UNIVERSITY FOR DEVELOPMENT STUDIES
FACULTY OF AGRICULTURE, FOOD AND CONSUMER SCIENCES
DEPARTMENT OF CROP SCIENCE

KNOWLEDGE FOR SERVICE

SOYBEAN (*Glycine max* L. Merr.) GROWTH AND YIELD RESPONSE TO INOCULATION, NPK, AND ALTERNATIVE PHOSPHORUS SOURCES

BY

ABDUL RAHMAN MOHAMMED MUHUTADI

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FACULTY OF AGRICULTURE, FOOD AND CONSUMER SCIENCES

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(BSc. AGRICULTURE TECHNOLOGY)

THESIS SUBMITTED TO THE DEPARTMENT OF CROP SCIENCE, FACULTY OF AGRICULTURE, FOOD AND CONSUMER SCIENCES, UNIVERSITY FOR DEVELOPMENT STUDIES IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER OF PHILOSOPHY DEGREE IN CROP SCIENCE

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DECLARATION

I hereby declare that this thesis is my original work and that no part of it has been presented for another degree in this university or elsewhere. The work of others that served as useful information has been duly acknowledged by references to the authors.

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(Student) Signature Date

Supervisors'

We, hereby declare that the preparation and presentation of the thesis was supervised following guidelines on supervision of thesis laid down by the University for Development Studies.

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ABSTRACT

Soybean cultivation has failed to achieve its potential yields owing to factors such as inadequate soil fertility, suboptimal nutrient management practices and imbalances in fertilizer application, among other challenges. A study was conducted at Kpalsogu. Tolon district, in the Northern region of Ghana to assess the impact of rhizobium inoculation, two OCP compound fertilizers, TSP, 20-40% substitution of TSP with Rock phosphate and inclusion of trace elements B and Zn on field performance of Favour soybean. The treatments were laid in a split-plot design replicated four times. The main plot factor was Rhizobium inoculation at two levels (inoculation vs no inoculation). The subplot factor was made up of fifteen fertilizer regimes. Generally, parameters associated with plant growth was significantly influenced by the application OCP compound fertilizer treatments NPK(14:18:18+B, Zn) and NPS+TE(14:31:5+B, Zn). Most of the growth and yield parameters were not affected by rhizobium inoculation. The complete substitution of TSP with rock phosphate as a source of phosphorus lagged behind other fertilizer treatments but it was better than untreated control. However, up to 40% substitution of the TSP with rock phosphate did not have any adverse effect. Indeed, 80%TSP+20%RP treatment produced the highest grain yield of 2006 kg ha^{-1}. Partial budget analysis showed that TSP and 80%TSP+20%RP treatments recorded marginal rate of return of 561.4% and 295.1% respectively. Ultimately, the study found the compound fertilizers improved growth and yield with TSP performing better than rock phosphate in terms of P sources. In order to maximize yield and increase profit margins, the study recommends the use of triple superphosphate or 80% TSP in combination with 20% rock phosphate. Further study should be conducted to ascertain if the absence of K in NPS+TE(14:31:5+B, Zn) is the cause of poor nodulation in that treatment.

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DEDICATION

This thesis is sincerely dedicated to Almighty Allah for His care, greatness and love He has shown me throughout the challenging years of my life.

I also dedicate this project to my late father, Alhaji Abdul Rahman, may his soul rest in peace.

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LIST OF ACRONYMS

NPK	Nitrogen Phosphorous Potassium
RP	Rock Phosphate
TSP	Triple Superphosphate
OCP	Office Chérifien des Phosphates
MOP	Muriate of Potash
TE	Trace Elements
Zn	Zinc
B	Boron
%	Percentage
<	Less than
Kg	Kilogram
Ha	Hectare
GY	Grain Yield
ABGDB	Above Ground Dry Biomass
SSA	Sub-Saharan Africa
WAP	Weeks After Planting
MOFA	Ministry of Food and Agriculture

CHAPTER ONE

INTRODUCTION

1.1 Background

One of the major food crops high in protein and vegetable oil is the soybean (*Glycine max*) (Sugiyama *et al*., 2015). In Ghana, the Portuguese missionaries were the first to introduce the soybean in 1909. This early introduction did not succeed because of the temperate origin of the crop (Mercer-Quarshie and Nsowah, 1975).

In 2021, global soybean cultivation reached a record high, covering over 129 million hectares. Brazil led with 39 million hectares, followed by the United States with 34.9 million hectares. In contrast, the European Union accounted for only approximately 900,000 hectares (FAOSTAT, 2023) Soybean cultivation success varies significantly across Africa. As of 2016, the continent produced over 2.**3** million tons of soybeans, representing just 0.76% of global production area (Khojely *et al*., 2018). Productivity in sub-Saharan Africa (SSA) remains low, with average yields of 1.1 tons per hectare, far below the global average of 1.77 tonsha^{-1} (Khojely *et al*., 2018; Lal, 2022). In Ghana, smallholder farmers are increasingly growing soybeans, especially in the Upper West region, where production is constrained by inefficiencies and limited access to resources. Given that the average technical efficiency of soybean production in this region is 59%, (Asodina *et al*., 2021), and 82.7% in the Northern region (Osman *et al*., 2018). Production efficiency is influenced by a number of factors, such as farmer experience, adoption of improved seed varieties, and access to extension services (Etwire *et al*., 2013; Osman *et al*., 2018).

According to Wilcox and Shibles, (2001), soybeans have roughly 37% to 42% high-quality protein, 6% ash, 29% carbohydrates, and 17% to 24% oil (Shoaib *et al*., 2015). Due to the high protein content of their seeds and the amount of nitrogen that builds up in the shoot, soybean plants need a lot of nitrogen (Board and Kahlon, 2013).

The economic feasibility of soybean production is substantiated by favourable net present values associated with investments in fertilisers and inoculants in multiple African nations (Kiwia *et al*., 2022). Smallholder farmers in Sub-Saharan Africa (SSA) realize yields that are markedly inferior to the potential outputs, with actual yields in Malawi, Zambia, and Mozambique being 3.8, 2.2, and 2.3 times lower than the achievable yields, respectively (Omondi *et al*., 2023). Additional physical limitations impacting production include soil erosion, elevated soil temperatures, and insufficient soil moisture availability (Lal, 2022).

Soybean remains a relatively new crop in Ghana's agricultural system (Dogbe *et al*., 2013). While U.S. soybean farmers achieve average yields of 4.6 t/ha, production in northern Ghana averages just 1.5 t/ha - a figure nearly identical to Ghana's national soybean yield average of 1.3 t/ha (Lawson *et al*., 2008). This significant yield gap highlights both the crop's recent introduction and the untapped potential for improved production practices. The low yield in Ghana has been attributed to numerous issues, including inaccessibility to certified seeds by farmers resulting in poor germination and plant stand, poor cultural practices and inherently low soil fertility (Lawson *et al*., 2008). Farmers in Ghana are gradually becoming aware of the economic importance of soybean (Etwire *et al*., 2013). This awareness could be because of market and non-market benefits (Dogbe *et al*., 2013). Among the market and non-market include the soybean ability to fix nitrogen through Biological Nitrogen Fixation (BNF) (Mpepereki *et al*., 2000) and the crop's wastes that are used to feed animals.

Soybean production is on the rise in Ghana, and this rise is attributable to technologies such as the applications of fertilisers and rhizobia inoculation (Rechiatu, 2015). When soil nitrogen and the indigenous rhizobia population are deficient, it is advisable to grow legumes through inoculation (Catroux *et al.*, 2001). Studies indicate that growth, yield and biomass are enhanced by nitrogen fertilisation (Umeh *et al.*, 2011; Riedell *et al.*, 2013). A lack of micronutrients can greatly hinder soybean growth, especially by disrupting bud development, flowering and pod formation. To address soil deficiencies, applying micronutrients before the flowering stage is an effective method (Yasari and Vahedi, 2012). Empirical research indicates that the application of P and K can markedly improve grain yield and economic viability, with optimal economic returns realized at specific nutrient combinations (Awuni *et al.*, 2024). Using different rhizobia strains in combination with phosphorus application has proven to be an effective method for enhancing soybean yield. Co-application of phosphorus and inoculants has shown the ability to increase grain yield up to threefold compared to untreated controls (Adjei-Nsiah *et al.*, 2022). Studies conducted under rainfed conditions have examined the use of lime, inoculants and phosphorus, indicating that even in low-input farming systems, significant marginal net benefits and returns can be achieved (Awuni *et al.*, 2024). The uptake of rhizobium inoculants and mineral fertilisers is influenced by many factors, including farm size, access to extension services, and gender, with women farmers showing a greater likelihood of adopting these technologies (Anang and Zakariah, 2022).

1.2 Problem statement

Smallholder farmers often avoid costly inputs due to uncertain returns, prioritizing short-term financial stability over potential yield gains. This is particularly critical in soybean production, where phosphorus (P) deficiency, common in the study area, severely limits nodulation, nitrogen fixation, and overall plant productivity (Yao *et al*., 2022; Chen *et al*., 2023). Low soil P further compromises rhizobia survival (Cassman *et al*., 1981), while inconsistent responses to nitrogen (N) fertilization (Barker and Sawyer, 2005) and flower abortion due to poor fertility exacerbate yield gaps.

