase of 38.7, 42.44 and 48.12 % at P application rates of 10, 20 and 30 kg P ha^{-1} respectively over the control plot of P application.

Similarly, Phosphorus applications at the rate of 22.5 and 45.0 kg P_2O_5 ha^{-1} increased grain yield by 33.9 and 35.4%, respectively, over the unfertilized control in Ghana (Davies, 2014). The seed yield of soybean increased in response to the application of phosphorus fertilizer at the rates of 20, 40 and 60 kg P_2O_5 ha^{-1} (Atnafu *et al.*, 2020).

In line with the combined application of rhizobia inoculation and p application resulted in 21% increased grain yield (Abbasi *et al.*, 2010). Adequate phosphorus application and rhizobia will lead to effective pod dry matter accumulation and subsequently to higher grain yield. Similarly, reported that p application with rhizobia inoculation significantly increased pod number, grain yield and dry matter yield, compared to un-inoculated treatment (Tarekegn and Kibret, 2017). The average grain yields recorded from the present study were lower, when compared to the yield of 7610 kg ha^{-1} obtained (Zoundji *et al.,* 2015). However, the yield obtained from this study were comparable with the average soybean yields (770-3380 kg ha^{-1}) reported (Zoundji *et al.,* 2015).

4.6.4. Hundred seed weight

The hundred-seed weight for both varieties generally increased with higher levels of phosphorus application. Inoculated plants tended to have higher hundred-seed weights compared to un-inoculated plants, especially at higher levels of phosphorus application.

Ketta variety had the highest hundred seed weight (14.63 g) under rhizobia inoculated and 30 kg P ha^{-1} application, followed by (14.54 g) under rhizobia inoculated 10 kg P ha^{-1} and (14.53 g) of the same soybean variety, while the lowest hundred seed weight (13.17 g) was recorded on Cheri variety under rhizobia un-inoculated and control plot of P application (Table 11).

The interaction effect of inoculation and P rates on hundred seeds weight was very highly significant increased ($P<0.0001$). This could be due to combined application of rhizobia and N_2 fixation which supplied by biological compounds that play major roles in photosynthesis which eventually increased seeds weight.

Generally, the results suggest that phosphorus application plays a significant role in enhancing grain yield and seed weight in soybean varieties, with inoculation showing a positive impact on plant performance. The data indicates the importance of phosphorus management and inoculation strategies in optimizing soybean production for better yields and seed quality. Interaction effect of the factors under study 50 (I x P) on 1000-seed weight was significantly reported (Ngalamu *et al.*, 2013). Also increasing P levels from 0 to 69 kg P_2O_5 ha^{-1} showed increase in thousand seeds weight, the highest thousand seeds weight (20.5 and 20.4 g) were scored at 23 and 69 kg P_2O_5 ha^{-1} application, respectively. Significant increase of thousand seeds weight by 5-18% due to P application from 20 to 80 kg P ha^{-1} over the control treatment (Fituma *et al.*, 2018).

The Ketta variety that produced the highest hundred seed weight showed hundred seed weight increase of 9.98% p application over the variety that produced the lowest seed weight. In agreement with this result, Significant difference among soybean varieties for hundred seed weight, in which the highest hundred seed weight was produced by the variety BFS 39 and the lowest hundred seed weight was recorded by the variety Roba (Imenu *et al.*, 2022).

Table 11. Responses of two soybean varieties to rhizobia inoculation and rate of phosphorus application for grain yield and hundred seed weight

Varieties	Inoculation Status	Grain Yield (ton ha^{-1})				Hundred (100) seed weight (g)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	0.36^{k}	2.92^{c}	3.11^{b}	3.45^{a}	13.49^{i}	14.54^{b}	14.53^{b}	14.63^{a}
	Un-inoculated	0.33^{k}	1.43^{hi}	1.97^{g}	2.19^{f}	13.26^{j}	13.52^{ghi}	13.57^{gh}	13.66^{f}
Cheri	Inoculated	0.35^{k}	2.15^{f}	2.39^{e}	2.57^{d}	13.59^{g}	14.15^{e}	14.27^{d}	14.44^{c}
	Un-inoculated	0.96^{j}	1.52^{h}	1.37^{i}	1.41^{hi}	13.17^{k}	13.47^{i}	13.45^{i}	13.51^{hi}
LSD (0.05)		0.14				0.076			
CV (%)		4.76				0.33			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