While rhizobia inoculation programs recommend P supplementation, nitrate inhibition of nodulation (Li *et al*., 2023) and micronutrient deficiencies further constrain symbiotic N fixation, sometimes prompting starter N (Ohyama *et al*., 2011). Rock phosphate, a cost-effective P source, offers promise, but its solubility depends on soil pH (Huang and Hue, 2022). Smallholder soybean farmers' production is critically limited by phosphorus deficiency, which reduce nitrogen fixation and yield, yet financial risks often prevent farmers from adopting high-cost fertilizers. While rock phosphate offers a cost-effective alternative, its inconsistent solubility and complex interactions with other nutrients create a significant barrier to closing the existing yield gap.

1.3 Justification

Rhizobium inoculation has been empirically demonstrated to markedly enhance soybean nodulation, nitrogen fixation, and grain yield. Inoculants such as Biofix and NoduMax have exhibited yield enhancements of up to 30% within the Northern Ghana context (Akley *et al*., 2023). In the semi-deciduous forest zone, the implementation of rhizobium inoculation resulted in a remarkable 108% increase in soybean grain yield relative to the control, underscoring its capacity to augment productivity in less advantageous agroecological zones (Adjei-Nsiah *et al*., 2022). It has been demonstrated that rhizobium inoculation combined with phosphorus greatly boosts soybean yield. In Ghana, 25.75% increase in yield were recorded when phosphorus was applied to inoculated soybeans (Guitton, 2022). Phosphorus application through sources such as TSP has been proposed to increase soybeans growth and yields (Lamptey *et al*., 2014). The substitution of TSP with rock phosphate has proven to be more cost-effective and increases available phosphorus, especially in areas where commercial fertilisers are scarce. (Adjei-Nsiah *et al*., 2019). The application of rock phosphate on inoculated soybeans promoted soybeans production and nutrient efficiency (Buernor *et al*., 2022). Given the need to increase soybean production and sustainability in Ghana, further studies are justified on technologies such as rhizobium inoculation, NPK application, nutrient supplementation, and the substitution of triple super phosphate for rock phosphate. By increasing soil nutrient availability, these integrated innovations seek to address important issues.

1.4 Objective

1.4.1 General Objectives

To assess the impact of rhizobium inoculation and fertilization on soybean production.

1.4.2 Specific objectives

- To assess the impact of Rhizobium inoculation on soybean yield indicators
- To measure the impact of single nutrient treatments on the growth and yield of soybean
- To assess the effects of combined nutrient treatments on soybean growth and yield
- To evaluate rock phosphate as a substitute for triple superphosphate (TSP) in phosphorus (P) supply for soybean production
- To assess the impact of Zn and B on crop performance
- To evaluate the effectiveness of the OCP compound fertilizers on soybean production.

CHAPTER TWO

LITERATURE REVIEW

2.1 Origin of Soybean

2.1.1 Early Domestication in China

It is generally acknowledged that soybeans originated in East Asia, with China serving as the main domestication hub. According to historical records and archaeological data, soybeans were initially domesticated in China more than 8,000 years ago (Barsan and Schierbaum, 2018; Gastaldo, 1984). It is thought that the oldest cultivation took place during the Longshan Culture period in northern China, specifically in the hilly regions of Liaoning, Hebei, and Shanxi (Yong-gan, 2014). The wild soybean (Glycine soja), the ancestor of the cultivated soybean, flourished in this area due to its temperate environment and fertile soil (Sedivy *et al*., 2017; Wu *et al*., 2024). For thousands of years, grain was the Chinese people's primary source of vegetable protein, milk, cheese, bread, and oil. This fact alone attests to the cultural and nutritional significance of soybeans to the Chinese, as the grain was used as a raw material for the production of tofu (curdled soy milk) as early as 200 BC. In the context of Argentina, soybeans assumed a critical function amid the imposition of currency exchange limitations, thereby underscoring their significance within the framework of national economic policies (Luzzi and Wilkis, 2018).

2.1.2 Spread to Other Regions

Between AD 1 and AD 1600, soybeans travelled from China to other Asian countries, such as Japan, Korea, and Southeast Asia (Gastaldo, 1984; Barsan and Schierbaum, 2018). Soybeans were first domesticated in Korea about 3,000 years ago, and in Japan about 5,000 years ago (Barsan and Schierbaum, 2018). Trade and cultural interchange helped soybeans spread to these areas, where local communities adapted the crop to suit their unique natural conditions (Gastaldo, 1984; Barsan and Schierbaum, 2018).

2.1.3 Introduction to the Western World

Much later, soybeans were brought to the West. While Argentina and Brazil started growing soybeans in the late 19th and early 20th centuries, respectively, the United States was first known to have imported soybeans in 1765 (Gastaldo, 1984; Barsan and Schierbaum, 2018). Argentina, Brazil, and the United States are currently the world's major producers of soybeans (Gastaldo, 1984; Barsan and Schierbaum, 2018).

2.1.4 Genetic and Archaeological Evidence

Additional proof of soybean origin has come from genetic research. Phylogenetic analysis of domesticated and wild soybean varieties indicates that cultivated soybeans originated from the annual wild soybean in southern China (Zhao and Gai, 2004). Old seed grains are among the archaeological discoveries found at historical sites, confirming the notion that the cultivation of soybeans was first done in northern China (Yong-gan, 2014). Genetic loci that are associated with features used to domesticate, including flowering time, and seed size were revealed by the genome-wide association (CWAS) studies, confirming more that soybeans came from China (Wang *et al*., 2016; Li *et al*., 2024). Glycine max (L.) Merr., a cultivar of soybean, belongs to the family Leguminosae, subfamily Papilionoideae, tribe Phaseoleae, genus Glycine Willd., and subgenus Soja. Being an annual herbaceous plant with an upright, growth habit that is bushy, soybeans typically reach 1.5m high. The three main growth types found in soybeans cultivars are determinate, semi-determinate and indeterminate. (Bernard and Weiss, 1973).

2.1.5 Role of Human Selection

The main factor that made soybean domestication a success is the human preference as shown by early farmers whose selection of soybean cultivars was based on characteristics such as larger seeds, oil content and the ability to resist environmental stresses (Sedivy *et al*., 2017; Wu *et al*., 2024). These preferences shape the adoption of many landraces and adapted cultivars that were developed and grown over several generations (Carter *et al*., 2016).

2.1.6 Genetic Diversity and Adaptation

Despite a restricted genetic base, soybeans have effectively adapted to diverse environmental conditions. The primary factor contributing to this adaptability is hybridization with wild relatives, resulting in the emergence of new varieties (Hou *et al*., 2023; Li *et al*., 2024). Genes that regulate photoperiod sensitivity and flowering time are essential for the sustainability of soybean cultivation across different regions, as indicated by the studies conducted by Hou *et al*. (2023) and Li *et al*. (2024). Key genes regulating traits such as flowering time and photoperiod sensitivity have been identified to enhance soybean cultivation across diverse geographical regions.

2.2 Soybean Introduction to Africa and Ghana

2.2.1 Historical Context of Soybean Introduction to Africa

In Africa, the cultivation of soybeans started in Egypt in 1958. South Africa was the first to start the early production in Sub-Saharan Africa in 1903 (Shurtleff and Aoyagi, 2009). The introduction of soybeans in Africa was carried out by the early missionaries who brought the crop from East Asia, after recognising the versatile potential and the nutritional benefits of the crop (Jackai *et al*., 2022). Soybeans were initially cultivated in limited areas; however, as their benefits became evident, production expanded significantly. The commercialization and mechanization of soybean production in Southern Africa, especially in Zimbabwe, serve as a model for other regions (Jackai *et al*., 2022).

2.2.2 Challenges of Soybean Production in Africa

Various challenges impede the optimal soybean production in Africa. Challenges which include:

Low Yields: In Africa, soybean yields often stall due to dependence on suboptimal varieties and inadequate application of fertilisers and rhizobia inoculants (Khojely *et al*., 2018; Omondi *et al*., 2023).

Soil Fertility: Many African soils lack the required nutrients needed for optimal soybean growth, leading to the need for the application of fertilisers and inoculants (Khojely *et al*., 2018; Omondi *et al*., 2023).

Climate Change: Climate change is expected to threaten soybean yields, particularly in semi-arid regions; however, high CO_2 levels may alleviate some of these effects (MacCarthy *et al*., 2022).

2.2.3 Soybean Introduction and Adoption in Ghana

Soybeans were introduced to Ghana in 1901. Currently, most agricultural production in the country occurs in the northern regions, where the crop provides income for needy farmers and enhances soil fertility (Nartey *et al*., 2022). To increase food security and diversify crop production, soybeans were brought to such regions (Danso-Abbeam, 2022). Initiatives to improve grain yield and nutrition through policy support for soybean cultivation in Africa (Khojely *et al*., 2018). The Savanna Agricultural Research Institute (SARI) of the Council for Scientific and Industrial Research (CSIR) in Ghana, has developed and released eight soybean varieties due to these policies: Songda, Suong-Pungun, Jenguma, Quarshie, Favour, and Salintuya 1 and 2 (Atuna *et al*., 2022). Increasing the crop awareness was essential to provide farmers with an alternative agricultural livelihood and enhance food security. Research and extension services are vital for advancing soybean as a commercial crop. The promotion of soybean production focus on boosting yield via good agricultural practices (GAP) and better seed quality (Adjei-Nsiah *et al*., 2019, 2022; Puozaa *et al*., 2023).

2.2.4 Factors Influencing Soybean Adoption

The introduction of soybeans was shaped by various factors, notably their nutritional value and economic significance. Soybeans represent a viable option for smallholder farmers due to their high protein content and ability to fix nitrogen (Atuna *et al*., 2022). The adoption of the crop is supported by key interventions from governmental and non-governmental organisations (Ragsdale *et al*., 2022).

2.2.5 Challenges in Soybean Production

In Ghana, soybean cultivation is mainly limited by poor planting density and lack of resources, despite its numerous benefits (Puozaa *et al*., 2023). The challenges faced by smallholder producers are further compounded by their lack of access to modern technology and funding. However, studies indicate that specific programmes like contract farming and assistance with input packages can significantly increase productivity and profitability (Ragsdale *et al*., 2022; Selorm *et al*., 2023).

2.3 Ecological Conditions for Soybean Cultivation

For their high protein and oil content, soybean (*Glycine max*) is a significant crop on a global scale. Their production was impacted by a variety of ecological factors, such as soil quality, climate and interactions with other organisms. The understanding of these ecological elements is crucial for soybean cultivation.

2.3.1 Climate Requirement

Temperature: Because soybeans are a warm crop, moderate temperatures are ideal for them. According to Staniak (2023), germination and growth require temperatures between 15° C and 30° C, and 20° C and 30° C, respectively. Excessive heat negatively impacts critical developmental stages, like flowering and podding. Soybeans grown at temperatures above 35 °C typically exhibit losses in flowers and pods (Sobko *et al*., 2020; Staniak *et al*., 2023).

Response to Daylight: Since soybeans are considered short-day plants, they need latitude-specific cultivars to reach full maturity before fall frosts. In higher-latitude areas, delaying full maturity may lead to low yields and incomplete pod filling (Kane *et al*., 1997; Staniak *et al*., 2023).

Rainfall and Water Supply: Soybeans need a sufficient quantity of water at critical growth phases in order to thrive. They need between 450 and 600 mm of water on average during the growing season. In the event of drought, yield losses could be significant during crucial developmental stages (Wójcik-Gront *et al*., 2022; Staniak *et al*., 2023). Irrigation is required in areas with low rainfall to meet the crop's water demands (Biradar *et al*., 2025).

Solar Radiation: Solar radiation is an important climate requirement for soybean production. High amounts of sun radiation are necessary for soybeans to grow and perform photosynthesis at their best. However, too much radiation during blooming might have a detrimental effect on the seeds' protein content (Sobko *et al*., 2020).

2.3.2 Soil Requirements for soybean cultivation

Suitable Soil Type and Structure: Although soybeans can grow in a variety of soil types, they do best on fertile, well-drained soils with a pH of 6.0 to 8.0. The best soils for promoting root development and nutrient uptake are those with a high water-holding capacity and sufficient organic matter (Shivaramu *et al*., 1998; Taylor and Kaspar, 2022).

2.3.3 Nutrient Availability

As a legume, soybeans require a lot of nitrogen (N). Although it may fix atmospheric nitrogen through rhizobia symbiosis, output is largely determined by soil fertility, especially phosphorus (P) and potassium (K). Applying organic and mineral fertilisers consistently can increase soil fertility and boost output (Прус, 2017; Sinegovskaya and Naumchenko, 2019).

2.3.4 Soil Depth and Waterlogging

Another crucial element is soil depth; deeper soils typically sustain bigger yields. Conversely, waterlogging can limit root development and lower nitrogen fixation, which lowers yield (Shivaramu *et al*., 1998; Taylor and Kaspar, 2022).

2.3.5 Ecological and microbial dynamics

Symbiotic relationship between soybeans and rhizobia: Soybean is able to fix atmospheric nitrogen through a symbiotic relationship with rhizobia, making the cultivation of soybean environmentally friendly. This process is however influenced by factors such as soil pH, soil moisture levels, and soil temperature. To promote a healthy nitrogen fixation and soil, it is important to maintain conditions that support healthy rhizobia activity (Taylor and Kaspar, 2022; Sharma *et al*., 2023).

Microbial Inoculants: Microbial inoculants, including stress-tolerant rhizobia and arbuscular mycorrhizal (AM) fungi, help soybeans better adapt to environmental stresses like drought and nutrient deficiencies. These beneficial microbes improve soil biological ecology and boost soil nutrient availability, leading to increased yields (Прус, 2017; Sharma *et al*., 2023).

2.3.6 Mapping Agroecological Zones and Regional Differences in Soybean Cultivation

Mapping Agroecological Zones: To identify regions with the most favourable soybeans productions conditions, agroecological zoning is conducted. This strategy classifies production lands in zones of high, moderate, or low suitability based on factors such as temperature, rainfall, soil characteristics, and landscape. Well-drained soils, moderate climates, and adequate rainfall are characteristic of a suitable areas (He *et al*., 2013; Kazemi *et al*., 2013).

Regional Variations: Due to variations in soils and temperature, soybean yield can vary between regions. For example, China's Northeast Plain and North China Plain are important high-sustainability regions, while Ukraine's Steppe and Forest-Steppe zones provide more suitable conditions for soybean cultivation (Korol *et al*., 2023; Zhu *et al*., 2023). MG 00 and MG 000 maturity types were the most suitable for the local conditions in Germany, where sunlight and rainfall affected yields (Sobko *et al*., 2020).

2.3.7 Management Practices

Crop Rotation and Fertilization

Crop rotation and proper fertilization are crucial for increasing soil fertility and soybean yields. The occurrence of pests and diseases is reduced when soybeans are rotated with wheat while soil health is enhanced. Organic and inorganic fertilisers, particularly phosphorus based fertilisers, significantly increased expected yields (Sinegovskaya and Naumchenko, 2019; Wójcik-Gront *et al*., 2022).

Irrigation and Water Management

In locations where rainfall is limited, it is advisable to irrigate soybeans with precision. This water supplementation involves the correct measurements of soil water levels and the required crop water, which leads to increased water use efficiency and good water resistance (Biradar *et al*., 2025).

Variety Selection

Soybean potential yield is improved by the selection of cultivars that adapt to the specific site and weather conditions. Early maturing cultivars are more beneficial in shorter growing seasons, while late maturing cultivars are suitable for longer seasons (Kane *et al*., 1997; Elmerich *et al*., 2023).

2.3.8 Environmental Stresses and Sustainability

Abiotic Stressors: Drought, excessive heat, and soil salinity can cause reduced soybean yield by reducing photosynthesis, nutrient uptake, and root development. Mitigating the effects of abiotic stresses requires the application of technologies such as conservation agriculture and the development of stress-tolerant soybean cultivars (Miransari, 2016; Staniak *et al*., 2023).

Eco-Sustainable Methods: The implementation of climate-smart agriculture, such as cover cropping, green manuring and the use of organic matter, supports environmental protection and soil health. More sustainable soybean production results from these systems' enhancement of soil organic matter, reduction of erosion, and promotion of microbial activity (da Silva *et al*., 2024).

2.4 Production of Soybeans in Ghana

Soybean grains are in high demand not just for home use but also for industrial processing into animal feed, particularly for the poultry business, and cooking oil (Mohammed *et al*., 2016). Over 300,000 MT of soybean grains are consumed domestically each year, with 91 % of that amount going toward Ghana's industrial sector. In the meantime, the local supply, which is now at 144,926 MT with a shortfall of over 150,000 MT, is frequently increased by imports from nations like China and Brazil (Mohammed *et al*., 2016).

Ghana has an astounding 700,000 tonnes of annual soybean-producing potential. Only roughly 26 % of this potential is being achieved, though. Of the 250,000 hectares of land suitable for production across the nation, an estimated 102,000 hectares are under cultivation. Ninety-six per cent of Ghana's soybeans are produced in the country's north, although average yields are still just about three tonnes per hectare. This can be blamed on inadequate precipitation and substandard quality of planting materials constitute significant environmental limitations. These elements are further intensified by the absence of enhanced seed cultivars and insufficient land preparation (Mbanya, 2011; Mohammed *et al*., 2016). The existence of insect pests, including defoliators and pod feeders, exerts a considerable influence on agricultural yield. Effective pest control technologies are usually overlooked, leading to considerable yield losses (Abudulai *et al*., 2012). Limited processing and marketing systems lead to reduced prices of soybeans, thereby discouraging farmers from increasing their production levels (Mbanya, 2011). It has been identified that the primary factor influencing soybean production is improper utilization of resources such as labour, seeds, and land size. Significantly, the application of fertiliser has been negatively correlated with yield levels, suggesting that inputs may not be applied correctly (Asodina *et al*., 2021).