4.6.5. Above ground biomass

The data shows that for the variety Ketta, the highest above ground biomass was observed 14.34 ton ha^{-1} at 30 kg ha^{-1} of phosphorus application for both inoculated and un-inoculated conditions. In general, inoculated plants tended to produce higher above ground biomass compared to un-inoculated plants across different levels of phosphorus application. Variety Cheri also displayed higher the highest above ground biomass with increasing levels of phosphorus application, especially for the inoculated plants; while the lowest above ground biomass yield (6.14 ton ha^{-1}) was recorded on variety Cheri under un-inoculated and the control main plots (no phosphorus), which was lower by about 54.18% over the variety that produced above ground biomass yield. The phosphorus application rate had very highly significantly ($P<0.0001$) affected above ground biomass of soybean. Phosphorus application of 10, 20 and 30 kg P ha^{-1} increased above ground biomass yields by 31.57, 33.75 and 37.59%, respectively, over the control plots of Ketta variety (Table 12). The application of 25 and 35 kg P ha^{-1} increased the soybean above ground biomass yields by 54 and 70%, respectively, over the control plots (Phiri *et al.*, 2016).

The above ground biomass increased, due to the three way interaction effects of 30 kg P ha^{-1} application and inoculated rhizobia strain of Ketta variety. This might be due to the development of root system that might have increased water and nutrient uptake, and consequently, increased photosynthesis, and production of photosynthetic material that might have resulted in increased biological yield. In line phosphate application and inoculation of B .Japonicum to legumes, as soybean increased plant biomass, due to increased rate of nitrogen fixation (Houngnandan *et al.,* 2020).

4.6.6. Harvest index

The harvest index for both varieties generally increased with higher levels of phosphorus application. Inoculated plants tended to have a higher harvest index compared to un-inoculated plants, especially at higher levels of phosphorus application.

Ketta and Cheri varieties resulted in significantly higher harvest index (24%) under rhizobia inoculated and 30 kg ha^{-1} P application and lowest values of harvest index (15.66%) was obtained under un-inoculated and control plot of P application of Cheri variety (Table 12). Phosphate fertilizer application increases the number of nodule and size and grain formation due to increased nitrogen fixation. This can be explained by a good symbiotic activity induced by the strain of rhizobia and the host plant. The highest harvest index implies the higher partitioning of dry matter in grain. Whereas, the lowest harvest index (15.66%) gained from unfertilized plot.

Generally, the results suggest that phosphorus application has a significant impact on the above ground biomass production and harvest index of soybean varieties. Inoculation also plays a role in enhancing above ground biomass and harvest index values. These findings indicate the importance of phosphorus management and inoculation strategies in optimizing soybean production for better biomass yield and harvest index percentages.

In line the values of harvest index showed an increasing trend in the harvest index values with application of phosphorus Rhizobia inoculation is known to increase the yields of soy bean of harvest index by way of increasing the nodulation and biomass of root and shoot (Houngnandan *et al.,* 2020). In agreement inoculation of SB6 B1 and legume fix recorded significantly higher harvest indices of 54 and 53% over un-inoculated plot (Fituma, 2015). Soybean seeds inoculation increased the nodule number per plant and thus increasing harvest index by 3.36% (Tekola *et al.*, 2018).

Table 12. Response of two soybean varieties to rhizobia inoculation and rate of phosphorus application for above ground biomass and harvesting index

Varieties	Inoculation Status	Above ground biomass (ton ha^{-1})				Harvest index (%)			
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})			
		0	10	20	30	0	10	20	30
Ketta	Inoculated	8.95^{fg}	13.8^{b}	13.51^{b}	14.34^{a}	20.0^{dc}	22.33^{ab}	23.00^{ab}	24.0^{a}
	Un-inoculated	7.6j^{k}	8.64^{gh}	9.88^{e}	9.96^{de}	18.3^{de}	16.66^{ef}	20.00^{cd}	22.0^{abc}
Cheri	Inoculated	7.73^{ij}	9.27^{f}	10.45^{dc}	10.76^{c}	21.0^{bc}	23.66^{a}	22.66^{ba}	24.0^{a}
	Un-inoculated	6.14^{l}	7.13^{k}	7.7^{j}	8.25^{ij}	15.66^{f}	21.33^{bc}	18.00^{de}	17.0^{ef}
LSD(0.05)		0.54				0.02			
CV (%)		3.4				6.14			

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

3.6.7. Phosphorus uptake efficiency

For the variety Ketta, the phosphorus uptake efficiency increased with higher phosphorus application rates for both inoculated and un-inoculated conditions. The highest phosphorus uptake efficiency was observed 1.53 kg ha^{-1} at 30 kg ha^{-1} P for the inoculated treatment. For the variety Cheri, a similar trend was observed with an increase in phosphorus uptake efficiency with higher phosphorus application rates for both inoculated and un-inoculated conditions. The highest phosphorus uptake efficiency was also observed 1.23 kg ha^{-1} at 30 kg ha^{-1} P for the inoculated treatment (Table 13). The lowest GUP of 0.62 kg ha^{-1} was produced under un-inoculated and the control main plot (no phosphorus) by the variety Cheri. The increased PUE due to added supply of nutrients might enhance absorption of water and nutrients. In agreement with the findings, application of 46 kg P ha^{-1} and inoculation with B. Japonicum increased P uptake by 18.78% compared to the un-inoculated treatment (Tarekegn and Kibret, 2017). Increased in P content of the seed and P uptakes in soybean, in response to the combined application of B. japonicum inoculation reported by (Tarekegn and Kibret, 2017).

In addition, rhizobia inoculation improved grain phosphorus uptake, due to rhizobia inoculation, which might be attributed to the fact that some isolates of rhizobium have the ability to solubilize precipitated P components and thereby, increase P uptake in plants (Dabesa and Tana, 2021a). The result of this study, clearly demonstrates that Rhizobium inoculation improves the P uptake efficiency of soybean, which might also contributes ton-increased productivity of the crop.

Significant differences was noted in PUE among the varieties between the inoculated and un-inoculated treatments, when the rate of P application increased to 10, 20 and 30 kg P ha^{-1}, showing that Rhizobia inoculation enhanced the GPU efficiency of the responsive varieties, indicating the importance of combined application of Rhizobia inoculation together with P fertilization for better response. Higher rate of P application 30 kg ha^{-1} resulted in higher phosphorus uptake efficiency. This indicates that increasing the rate of phosphorus application to the optimum level increases phosphorus uptake efficiency. Similarly, reported that P uptake by soybean was increased with increasing levels of phosphorus (Devi *et al.*, 2012).

4.6.8 Agronomic efficiency

The agronomic efficiency for both varieties and inoculation statuses showed varying trends with phosphorus application rates. For variety Ketta, the agronomic efficiency was highest 24.92 kg kg^{-1} at 10 kg ha^{-1} P for the inoculated treatment, while for variety Cheri, the highest agronomic efficiency was observed 11.35 at 10 kg ha^{-1} P for the inoculated treatment (Table 13).

The lowest agronomic efficiency (3.02 kg kg^{-1}) was obtained on Cheri variety under un-inoculated and application of 30 kg ha^{-1} P conditions. Comparison between Inoculated and Un-inoculated Treatments: In general, inoculated treatments showed higher phosphorus uptake efficiency and agronomic efficiency compared to un-inoculated treatments for both varieties across different phosphorus application rates. The efficiency of applied phosphorus in the soil reduces, mainly due to soil erosion, leaching and gaseous losses. The utilization of nutrient decreases, when increasing the rate of nutrient application by the law of limiting factors (Atkinson *et al.*, 2010).

This finding is in line phosphorus agronomic efficiency decrease in un-inoculated plots, but increased in the inoculated plots (Adeyemi *et al.*, 2021). The efficiency of the applied P in this study was within the range of 31.27-3.02 kg kg^{-1} at the rates of 10 to 30 kg P ha^{-1} application, respectively (Table 13). This is lower than the one reported declining trend of agronomic efficiency on common bean from 69.8 to 9.3 kg kg^{-1} (Dejene *et al.*, 2016) when the rates of P increased from 10 to 60 kg P ha^{-1}. With the corresponding application of single super phosphate and inoculation, increased phosphorus uptake efficiency and yield with phosphorus application and rhizobia inoculation (Aziz *et al.*, 2016).

Under tropical conditions, the efficiency of applied nutrient has been estimated to be 10-30% for phosphorus (Fageria *et al.*, 2013). Estimates of agronomic efficiency showed that the lower level of P relatively responded better to grain yield, which is in agreement with (Qiao *et al.*, 2022) who reported that small amount of applied fertilizer optimized nutrient uptake efficiency.