2.4.1 Agricultural Practices

Contract Farming and Its Impact

In Ghana, contract farming has emerged as a significant soybean production venture. It has raised the technical efficiency and production of smallholder farmers. For example, Northern contract farmers had a higher technical efficiency rate (77 %) than non-contract farmers (69 %) (Selorm *et al*., 2023). Also, contract farming gives farmers access to markets, credits, and inputs, all of which increase income and yields. However, the farmers' ability to fulfil their contractual duties and the level of support provided by governmental and non-governmental organizations are what determine whether contract farming is successful (Selorm *et al*., 2023; Abdulai *et al*., 2024).

Technical Efficiency and Profitability

Factors such as farm size, use of pesticides and labour vary the technical efficiency of soybean farmers in Ghana. Peasant farmers in Upper West have an average technical efficiency of 59 %, according to research, which suggests that production might increase by 41 % with better practices (Asodina *et al*., 2021). Farmers in the Tolon district also consider the profit efficiency, which, for instance, farmers who attain an average of 70 % lose almost 30 % of their potential income due to inefficiencies (Amesimeku and Anang, 2021).

Climate Change and Its Implications on Soybean Production in Ghana

One of the obstacles to Ghana's soybean production in climate change. Climate change is characterised by high temperatures and irregular rainfall patterns, which result in low and unpredictable yields. The increase in atmospheric carbon dioxide levels, however, might improve production and mitigate the negative impact of climate change (MacCarthy *et al*., 2022; Ntiamoah *et al*., 2022). Farmers adopt climate-smart technologies, such as improved water efficiency and soil conservation, to minimise these climate change-related challenges.

Gender and Agricultural Productivity

Gender plays a substantial role in the cultivation of soybeans in Ghana. Researches indicate that women in soybean farming encounter several challenges because they have little access to capital and agricultural inputs, which leads to low income and yield. The negative impacts of these challenges can be mitigated through targeted policy interventions. Female farmers who were awarded with soybean success kits, made up of certified seeds and inoculants, reported yields and revenue that improved by 170 % compared to those who did not receive the kits (Ragsdale *et al*., 2022).

2.4.2 Government of Ghana Policies

Government of Ghana Expenditure on Agriculture

Studies have shown that agricultural funding by the Government of Ghana increased agricultural productivity. A study shows that increased government investment in the industry support food security and elevated crop yields. The Ghana Fertiliser Subsidy Program (GFSP) has demonstrated an increment in the productivity of key crops, such as soybeans, by up to 8.3 % in the short term, with potential for greater long-term gains (Iddrisu *et al*., 2020; Sogah *et al*., 2024).

Fertiliser Subsidy Program (GFSP)

The Ghana Fertiliser Subsidy Programme (GFSP) represents a great initiative by the government within the agricultural sector. The program has promoted economic growth, increased job creation, and improved agricultural productivity, resulting into enhanced nutrition and well-being of household food, especially in rural areas. The distribution and accessibility of subsidized inputs to farmers will significantly influence their effectiveness of the programme (Iddrisu *et al*., 2020).

Institutional and Public Expenditure Review

The Ministry of Food and Agriculture (MOFA)'s ability to formulate and implement effective policies is essential for the efficiency of Ghana's agricultural sector. The effectiveness of these policy measures may not achieve the expected output due to institutional challenges such as inefficient operational bureaucracy and limited resources. To achieve the objectives of the Comprehensive Africa Agriculture Development Programme (CAADP), it is important to support MOFA and encourage the responsible allocation of public funds (Kolavalli *et al*., 2010).

2.4.3 International Trade Agreements

Agricultural Export Growth

Ghana's agricultural export industry has a lot of potential to promote the country's economic growth. The export industry, however, is marked by frequent challenges, which include structural flaws in the trade, marketing, and production systems. In order to maintain and accelerate the growth of the Ghanaian export industry, these challenges must be resolved. Export goods diversification, trade expansion, and promotion of direct foreign investment are measures that can be employed to make Ghana’s agricultural exports more competitive (Boansi and Appah, 2014).

Trade and Marketing Environments

The trading and marketing landscape for soybeans in Ghana is shaped by the interplay of domestic and international influences. Although Ghana may boost its soybean exports, other significant soybean-producing nations compete with it. Enhancing the supply chain's effectiveness and raising the norms and quality of soybean products are crucial for growing Ghana's market share internationally (Boansi and Appah, 2014).

Regional and International Cooperation

Ghana's soybean commerce and production can be greatly aided by regional and global collaboration. Common issues like market access and climate change can be addressed through cooperation with international organisations and neighbouring nations. For instance, Ghana's soybean industry can become more competitive in the global market through regional efforts to advance sustainable farming methods and better trade facilitation (Ferreira *et al*., 2022).

2.5 Nutrition

2.5.1 Protein and amino acid

It is well known that soybeans are an oilseed that includes several beneficial elements, such as protein, carbohydrates, vitamins, and minerals. Thirty-six per cent of dry soybean is composed of protein, nineteen per cent oil, thirty-five per cent carbohydrates (17% dietary fibre), five per cent minerals, and several additional ingredients, including vitamins (Liu, 1997). One of the most affordable sources of protein in the diet is soy (Derbyshire *et al*., 1976). Except for sulphur amino acids (methionine and cysteine), soybean proteins' nutritional profile is nearly identical to that of animal protein because they include the majority of the essential amino acids needed for both human and animal nutrition (Sacks *et al*., 2006). Soybean protein is thought to be a good replacement for animal protein. Studies conducted on rats revealed that when enhanced with the sulphur-containing amino acid methionine, the biological value of soy protein is comparable to that of several animal proteins, including casein (Hajós *et al*., 1996). As per the Protein Digestibility Corrected Amino Acid Score standard, which is used to measure the quality of protein, the biological value of soybean protein is 74, that of whole soybeans is 96, that of soybean milk is 91, and that of eggs is 97 (Bethesda, 1989). The genetic improvement of soybean has focused on enhancing protein content and quality, with advanced breeding technologies like CRISPR/Cas9 being employed to optimize these traits (Singer *et al*., 2023).

Soybeans are considered a high-quality protein source, with a protein digestibility-corrected amino acid score (PDCAAS) of 1.00, comparable to animal-based proteins (Qin *et al*., 2022). While their sulphur-containing amino acid like methionine content is marginally low, soybeans still offer a well-rounded profile of essential amino acids (Qin *et al*., 2022). Phosphorus fertilisation can enhance the nutritional quality of soybean seeds, which boost the levels of keys amino acids such as lysine, leucine, and valine (Szuba-Trznadel *et al*., 2023; Ran *et al*., 2024).

2.5.2 Essential Fatty Acids, Isoflavones and Other Bioactive Compounds

Soybeans, in addition, include phytosterols, lecithin, and saponins, which support their antioxidant and cholesterol-lowering qualities (Guo, 2009). Individuals of Asian descent typically ingest approximately 20–80 grams of conventional soy products daily, encompassing items such as tofu, miso, and tempeh, in stark contrast to Western individuals who consume merely around 1–3 grams per day, predominantly in processed forms such as soy beverages and energy bars (Feng and Ming, 2011). This amount of soy food consumption is equal to between 8 and 50 g of soy protein (Erdman *et al*., 2004) and between 25 and 100 mg of total isoflavones (Messina *et al*., 2006). Soy has constituted a fundamental component of Asian dietary practices for centuries; in contrast, its incorporation into Western culinary habits has occurred in a relatively recent timeframe, often serving as a substitute in vegetarian alternatives (Rizzo and Baroni, 2018). The bioavailability of soy isoflavones is modulated by ethnic background and dietary circumstances, with individuals of Asian heritage demonstrating superior absorption rates compared to their Caucasian counterparts, irrespective of whether their diet aligns with Western or Asian traditions (Vergne *et al*., 2009). The principal application of the residual (soybean meal) after oil milling is as a source of protein feed for domestic animals, such as pigs, chickens, cattle, horses, sheep, and fish, as well as for many prepared meals (Liu, 1997). It is frequently used in animal diets, such as that of pigs, chickens, cattle, horses, sheep, and fish, as a filler and source of protein (Riaz, 2006).

2.5.3 Dietary Fibre and Micronutrients

Iron, zinc, and folate are among the minerals and micronutrients found in soybeans that are essential for several body processes (Agyenim-Boateng *et al*., 2023). Even though soybeans have several health advantages, there are some things to keep in mind when consuming them. Certain components in soy can interact with drugs, and some people may have soy allergies (Kang *et al*., 2023). Furthermore, anti-nutritional factors may impact the digestion of soy protein; however, these can be lessened by processing techniques such as fermentation and boiling (Asghar *et al*., 2024; Kohli and Singha, 2024).

2.6 Rhizobium inoculation in soybean production

2.6.1 Historical context of inoculation

In the early 20th century, inoculating soybean seed with B. japonicum at planting became a standard technique in the United States (Pueppke, 2005) and in Argentina in the mid-1970s (Hungria *et al*., 2005). In South America, soybeans are more frequently inoculated at planting than they are in the US. In Argentina, approximately 80 % of soybeans are inoculated yearly (Perticari, 2015), while in the United States, only 15 % of farmers use inoculants (Graham and Temple, 1984). A reduction in the usage of inoculation techniques in the United States may have resulted from several factors, including the adoption of plant varieties that are less able to fix nitrogen dioxide in symbiosis and edaphic restrictions such as soil acidity, drought, and a lack of certain nutrients (Graham and Temple, 1984) as well as the restricted boost in yield that seed inoculation in soils with a soybean history causes (de Bruin *et al*., 2010). Research conducted in 2000 found that dryland soybeans in the U.S. fixed an average of 100 kg of nitrogen per hectare in above-ground biomass. When root biomass was included, this figure increased to as much as 142 kg of nitrogen per hectare (Pueppke, 2005).