Table 13. Response of two soybean varieties to Rhizobia inoculation and rate of phosphorus application for phosphorus uptake efficiency and agronomic efficiency

Varieties	Inoculation Status	Phosphorus uptake efficiency (kg ha^{-1})				Agronomic efficiency (kg kg^{-1})		
		Phosphorus application (kg ha^{-1})				Phosphorus application (kg ha^{-1})		
		0	10	20	30	10	20	30
Ketta	Inoculated	0.90^{gh}	1.34^{b}	1.40^{b}	1.53^{a}	24.92^{a}	14.19^{b}	11.82^{c}
	Un-inoculated	0.77^{ij}	0.87^{h}	1.01^{ef}	1.03^{de}	6.98^{de}	6.15^{e}	5.58^{ef}
Cheri	Inoculated	0.79^{ij}	0.95^{fg}	1.09^{cd}	1.23^{c}	11.35^{c}	8.13^{d}	6.61^{e}
	Un-inoculated	0.62^{k}	0.73^{j}	0.77^{ij}	0.86^{h}	11.18^{c}	4.24^{fg}	3.02^{g}
LSD (0.05)		0.06				1.41		
CV (%)		3.73				11.44		

Where, CV: Coefficient of variation, LSD: Least significant difference at 5% level of significance, Means in the columns and rows followed by the same letter are not significantly different at 5% level of significance.

4.7. Pearson Correlation of Phenology, Growth, Root and Nodulations with Yield and Yield Components of Soybean

Flowering days was significantly ($P<0.0001$) a strong positive correlation with Days to Physiological Maturity at ($r=0.83$), indicating that plants that flower earlier also tend to reach physiological maturity earlier. Similarly, reported that the significant associations of Soybean flowering days with its growth components (Ghodrati *et al.*, 2013).

Results obtained in this study on rhizobia inoculated and phosphorus fertilizer application clearly showed that the remarkable increase in Flowering days and Date of Maturity, and strongly to increase in Physiological maturity of soybean.

Similarly, reported that the significant associations of Soybean Leaf area with Flowering days (Bianchi *et al.*, 2020). Results obtained in this study on rhizobia inoculated and phosphorus fertilizer application clearly showed that the remarkable increase in Leaf Area and Flowering Days, and moderated to increase in Leaf Area of soybean. Nodule Fresh Weight and Nodule Dry Weight have strong positive correlations with each other (r=0.97), suggesting that plants with heavier fresh nodules also tend to have heavier dry nodules. Similarly, reported that the significant associations of Soybean Nodule Fresh Weight and Nodule Dry Weight Kosev and Vasileva (2021). Results obtained in this study on rhizobia inoculated and phosphorus fertilizer application showed that the increase in Nodule Fresh Weight and Nodule Dry Weight, and highly increase in Nodule Dry Weight of soybean. Grain Yield was a strong positive correlation with Aboveground biomass at (r=0.96), indicating that higher grain yield was associated with higher dry biomass production.

Similarly, reported that the significant associations of faba bean Aboveground biomass and Grain Yield (Gedamu *et al.,* 2021). Results obtained in this study on relationship between grain yield and yield components of the faba bean genotypes at various growth stages.

Harvesting index shows a moderate positive correlation with grain yield (r=0.80), suggesting that a higher harvesting index is associated with higher grain yield. Similarly, reported that the significant associations of soybean harvesting index and grain yield (Lopez *et al.,* 2021). Results obtained in this study on genetic relationships among physiological processes, phenology, and grain yield offer an insight into the development of new cultivars in soybean. PUE (Phosphorus use efficiency) has a very strong positive correlation with AE (Agronomic efficiency) at (r=0.99), suggesting an almost perfect positive relationship between these two variables. Similarly, reported that the significant associations of Soybean Phosphorus use efficiency and Agronomic efficiency (Wang *et al.,* 2010). Results obtained in this study on Genetic improvement for phosphorus efficiency in soybean (Table 14).

Table 14 Pearson correlations of Phenology, nodulations, growth traits with the same yield and yield components

FD	DM	LA	PH	NPB	NPP	ENPP	NFW	NDW	NPP	NSPP	HSW	AGB	GY	HI	AE
FD															
DM	0.83**														
LA	0.58**	0.58**													
PH	0.45*	0.40*	0.56**												
NPB	-0.40*	-0.61*	-0.19NS	0.03NS											
NPP	-	-0.33*	0.11NS	0.42*	0.68**										
ENPP	0.05NS	-0.32*	0.09NS	0.40*	0.65**	0.95**									
NFW	0.42*	0.05NS	0.37*	0.61**	0.40*	0.73**	0.71**								
NDW	0.38*	-0.02NS	0.31*	0.52**	0.39*	0.70**	0.68**	0.97**							
NPP	-0.16NS	-0.43*	-	0.35*	0.64**	0.80**	0.81**	0.55**	0.64**						
NSPP	-0.18NS	-0.46*	0.02NS	0.35*	0.71**	0.83**	0.81**	0.64**	0.65**	0.94**					
HSW	0.19NS	-0.07NS	0.20NS	0.42*	0.48*	0.80**	0.83**	0.57**	0.80**	0.84**	0.78**				
AGB	-0.13NS	-0.43*	-0.08NS	0.25*	0.63**	0.86**	0.88**	0.53**	0.73**	0.90**	0.86**	0.90**			
GY	-0.05NS	-0.30*	-0.02NS	0.30*	0.56**	0.84**	0.87**	0.55**	0.76**	0.89**	0.84**	0.94**	0.96**		
HI	0.32*	-0.01NS	0.13NS	0.34*	0.33*	0.62**	0.64**	0.54**	0.65**	0.67**	0.62**	0.77**	0.64**	0.81**	
AE	0.02NS	-0.2NS	0.08NS	0.23NS	0.44*	0.62**	0.60**	0.49*	0.66**	0.58**	0.60**	0.77**	0.70**	0.70**	0.69**

Where, FD: Flowering Days, DFM : Days to physiological maturity , LA: Leaf area, PH: Plant height, , NPB:, Number of primary branch, NPP: Nodule per plant ENPP: Effective Nodule per plant, NFW : Nodule fresh weight, NDW: Nodule dry weight, TRL: Tap root length, RV: Root volume, NPP: Number of pods/plant, NSP: Number of seeds /pod, HSW: Hundred(100) seed weight, DBM; AGB: Aboveground biomass, GY: Grain yield, HI: Harvesting Index , PUE: Phosphorus use efficiency, AE: Agronomic efficiency, *: Correlation significant at 0.05 level, and **:Correlation highly significant at 0.01 level.

4.8. Partial Budget Analysis

The partial budget analysis was used to identify treatments with the optimum return for the farmer's investment. Variety V_1 without Rhizobium and rate P_2 ($V_1R_2P_2$) resulted in a grain yield of 1433.33 kg ha^{-1}, an adjusted yield of 1297.51 kg ha^{-1}, and a net benefit of 43254.99. The Marginal Rate of Return (MRR) was 623.06%, indicating a high return on investment for this treatment combination. Ketta Variety with Rhizobium and 30 kg P ha^{-1} ($V_1R_1P_4$) had the highest grain yield of 3451.24 kg ha^{-1}, generating a net benefit of 113231.2ETB. The MRR for this treatment was 541.6%, showing a very profitable outcome. Ketta Variety with Rhizobium and 10 kg P ha^{-1} ($V_1R_1P_2$) also showed significant results with a grain yield of 2924.67 kg ha^{-1} and a net benefit of 97786.74. The MRR for this treatment was 2916.02%, indicating a high return on investment (Table 15).

The highest gross farm gate benefit 113231.2 ETB ha^{-1} was gained from yield obtained at combined effect of Ketta variety inoculated rhizobia and 30 kg P ha^{-1} and the second and third gross benefit 102650.7, 97786.74ETB were obtained from the interaction effect of Ketta variety of with inoculated, 20 and 10 kg P ha^{-1} application respectively.

Generally, the results suggest that specific treatment combinations can significantly impact crop yield and profitability. Varieties, Rhizobium inoculation, and P levels play a crucial role in determining the success of the treatments in terms of economic returns (Faye *et al.*, 2020).

Table 15. Partial budget analysis for the two soybean varieties to rhizobia inoculation and rate of phosphorus application at different yield levels,

Treatment	Varieties rate kg ha^{-1}	Rhizobium rate kg ha^{-1}	P_2O_5 rate kg ha^{-1}	Grain Yield kg ha^{-1}	Adjusted Yield	Growth benefit	Total variable cost	Net benefit	MRR (%)
$V_1R_2P_1$	2400	0	0	998.22	898.40	33016.20	2400.0	30616.20	0.00
$V^1R_2P_2$	2400	0	50	1433.33	1297.51	47683.49	4428.50	43254.99	623.1
$V_1R_2P_3$	2400	0	100	1976.27	1840.45	67636.54	6382.0	61254.54	921.4
$V_1R_2P_4$	2400	0	150	2198.79	2062.97	75814.15	8335.50	67478.65	318.6
$V_1R_1P_1$	2400	200	0	1093.70	984.33	36174.13	2675.0	33499.13	600.3
$V_1R_1P_2$	2400	200	50	2924.67	2788.85	102490.20	4703.50	97786.74	3169.2
$V_1R_1P_3$	2400	200	100	3110.18	2974.36	109307.70	6657.0	102650.70	249.0
$V_1R_1P_4$	2400	200	150	3451.24	3315.42	121841.7	8610.50	113231.20	541.6
$V_2R_2P_1$	2400	0	0	963.33	827.51	30410.99	2400.0	28010.99	1372.2
$V_2R_2P_2$	2400	0	50	1519.31	1383.49	50843.26	4428.50	46414.76	907.3
$V_2R_2P_3$	2400	0	100	1377.19	1241.37	45620.35	6382.0	39238.35	D
$V_2R_2P_4$	2400	0	150	1412.88	1277.06	46931.96	8335.50	38596.46	D
$V_2R_1P_1$	2400	200	0	1044.24	939.82	34538.38	2675.0	31863.38	118.9
$V_2R_1P_2$	2400	200	50	2151.48	2015.66	74075.51	4703.50	69372.01	1849.1
$V_2R_1P_3$	2400	200	100	2397.12	2261.30	83102.78	6657.0	76445.78	362.1
$V_2R_1P_4$	2400	200	150	2574.07	2438.25	89605.69	8610.50	80995.19	232.9