2.6.2 Benefits of Rhizobium Inoculation

Bradyrhizobium japonicum is widely acknowledged to improve nitrogen fixation and soybean yield. This technique reduces the reliance on synthetic nitrogen fertilisers. This technique reduces the reliance on synthetic fertilisers and improves dry weight quantity of root nodules a component vital for nitrogen fixation. As a result, it is an environmentally benign technology (Jarecki, 2020; Sogut, 2006). Beyond promoting nodulation, rhizobium inoculation has been shown to improve soybean seed yield, oil production, and protein levels. For instance, HiStick® Soy, a commercial inoculant that contains *Bradyrhizobium japonicum*, has been shown to improve seed yield by 0.58 tha^{-1}, protein and oil yields by 318 kgha^{-1} and 101 kgha^{-1}, respectively, as compared to the untreated control. (Jarecki, 2020). Other studies also found yield improvements ranging from 4.8 % to 11 % over the traditional practices (Venancio *et al*., 2024).

Legumes inoculated with rhizobium species can fix a significant amount of atmospheric N if other environmental or microbiological conditions do not limit the N fixation, contributing to the soil N pool (Achakzai *et al*., 2002). *Rhizobium sp*. inoculation of seeds resulted in enhanced nodulation by symbiotic absorption of ambient nitrogen. Rainfall, drought, acidity, salinity, low P, and the presence of harmful ions prevent symbiotic N fixation from forming (Rajput *et al*., 2001). Seeds inoculation boosts soybean yield and yield components (Rajput *et al*., 2001; Oad *et al*., 2002). Among the many beneficial soil microbes, associative plant growth-promoting rhizobacteria (PGPR) are outstanding for their successful use in sustainable agriculture, where they have delivered consistently positive outcomes (Marschner, 1995). Plant growth-promoting rhizobacteria (PGPR) benefit plants through a range of biological activities, which include the production of growth hormones like auxins, gibberellins, and cytokinins (Tien *et al*., 1979; Bottini *et al*., 1989; Strzelczyk *et al*., 1994; Hirsch *et al*., 1997; Saharan and Nehra, 2011). In addition to growth promotion, PGPR also enhance plant resistance to environmental stresses and diseases (Gurska *et al*., 2009), helps solubilise phosphate (Bashan and Holguin, 2002; Saikia *et al*., 2010), and contributes to nitrogen fixation from the atmosphere (Dobereiner and Pedrosa, 1987). While other native rhizobia species can infect soybean plants in south America, their nitrogen fixing efficiency tends to vary (Althabegoiti *et al*., 2008).

2.6.3 Co-Inoculation with Other Microorganisms

The effectiveness of rhizobium can significantly be enhanced by its combination with fungi or other plant growth-promoting bacteria (PGPR). Nodulation, root, root development and plant growth were enhanced by the co-inoculation with phosphate-solubilising bacteria (Jaybhay *et al*., 2017; Leite *et al*., 2024). According to research conducted by Alessandro *et al*. (2023), nodule count, shoot and dry weight and overall production were impacted positively when rhizobium and *Azospirillum brasilense* were applied together. Co-inoculation of rhizobium and arbuscular mycorrhizal fungi (AMF) not only increases total and accessible nitrogen and phosphorus levels but also enhances soybean yields in vertisols soils (Ishaq *et al*., 2023). Balanced and good symbiotic relationships which result into improved grain yield are due to the interactions between these organisms.

2.6.4 Timing of Production

For effective rhizobium application and delivery, it is important to consider the timing of application. According to research, nodulation and grain yield improved significantly when pre-inoculation with *Bradyrhizobium* species was carried out between 15-60 days before planting. A study indicates that the application of the commercial inoculant Biofix Protec at an early stage resulted in a 4.8-11% increase in nodule dry weight and yield compared to the untreated controls (Venancio *et al*., 2024, Venancio *et al*., 2024). This technology ensures the bacteria grow before planting and colonise the root to enhance nitrogen fixation.

2.6.5 Strain Selection and Symbiotic Effectiveness

The inoculant strain's performance depends on the type of rhizobium strain used for inoculation. The *Bradyrhizobium japonicum* performance of nitrogen fixation and support to soybean growth and development varies among the inoculants. In specific agroecological zones, the strain USDA 110 showed significant effectiveness in enhancing nodulation and overall yield (Kyei-Boahen *et al.*, 2023). The different combinations of several Bradyrhizobium strains enhance nodulation and nitrogen fixation (Krutylo, 2023; Vorobey *et al.*, 2023).

2.6.6 The Combination of Inoculation with Other Farming Practices

Rhizobium is applied with other farming practices for the plants to fully benefit from the inoculation. Studies have shown that using nutrient-rich products and microbial consortia can enable a conducive environment for the rhizosphere microbiome, while increasing plant growth and yield in soybean (Miljaković *et al.*, 2024). Also, applying phosphorus with rhizobium inoculation had a positive impact on production factors such as root volume and plant height (Nasir *et al.*, 2023).

2.6.7 Economic Impact and Sustainability

As economic returns are improved, rhizobium inoculation is also able to increase soybean yield and minimise chemical fertilisers dependence. For example, compared to fields that were not infected *Bradyrhizobium japonicum* inoculation has increased net returns by $ 182.57 to $395.35 per hectare (Kyei-Boahen *et al.*, 2023).

2.7 Rhizobium Inoculation in Africa and Ghana

2.7.1 Rhizobium Inoculation in Africa

Successful cases were recorded when rhizobia were applied to legumes in Europe, Australia, and America (Martins *et al*., 2003; Yates, 2004; Albareda *et al*., 2009). Except for farmers from Ghana and Africa in general, this technique is relatively recent. Performance of inoculations technique in Africa has been mixed due to variations in strain types, the quality and viability of the inoculants. In Nigeria, Sanginga *et al*. (1997) and Sanginga and Okogun, (2003) did not discover a discernible rise in soybean grain yield following inoculation. Mpepereki *et al*., (2000) reported a greater yield of soybean grain in Zimbabwe as a result of Rhizobium inoculation. In Kenya, Thuita *et al*., (2012) provided evidence of the advantages of rhizobia inoculant on soybeans. While inoculating legumes with Rhizobium can boost grain yield in nitrogen-deficient soils, few research has been conducted in Ghana to show the impact of legume inoculation and its financial significance for farmers. Because cowpea is thought to be highly promiscuous, it has gotten very little attention when it comes to rhizobia inoculation. This has led to an average production that is significantly less than the potential output of 2.5 tha^{-1}, at 0.6 tha^{-1}. In her 2015 study, Rechiatu (2015) examined the impact of Rhizobium inoculation and its financial significance on Northern Ghanaian farmers' fields. She found that at 67 % of the sites they examined, grain yield significantly increased. Thus, they concluded that employing Rhizobium inoculants had more financial advantages. Therefore, the introduction of proven highly competitive and successful indigenous or foreign strains has the potential to boost grain legume output.

2.7.2 Yield Improvement and Economic Benefits

The ability of inoculants to provide the nitrogen required for soybean production was demonstrated in Mozambique, where inoculation with *Bradyrhizobium* strains enhanced soybean yields by 37% to 95% (Savala and Kyei-Boahen, 2020). Phosphorus and rhizobium inoculation together increased soybean output in Northern Nigeria by 27.4% as compared to control treatments (Kabiru *et al*., 2024). In Tanzania, the yield of soybean grain improved by 127–139% when inoculation was used alone, and by 207–231% when phosphorus was added (Ndakidemi *et al*., 2006).

2.7.3 Strain Effectiveness and Soil Improvement

It has been demonstrated that native rhizobia strains in Kenya and Côte d'Ivoire are more efficient than some alien strains, greatly increasing yield and nodulation (Amani *et al*., 2024; Amani *et al*., 2024). Comparison between local and imported strains in Ethiopia has revealed that the local strain *Sinorrhizobium spp.* produced more grain yield and was more effective than the foreign imported strains (Temesgen and Assefa, 2020).

2.7.4 Soil Fertility and Sustainability

With a balanced soil bacterial ecosystem, soybean yield was positively influenced by rhizobium inoculation, in Tanzania and other African countries, resulting in sustainable farming practices (Wei *et al*., 2023). Long-term soil conditions and health with increased organic materials and lower soil acidity is also enhanced by rhizobium inoculation (Amani *et al*., 2024).

2.7.5 Rhizobium Inoculation of Soybean in Ghana

Soybean yields were increased by 7.8 % due to rhizobium inoculation, according to a meta-analysis conducted in Ghana and other African countries. However, phosphorus application together with inoculation can improve yields by 10.5% (Buernor *et al*., 2022). Studies indicate that the combined application of phosphorus and rhizobium inoculation significantly improved soybean yield in Sub-Saharan Africa, with a 25.7% increase in Ghana and 57.1 % in Malawi (Kiwia *et al*., 2022). Soil fertility, organic matter content, and soybean farming history are the factors that influence the efficiency of inoculants (Nartey *et al*., 2022). Organic matter can be added to phosphorus and applied to inoculated soybeans in areas with unpredictable rainfall patterns to improve the effectiveness of the inoculants (Ulzen *et al*., 2020).