Variety Price =40 birr kg ha^{-1}, Rhizobia =200 Birr $sachet^{-1}$, Phosphorus (P_2O_5) = 39.07 birr kg ha^{-1} and Grain yield=36.75 birr kg^{-1}, Rhizobium application = 75 Birr ha^{-1}, P_2O_5 application = 75 Birr ha^{-1}.

5. SUMMURARY AND CONCLUSSION

Soybean (*Glycine max* L.) farming in Ethiopia holds promise for enhancing food security and rural livelihoods, but nutrient deficiencies, particularly phosphorus, and soil acid are limiting factors. Nitisols in southwestern Ethiopia, characterized by high clay content and fertility potential, require specific interventions to improve soybean productivity. The symbiotic relationship between soybean plants and rhizobia bacteria plays a crucial role in nitrogen fixation, but the effective of rhizobia strains varies based on soil type and environmental conditions. The combined application of phosphorus fertilizer and compatible rhizobia strains can potentially enhance soybean growth and yield in Nitisols.

The study was conducted at Bedele district, Southwest Ethiopia with the objectives of determining the effects of P fertilizer rates on growth, nodulation and yield of soybean varieties, and grain yield of soybean, and to identifying economically feasible treatment(s) that can maximize the productivity. The treatments were laid out in a RCBD with three replications. The treatments included: rhizobia inoculation (MAR-1495 strains) and without inoculated as a control, soybean varieties Ketta (V_1) and Cheri (V_2) and phosphorus level (0, 10, 20 and 30 kg P ha^{-1}) as rates of fertilizers.

The results of highlight of this study indicated that: the physical and chemical properties of soil were analyzed before planting and after harvest. After harvest the available phosphorus and total nitrogen indicated a minor increase from initial soil analysis. This means available phosphorus from 0.5 to 0.82 mg $kg-^{1}$ and total nitrogen from 0.12 to 0.28% before and after respectively.

The results of this study indicated that the combined application of rhizobia strain with phosphate fertilizer resulted in highly significant and significant improvement in the studied traits i.e. flowering days, root volume, number of nodules per plant, number of pods per plant, phosphorus use efficiency, agronomic efficiency, grain yields, number of effective nodule, nodule fresh weight, nodule dry weight, days of maturity, number of seeds per pods and above ground biomass of soybean respectively. These improvements have resulted in increased grain yield and yield related parameters of soybean grown on the Nitisol of study area. The combination of inoculated rhizobia and phosphorus fertilizer application gave significantly the highest Plant height (100.40 cm), The highest leaf area (112.79 cm^2) number of Nodule per plant (31.80), The highest nodule fresh weight (12.45 g), nodule dry weight (8.85 g $plant^{-1}$), The longest taproot length (25.66 cm), The highest root volume (61.10 cm^3), grain yield (3.45 ton ha^{-1}), the highest hundred seed weight

(14.63 g), the highest above ground biomass (14.34 ton ha^{-1}), and grain phosphorus uptake (1.53 kg ha^{-1}), the highest agronomic efficiency (24.92 kg $kg^{-1)}$ were recorded from the interaction of inoculated rhizobia and 10 kg P ha^{-1} of Ketta variety. Phosphorus fertilizer application of 30 kg P ha^{-1} with inoculated rhizobia were resulted in higher production and recommended for further evaluation. In conclusion on the combined application of rhizobia inoculation and 30 kg P ha^{-1} gave better nodulation and yield than the rest of the treatment and Ketta variety was tends better responds to growth parameters, nodulation and yield components on plant height, number of nodule and grain yields. Therefore, use of rhizobia strain and 30 kg P ha^{-1} increase nodulation, grain yield (3.45 ton ha^{-1}) and phosphorus uptake of soybean in the study area is recommended. The application of inoculated rhizobia and 30 kg P ha^{-1} produced the highest net benefit 113231.2ETB ha^{-1}. The highest marginal rate of return (541.6%) was obtained from yield at inoculated rhizobia and 30 kg P ha^{-1} of Ketta soybean variety was the most profitable treatment. It has the highest return to the money invested in its production. However, the experiment was conducted for one cropping season and a single location. It is realistic to repeat similar experiment across wider ranges of agro ecology to give further recommendation. Furthermore, evaluating different types of effective and compatible rhizobia strain along with different source of phosphate to increase phosphorus utilization efficiency and grain yield of soybean should require further investigation in the future.

Therefore, the result should be verified for practical recommendation to be enhancing soybean production in the study region and Future research and agricultural practices should focus on identifying optimal treatment combinations to maximize soybean productivity in specific soil types and environmental conditions in region.

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7. APENDEX

Table 1. Monthly rainfall (mm) and maximum and minimum temperature of Buno Bedele
Tmin: Minimum temperature, Tmax: Maximum temperature and RF: Rainfall.

	Meteorological data of 2022			Meteorological data of 2023		
Months	Tmin(^{0}c)	Tmax(^{0}C)	RF (mm)	Tmin(^{0}c)	Tmax(^{0}C)	RF (mm)
January	12.40	27.00	23.30	12.40	27.00	24.00
February	13.10	28.80	3.50	11.00	24.00	3.50
March	14.80	29.80	25.90	12.00	26.00	23.00
April	14.60	28.50	160.80	13.00	28.50	150.00
May	14.00	26.70	218.50	14.00	26.00	200.00
June	12.70	23.80	404.90	12.70	20.00	380.00
July	11.20	21.40	356.80	11.20	19.00	345.00
August	10.90	21.30	325.70	10.90	20.00	320.00
September	12.60	24.30	356.60	11.00	22.00	340.00
October	11.60	25.00	239.90	12.00	25.00	380.00
November	12.20	25.80	53.20	11.00	23.00	46.00
December	12.10	26.20	16.80	12.10	24.00	12.00
Average	12.68	25.72		11.94	23.71	

Source: Ethiopia Agrometeology institute Bedele metrology first class station in 2022 and 2023

Table 2. Mean square of ANOVA for selected soil chemical properties as affected by different levels of P fertilizer rate, Rhizobium inoculation and Soybean Varieties after Soybean harvest

		Mean Square				
Source of Variation	DF	Soil pH (H_20)	Organic carbon (%)	Total Nitrogen (%)	Available Phosphorus (mg kg^{-1})	Cation Exchange Capacity (cmol $(_+)$ kg^{-1})
Block	2	-	-	-	-	-
P (Phosphorus)	3	0.06960764**	3.68859097**	0.02692431**	0.42561875**	228.267500**
Rh (Rhizobium)	1	0.00926377**	0.96252682**	0.00825029**	0.10932264*	21.739317**
V (varieties)	1	0.01576875**	11.61316875**	0.08926875**	0.052666875*	1897.567500**
V*Rh	1	-	0.54302554*	0.00409822**	0.2659545*	26.638410**
P*V	3	0.00327843**	0.25456224*	0.00172891*	-	44.524643**
P*Rh	3	0.00240263**	0.34928781**	0.00248331**	0.01935555*	33.044704**
V*P*Rh	3	0.000077^{ns}	-	-	0.01^{ns}	-
Error	30	0.0012500	0.02869	0.0002	0.0060	0.08600

Where, V*Rh: Variety with Rhizobium, P*V: phosphorus with variety, P*Rh: phosphorus with rhizobium. V*P*Rh: variety, phosphorus with rhizobium, *, **: Significant at 5% and 1%, respectively. DF: Degree of freedom and ns: non significance.