2.7.6 Impact of Rhizobium Inoculation in Ghana

Applying phosphate fertilisers and rhizobium-inoculated soybean plants recorded grain yields three times those of the untreated plants, in Ghana's semi-deciduous forest zone (Adjei-Nsiah *et al*., 2022). Interaction between P fertilisers and inoculants supports efficient nutrient absorption, which further results to higher crop performance and increased productivity. This approach led to yield increases of up to 57.1% in other African countries and 25.7% in Ghana (Kiwia *et al*., 2022). Positive net present values, which offer substantial long-term net financial benefits, attest to the cost-effectiveness of inoculation. Smallholder farmers may now view inoculants as a viable option to maximize their return on investment (Kiwia *et al*., 2022).

2.7.7 Adoption and Challenges of Rhizobium Inoculation in Ghana

Adoption Factors: The acceptance of inoculant-based technologies is influenced by factors such as farmer group participation, access to extension, and education. These play a crucial role in encouraging smallholder farmers to adopt inoculants (Anang *et al*., 2023).

Barriers to Adoption: Although the benefits are clear, little awareness and access hinder widespread use. Addressing these challenges through supportive policies and market-driven incentives is key to promoting broader adoption (Kiwia *et al.*, 2022).

2.8 Fertilization of Soybean

Soybean seeds are rich in protein, containing about 35–40%, and often require substantial amounts of nitrogen, phosphorus, and potassium compared to many other crops.

Rhizobia are used by soybean plants to form root nodules, and these nodules can then hold onto air nitrogen and transfer it to the host soybean plants. Furthermore, nitrogen from soil or fertilizers typically nitrate can be absorbed by soybeans. The total amount of nitrogen assimilated in the shoot is directly correlated with the yield of soybean seeds, whether through nitrogen fixation or absorption. Therefore, the availability of nitrogen is crucial for the growth of soybeans. Sustaining a high level of nitrogen fixation activity over the long term is critical to soybean yield. Nevertheless, nitrogen fixation and nodule growth are typically inhibited by the use of artificial nitrogen fertilizers. Because soybeans can use both soil nitrogen (primarily in the form of nitrate) and atmospheric nitrogen (via symbiotic nitrogen fixation), their nitrogen (N) requirements are satisfied in a complex way (Milić *et al.*, 2002). One of the key elements thought to be crucial for raising crop output is fertilizer application. Research has demonstrated the importance of phosphorus as a necessary element for the growth, development, and yield of soybeans when applied (Kakar *et al.*, 2002). Lack of phosphorus is most likely one of the biggest obstacles to agriculture. According to Islam *et al.*, (2010), when potassium is applied at the rate of 40 kgha^{-1} an increase in Soybean yield is observed in Sudan.

The amalgamation of organic and inorganic fertilizers has the potential to augment the yield of soybeans and enhance the health of the soil. Under arid conditions, the application of compost in conjunction with diminished levels of urea has resulted in an increase in seed yield by 35-38% when compared to the utilization of chemical fertilizers solely. The effectiveness of the use of organic fertilizers in soybean farming is proven by this method while increasing profit margins (Sandrakirana and Arifin, 2021). The other biological fertilization alternative options include *Bradyrhizobium japonicum* and arbuscular mycorrhizal fungi have shown encouraging benefits to the sustainable environment and economic viability.

These techniques have as objective, decrease the usage of chemical fertilisers (Diaz-Franco *et al*., 2021). Basic fertilization techniques significantly affect both yield and soil microbial ecosystem. Higher microbial activities indicated that the change in chemical properties of the soil as a result of the basic application of chemical fertilizers was marginal, suggesting that basic fertilisation improved soil health and supports sustainable soybean production (Cazarim *et al*., 2023).

2.8.1 Integrated Nutrient Management

One important nutrient management strategy is the Integrated Nutrient Management (INM). This technique involves the use of both organic and chemical fertilisers to promote optimal crop yield and soil health. Studies have revealed that the application of this strategy increased growth and yield in soybean plants. An example of this technique is the use of cow dung manure on soybeans that were inoculated using rhizobium and phosphorus-solubilizing bacteria (PSB) resulting into taller plants, higher nodulation and seed yield compared to plants that were subjected to only synthetic fertilisers (Samad *et al*., 2024).

Another instance of INM was demonstrated when synthetic fertilisers were applied with organic matter, leading to enhanced soybean yield and nutrient absorption, highlighting that a balanced nutrient management strategy is essential (Nissa *et al*., 2023; Singh *et al*., 2024). The strategy involving putting together rhizobium, with PSB and organic matter has been shown to help soybeans increase nodulation and absorb nutrients more effectively, resulting in better yields and high protein content (Ismail and Bodkhe, 2023; Samad *et al*., 2024). Better soil health, and high levels of available nutrients were achieved with INM approach involving inorganic fertilisers and organic fertilisers such as vermicompost (Lohar and Hase, 2022; Nissa *et al*., 2023).

It is important to consider several factors when considering the type of fertilisers to apply; among the factors include soil characteristics, cost-effectiveness and environmental considerations. It is important to note that inorganic chemical fertilisers make nutrients available immediately, while organic ones make nutrients available gradual, thereby enhancing soil structure and fertility.

2.8.2 Organic Fertilizers

The contribution of organic fertilisers is beneficial, facilitating nutrient cycle and organic carbon build-up, leading to a more sustainable soybean farming. Studies have shown that inputs like vermicompost can improve soybean yields and seed quality (Lohar and Hase, 2022; Nissa *et al*., 2023). However, the benefits of organic manure may take more time to become evident due to their slow release.

2.8.3 Inorganic Fertilisers

Inorganic fertilisers, particularly nitrogen, phosphorus and potassium are essential due to soybeans' high nutrient demand. Studies have shown that balanced NPK application significantly improves yield and nutrient uptake (Khan *et al*., 2023; Ismail and Bodkhe, 2023). However, the overuse of these fertilisers is harmful to the environment and contribute to soil degradation.

Phenological Stages

R3 Stages: Studies on organomineral fertilisers application during R3 stage (pod formation) influenced positively pod number and grain yield (Olivieira *et al*., 2024). R5 Stage**:** Fertilising at the R5 stage (seed development) can further improve yield and seed quality, especially when sulphur-silicate fertilisers are used (Slameto, 2023; Slameto *et al*., 2024).

2.8.4 Predecessor Crops

Winter Wheat and Corn: Planting soybeans after winter wheat or corn, along with the use of organo-mineral fertilisers, has been found to significantly boost grain yield and overall productivity (Sokolovska *et al*., 2024).

Soybean-Maize Intercropping: Balanced nutrient input is key in intercropping systems. The combination of chemical and organic fertilisers improves crop yield and fertiliser use efficiency (Lin *et al*., 2022).

2.8.5 Role of Microbial Inoculants

Microbial inoculants like rhizobium and arbuscular mycorrhizal fungi (AMF) significantly enhance soybean productivity by boosting nutrient uptake and root nodulation. Co-inoculation rhizobium with phosphate-solubilizing bacteria (PSB) has been found to increase seed yield, nitrogen uptake, and nodulation (Ismail and Bodkhe, 2023; Samad *et al*., 2024).

Arbuscular mycorrhizae used with plant growth-promoting bacteria (PGPB) have been shown to increase root nodules, improve acid phosphatase activity, and increase soybean production (Ngosong *et al*., 2022).

Economic and Environmental Considerations

Sustainable fertilisation strategies ensure a balance between revenue generation and environmental protection in nutrient management strategies. The management strategies that involve the use of biofertilizers minimise the reliance on synthetic fertilisers, thereby making it cost-effective and protecting the environment. This minimal reliance on synthetic fertilisers makes biofertilizers and organic manuring more economically sustainable (El-Shaboury and Elnefili, 2022; Samad *et al*., 2024). Integrated Nutrient Management (INM) ensures an eco-friendly farming by reducing soil contaminants and reducing nutrient losses (Reddy *et al*., 2023; Singh *et al*., 2024).