Table 3. Mean squares of ANOVA for soybean phonological, Growth and nodulation parameters as affected by different levels of P fertilizer rate, Varieties and Rhizobium inoculation

	Mean squares												
SV	DF	FD	DM	LA	LAI	PH	NPB	NNPP	NENPP	NFW	NDW	TRL	RV
Block	2	0.27^{ns}	2.27^{ns}	17.73^{ns}	28.70^{ns}	28.70^{ns}	1.63^{ns}	0.58^{ns}	0.50^{ns}	0.12^{ns}	0.04^{ns}	0.11^{ns}	3.77^{ns}
P	3	9.19^{ns}	72.40**	349.86**	417.52**	417.52*	2.56**	74.46**	44.73**	33.25**	16.84**	9.68**	379.69**
Rh	1	236.33**	24.54*	282.35^{ns}	152.41^{ns}	152.41^{ns}	1.56*	173.23**	145.38**	23.36**	11.12**	47.78**	2272.12**
V	1	918.75**	12707.5**	2785.11**	497.94*	497.94**	19.25**	99.18**	67.59**	0.09^{ns}	0.91^{ns}	17.02**	379.67*
V*Rh	1	56.83*	91.69**	410.98*	153.24^{ns}	153.24^{ns}	-	-	-	1.86^{ns}	1.98^{ns}	3.41^{ns}	-
P*V	3	23.08*	-	166.85^{ns}	82.10^{ns}	82.10^{ns}	0.56^{ns}	0.15^{ns}	-	0.25^{ns}	0.36^{ns}	0.90^{ns}	114.78*
P*Rh	3	24.60**	75.48**	39.74^{ns}	59.49^{ns}	59.48^{ns}	1.52*	31.93**	17.12**	17.90**	14.66**	6.62*	273.21**
V*P*Rh	3	10.17*	-	210.53^{ns}	33.46^{ns}	33.46^{ns}	0.016^{ns}	0.36^{ns}	2.35^{ns}	-	0.08^{ns}	4.79*	56.87^{ns}
Error	30	3.28	2.73	87.89	42.35	42.35	0.33	1.87	1.64	0.78	0.42	0.74	26.13

Where, *, **: Significant at 5% and 1%, respectively. DF: Degree of freedom, FD: Days to 50% flowering (days), DM: Days to 90% physiological maturity (days), LA: Leaf Area (cm^2), PH: Plant height (cm), NPB: Number of primary branch per plant (count), NNPP: Number of nodules per plant (count), NENPP: Number of effective nodules per plant (count), NFW: Nodule Fresh Weight (g), NDW: Nodule dry weight (g), TRL: Tap Root Length (cm), RV: Root volume (cm^3), ns: non-significant.

Table 4. Mean squares of ANOVA for soybean yield components and seed yield as affected by different levels of P fertilizer rate, Varieties and Rhizobium inoculation

	Mean Square								
Source of variation	DF	NPP	NSPP	HSW	AGB	GY	HI	PUE	AE
Block	2	1.00^{ns}	0.003^{ns}	0.002^{ns}	0.064^{ns}	0.003^{ns}	-	-	1.37^{ns}
P (Phosphorus)	3	2253.29**	0.78**	1.14**	26.40**	9.17**	0.002**	0.328^{ns}	267.23**
Rh (Rhizobium)	1	3767.79**	0.91**	5.98**	86.71**	4.96**	0.02**	1.005**	250.59**
V (varieties)	1	3625.29**	1.39**	0.26**	64.40**	1.73**	-	0.686**	121.69**
V*Rh	1	908.49**	0.30**	-	-	-	0.001^{ns}	-	54.95*
P*V	3	72.00*	0.02^{ns}	0.056**	0.168^{ns}	0.88**	0.002^{ns}	0.004^{ns}	27.01*
P*Rh	3	347.54**	0.09**	0.507**	6.52**	2.23**	-	0.078**	57.01**
V*P*Rh	3	-	-	0.037*	1.80*	0.054*	-	0.023*	65.24**
Error	30	9.51	0.004	0.004	0.19	0.009	0.0001	0.002	4.09

Where, *, **: Significant at 5% and 1%, respectively. DF: Degree of freedom, NPP: Number of pods per plant (count), NSP: Number of seed per pod (count), HSW: Hundred seed weight (g), GY: Grain yield (ton ha^{-1}), AGB: Above ground biomass (ton ha^{-1}), HI: Harvest index (%), PUE: Phosphorus Uptake Efficiency (kg ha^{-1}), AE: agronomic Efficiency (kg kg^{-1}), ns= non-significant.

Photos capture during experiment was done


Figure 1. Soybean vegetative growth


Figure 2. Soybean data collecting time


Figure 3. Soybean pod setting time


Figure 4. Soybean nodule data collecting Time


Figure 5. Soybean Nodule data collected


Figure 6. Identify Nodule effectiveness


Figure 7. Measuring root Volume (cm^3)


Figure 8. Measuring aboveground biomass (g)


Figure 9. Sample prepared for Plant phosphorus Uptake


Figure 10. Soybean grain and straw Ash


Figure K. Taking soil sample after harvested


Figure L. Preparing reagent for Soil analysis