2.8.6 Importance of NPK Fertilization on Soybean Yield and Quality

Nitrogen

The role of nitrogen is very key to yield parameters like plant height, podding and seed weight in the cultivation of soybeans. Nitrogen influences the chemical composition of soybean seeds. Nitrogen also affects fat and protein content levels, with lower nitrogen concentration increasing fat levels and higher nitrogen concentration increasing protein levels in soybean seeds (Pisulewska *et al*., 1999; Bobrecka-Jamro *et al*., 2018; Szostak *et al*., 2020). It is important to note that the rate and time of nitrogen application are critical (Szostak *et al*., 2020; Kulig and Klimek-Kopyra, 2022). The application of nitrogen before planting has been found to boost seed yields by making the nutrient available to plants at early growth stage which is a critical stage of development (Pisulewska *et al*., 1999;

Bobrecka-Jamro *et al*., 2018; Lošák *et al*., 2018; Szostak *et al*., 2020). Caliskan *et al*. (2008) state that soybeans require a comparatively high amount of nitrogen during the pod-filling stage. For example, the application of 120 kg Nha^{-1} resulted in an increase in yield by 10-12 % in comparison to unfertilized control groups (Kakabouki *et al*., 2022). Subsequent nitrogen applications during the stages of grain development have the potential to enhance yields, as evidenced by field trials conducted in India (Naj *et al*., 2023). Soybeans depend on symbiotic nitrogen fixation to fulfill a substantial portion of their nitrogen requirements. Nonetheless, elevated rates of nitrogen fertilisation for instance, 112 kg Nha^{-1} may impede nodulation, which is essential for biological nitrogen fixation (Bais *et al*., 2023). The co-inoculation with microorganisms such as *Bradyrhizobium japonicum* and *Azospirillum brasilense* has the capacity to augment nodule size and volume; however, it may not significantly influence yield when compared to conventional inoculation methods (Bais *et al*., 2023). The efficacy of nitrogen fertilisation may fluctuate markedly in relation to environmental conditions. In certain instances, nitrogen application has been associated with an increase in seed protein concentration, whereas in other cases, it has led to a decrease (Epie *et al*., 2023). Nitrogen fertilization can improve soybean yields, but the economic justification for such costs may be questionable, especially with higher application rates (Bais *et al*., 2023). Nitrogen application can increase weed biomass, thereby influencing weed dynamics and potentially necessitating additional weed management strategies (Kakabouki *et al*., 2022). Research conducted in Nigeria indicated that optimal yields were achieved with the application of 20 pounds of nitrogen per acre, with phosphorus (Tewari, 1965). Research revealed that the timing of nitrogen application in soybean significantly influences production. In certain instances, delayed nitrogen application did not improve yields, early nitrogen availability during growing stages is more critical (Zuffo *et al*., 2018).

Optimal Nitrogen Rates for Soybean Yield

The required nitrogen fertilization rate for soybean depends on factors like cultivar, soil fertility, and local environmental conditions. Research generally supports the moderate nitrogen levels promotion of yield, while excessive levels offer diminishing returns and lower nitrogen use efficiency.

Moderate rates (60-120 kgNha^{-1}): This rate range is often ideal for maximising soybean yield. For instance, in Northwest China, combining 120 kg Nha^{-1} with film mulching significantly improved grain yield, nitrogen and water use efficiency, and dry matter accumulation (Wang *et al*., 2023). Similarly, a rate of 144 kg Nha^{-1} was found most effective for second-season soybeans in Southeast Anatolia, enhancing both yield and profitability (Hatipoğlu and Haliloğlu, 2024).

Excessive Rates (>120 kg Nha^{-1}): Applying more than 120 kg N/ha doesn't always lead to better results. Once nitrogen needs were met, further application did not improve soybean seed yield or protein content as U.S. study revealed (Wysokinski *et al*., 2024). Nitrogen use efficiency decreased with excessive application of nitrogen which resulted to a disproportionate production gains, according to another Brazilian study (Figueiredo *et al*., 2024).

Physiological Responses to Nitrogen Fertilization

Plant vegetative growth, which relates to the accumulation of dry matter is promoted by the application of nitrogen as evidenced in a study on dryland farming found that the application of 120 kgha^{-1}of nitrogen fertiliser improved yield and dry matter accumulation

(Wang *et al*., 2023). Nitrogen application increases leaf area index (LAI), which improves radiation-use efficiency and light interception. According to research conducted under ideal optimum conditions, full nitrogen application produced a higher LAI and more effective light use than the controls without fertilization (Cafaro *et al*., 2020). Nitrogen transfer from vegetative parts of developing seeds that leads to heavier seeds is supported by nitrogen fertilisation. In the same research, full nitrogen application significantly improved nitrogen remobilisation and supported seed yield (Cafaro *et al*., 2020).

Interactive Effects of Nitrogen Fertilisation and Other Factors

Inoculation with *Bradyrhizobium japonicoum*

Higher nodulation and nitrogen fixation, which eventually leads to increased yield are supported by *Bradyrhizobium japonicum*. The application of nitrogen to inoculated soybean enhanced seed quality and yield. In research conducted in Poland, the application of 30 kg Nha^{-1} with B. japonicum inoculation increased seed yield and protein content, compared to the untreated controls (Szpunar-Krok *et al*., 2023). Similarly, grain yield, seed weight, and effective nodulation in another study were boosted by inoculation, with the maximum yield recorded at 144 kg Nha^{-1} (Hatipoğlu and Haliloğlu, 2024). The adverse effects of drought can be mitigated by nitrogen fertilization, as evidenced in a study conducted in Hungary, which found that nitrogen application in dry conditions produced higher yields, despite high nitrogen resulting in decreased oil content in the seeds (Basal and Szabó, 2020).

Sulphur is essential for nitrogen metabolism and improves nitrogen utilisation efficiency. According to a study, fertilisation with sulphur and nitrogen, especially at lower nitrogen rates, significantly increased seed yield in temperate regions (Szostak *et al*., 2020).

Impact of Nitrogen Fertilization on Seed Quality

Protein Content: Generally, nitrogen affects protein levels in soybean seeds. A research conducted taking into consideration the specific environmental conditions of the site in the Southeast United States revealed an increase in the protein content of soybean when nitrogen was applied; the results were, however, dependent on the local factors (Epie *et al*., 2023).

Oil Content: Lower oil content is associated with high rates of nitrogen. Lower oil content was recorded in Hungary during drought when soybeans were supplemented with nitrogen (Basal and Szabó, 2020).

Seed Quality: Seedlings' strength and resilience, seed vigour and viability, germination and the overall chemical composition of the seed are enhanced by nitrogen. Split application of 120 kg Nha^{-1} during the R2 and R5 growth stages increased seed yield and quality, according to a Paraguayan study (Bagateli *et al*., 2023).

Environmental and Economic Considerations

Nitrogen Use Efficiency (NUE): The abuse of nitrogen lowers NUE and raises the possibility of environmental pollution. According to a Brazilian study, NUE dropped as nitrogen rates rose, emphasizing the necessity of balanced fertilisation (Figueiredo *et al*., 2024).

Economic returns. In addition to increasing production, optimal nitrogen application rates also increase financial returns. For instance, research conducted in Şanlıurfa, Turkey, discovered that inoculation with 144 kg N/ha increased grain yield and financial gains (Hatipoğlu and Haliloğlu, 2024).

2.8.7 Phosphorus (P), Rock Phosphate (RP) and TSP (Triple Superphosphate) as sources of P

Phosphorus

A lack of phosphorus can result in greater yield reductions compared to nitrogen, with losses projected to range from 29% to 45% (Hellal and Abdelhamid, 2013).

Regular use of phosphorus fertilisers can provide enduring advantages, enhancing soil fertility and boosting soybean production in subsequent growing seasons (Boswell and Anderson, 1976). Phosphorus frequently regulates how legumes fix nitrogen (Pérez-Fernández *et al*., 2019), and in Ghana, this macronutrient is sporadically found in the soil (Rastilantie *et al*., 2010; Masso *et al*., 2016). The primary nutrient-stabilizing biological nitrogen in soybeans is phosphorus, which also removes 28 kg of Pha^{-1} from the soil (Goswami, 2016). Phosphorus leaks from the soil imperceptibly; to nourish the crop, it has to be liberated from the soil. It is the nutrient that restricts soybean productivity the most (Brennan *et al*., 2004). For oilseeds like soybeans, it is more crucial than other nutrients to raise production. Phosphorus is regarded as the most important element and has been demonstrated to be essential for the growth, development, and productivity of soybeans (Kakar *et al*., 2002).

Effects of Phosphorus Fertilization on Soybean Growth and Yield

Growth Parameters

Root development, and plant height are significantly influenced by phosphorus application. Plant height and root-related development, such as dry biomass and root length, which are crucial for drought resistance and nutrient uptake, were improved by P fertilization (Salim *et al*., 2023, 2024). The extent of influence on soybean yield by P fertilization depends on the rate of application and the soil conditions. Higher levels may decrease efficiency or cause diminishing return; rates between 30 and 60 kg Pha^{-1} usually yield optimal results (Mabapa *et al*., 2010; Kabiru *et al*., 2024). For example, yield was significantly increased at the rate of 39 kg Pha^{-1}, however. lower rates were less impactful according to a study in Nigeria (Mangwa *et al*., 2024).

Cultivar Variability: Cultivars respond differently to phosphorus application. In south Africa, for example, Pan 520RR and Highlevel Top outperformed LS 555 in grain yield, indicating the importance of selecting suitable cultivars alongside effective phosphorus management (Mabapa *et al*., 2010).

Impact on Seed Quality and Nutritional Value

The application of phosphorus boosts yields and also enhances the seed quality of soybean. These benefits include: **(i) Protein and oil composition:** phosphorus increases the protein content and moves the oil profile towards a higher proportion of unsaturated fatty acids, which are beneficial for human consumption (Ran *et al*., 2024; Bagade *et al*., 2025), **(ii) Essential amino Acid:** It also improves the seeds nutritional quality by increasing the levels of essential amino acids (Ran *et al*., 2024), and **(iii) Micronutrient Absorption:** Phosphorus fertilisation supports better uptake of key micronutrients like iron and zinc, further enhancing seed quality (Bagade *et al*., 2025).

Optimal Phosphorus Application Rates and Methods

Application Rates

The optimal P rate varies by soil type, cultivar, and environmental conditions. Studies suggest: (i) low to moderate rates for good and effective nutrient usage and financial returns, rates of 15 to 45 kg Pha^{-1} are frequently enough, particularly in environments with limited resources (Kabiru *et al*., 2024), and (ii) higher rates: in soils with poor P content or high-yield systems, rates of 60 to 100 kg Pha^{-1} can be necessary (Salim *et al*., 2023; Elaldı *et al*., 2024).

Economic and Environmental Considerations

Economic Viability

Phosphorus fertilization is a crucial expense for soybean farmers. Research indicates that applying optimal P levels, such as 35 kg Pha^{-1}, can enhance profitability, whereas higher application rates may sometimes lead to reduced returns and efficiency (Meetu *et al*., 2023; Kabiru *et al*., 2024).

Environmental Impact

Overuse of P can pollute the environment and cause nutrient leaching. Productivity is maintained while these dangers are reduced with balanced P use, which is frequently accomplished through reduced rates and effective application techniques (Elaldı *et al*., 2024; Kabiru *et al*., 2024).

Interactive Effects of Phosphorus with Other Nutrients and Factors

Nitrogen and Sulphur: Phosphorus works in concert with sulphur and nitrogen. For example, soybean production and quality were greatly increased by P and sulphur fertilisation at 60 kg P/ha and 45 kg S/ha (Khan *et al*., 2023).

Water Shortage: Phosphorus creates an enabling environment for the roots to use water more efficiently, when there is a soil water shortage, making soybeans drought-resistant (Salim *et al*., 2024).

Soil Type and Organic Amendments

The uptake of P in soybeans becomes more coherent, most especially in soils that contains more calcium. This ability is induced by the application of organic materials like phosphorus-rich manure, thereby making farmers less dependent on synthetic fertilisers (Meshram *et al*., 2024; Bagade *et al*., 2025).

Sources of P, Rock Phosphate (RP) and TSP

Among the various sources of soluble P, TSP is the best; crude rock phosphate (RP) has a long-term advantage due to its slow-release of P in developing countries, making it the preferred choice among soybean farmers of those countries (Silva *et al*., 2017). Rock phosphate is made up of tricalcium phosphate which is unavailable to plants due to its insolubility in water (Sharif *et al*., 2013). Several factors, such as soil type, climate, particle size, moisture levels, timing and modes of application, affect the effectiveness of RP as a source of P (Zoysa *et al*., 2001). Chemical fertilisers are more reactive than RP, when they are applied straight into the soil, however, microorganisms slowly make RP available, through their activities in the soil ecosystem (Coutinho *et al*., 1991). When applied to acidic, phosphorus-deficient soils with pH below 5.5, RP works better (Sanchez, 1977; Rajan *et al*., 1996). Phosphorus and nitrogen are two essential nutrients, that are easily absorbed when RP is applied with other nutrient inputs like sulphur, impacting positively on soybean yield (Brahim *et al*., 2017). The combination of RP with organic inputs such as manure and zeolite improved nutrient such as N, P, and K uptake and increased Allison’s yields partly due to enhanced soil pH and cation exchange capacity (CEC) (Haniati *et al*., 2020). The RP is more suitable for acidic soils due to its solubility. Liming acidic soils can maintain RP solubility and balance pH levels, while mitigating the detrimental effects on plant growth caused by soil acidity (Huang and Hue, 2022). Research in the Brazil Cerrado region, which has high-P soil characteristics, revealed that adding a soluble source of P, such as TSP, to RP increases phosphorus availability and boosts soybean productivity (de Oliveira *et al*., 2011). Yields that were at par with or above those obtained from only water-soluble phosphorus sources were recorded when RP was combined with more soluble P source fertilisers (de Oliveira *et al*., 2011). Organic matter such as manure can boost the effectiveness of RP through enhanced soil structure and nutrient retention (Haniati *et al*., 2020). It is therefore important to select the appropriate source of P, which can affect the environment and the economy. Although the type of fertiliser used (RP vs. TSP) may not significantly affect the efficiency of phosphorus use (Guera *et al*., 2020), The application method and the state of the soil are often more important. In organic settings, where it works well with natural amendments to preserve soil health, RP is frequently regarded as a more cost-effective choice. (Huang and Hue, 2022).

The TSP has proven to be an enhancer of good yields. In Brazil's Cerrado, the application of TSP at a rate around 100 kgha^{-1} of P_2O_2 produced notable yield gains from the genotypes tested. The AS3680 genotype achieved 91.57 bags per hectare, representing a 21.57% rise (Ferreira *et al*., 2022). TSP is also effective at inducing phosphorus use efficiency (PUE), as studies have shown an upward adjustment in grain yield, shoot biomass and phosphorus levels in the grain (Guera *et al*., 2020). Aside the positive influence TSP has on soil fertility and grain yield when applied to inoculated soybean seeds, it also enhances the plant's ability to fix nitrogen (Anani *et al*., 2021). The crop genotypes and the amount of P in the soil affect the rate at which TSP should be applied, with a range of 75-95.65 kgha^{-1} of P_2O_2 application rate ideal (Santini *et al*., 2020; Ferreira *et al*., 2022). Farming systems that involve crop-livestock inter-farming make TSP the best for this system to boost soil fertility and crop yield (Guera *et al*., 2020). TSP has many benefits, and for one to consider choosing TSP, its benefits must be compared with its cost and environmental impact. The time of application of highly soluble sources of P is critical, and when the timing is right, the negative influence of the P sources on the environment is reduced, thereby increasing productivity (Cahyono and Minardi, 2021). Nutrients can also be derived from organic materials, which offer minerals that can be sustained and still give appreciable levels of yield (Cabral *et al*., 2020).

2.8.8 Potassium (K)

The levels of K supplied to the soil affect nodulation, nitrogen fixation, and the overall soybean productivity. The amount of nitrogen fixed by soybean depends on the rate at which P is applied, leading to an enhanced nodules mass and quantity (Jones *et al*., 1977). Available K affect soybean crop stress tolerance, enzyme activation, osmotic regulation, protein synthesis and photosynthesis (Kafkafi *et al*., 2001). Research conducted by (Steiner *et al*., 2022) revealed that the application of P supported yield under stress by lowering leaf and pod losses. Potassium fertilisation boosts pod and seed count per plant and grain yield, with ideal rates varying by cultivar (Kibet *et al*., 2023). Higher potassium levels are also linked to improved protein and oil concentrations in seeds; for instance, applying 45 kg K_2O ha^{-1} to the DPSB19 variety resulted in a protein content of 42.99% and optimal oil levels (de Lima *et al*., 2017; Kibet *et al*., 2023).

The mode and timing of potassium application can influence yield outcomes. Foliar applications, particularly when combined with magnesium, have shown benefits in crops like wheat and are likely to offer similar advantages in soybeans (Singh *et al.*, 2020; Yadav *et al*., 2024). Potassium availability is also influenced by soil structure; in no-till systems, potassium tends to accumulate in the topsoil, which may improve uptake (Fernández *et al*., 2009; Nurlaeny *et al*., 2022). However, over-application does not always equate to better yields.

Potassium fertilization enhances plant resilience to environmental stresses. In saline conditions, potassium application increased yield by over 92 % compared to untreated crops (Taha *et al*., 2020). In water-limited environments, potassium also improves water use efficiency, supporting yield stability (Kumar *et al*., 2022). The benefits of potassium vary by soil type; in sandy soils with low native potassium, fertilisation significantly boosts yield by improving potassium use during grain filling (Ma *et al*., 2013). Without adequate potassium, yield losses of up to 30 % can occur (Hellal and Abdelhamid, 2013).

2.8.9 Application of Muriate of Potash

Yield and Economic Benefits: When applied 15 to 30 days after the first flower, in-season MoP applications in Arkansas at 74–112 kgKha^{-1} demonstrated economic viability and greatly boosted soybean yields and partial returns (Ortel *et al*., 2024).

Potash application in Madhya Pradesh and Maharashtra, India, raised soybean yields by 26 % and 36 %, respectively, which resulted in significant improvements in smallholder farmers' net profits (Nachmansohn *et al*., 2019).

Recommended Application Rates and Methods: Applying 120 kgha^{-1} of MoP enhances soybean yield and growth metrics, including pod quantity and seed, according to studies conducted in Bangladesh and Brazil (Khanam *et al*., 2016; Barbosa *et al*., 2025).

Different soybean varieties in Kenya reacted differently to K rates; for some, 67.5 kg K_2O ha^{-1} was ideal, suggesting that suggestions tailored to individual varieties are necessary (Kibet *et al*., 2023).

Soil and Nutrient Management

Crop response and soil K availability are impacted by potassium delivery techniques, such as banding versus broadcasting. In some soil types, banding can improve nutrient absorption by increasing K desorption (Pesini *et al*., 2024).

Results from Brazil suggest that alternative potassium sources, including remineralizers, can be as effective as conventional potassium chloride, offering potential for sustainable and cost-effective potassium fertilisation options (Brasil *et al*., 2025).

Synergistic Effects and Long-term Considerations

In Ghana, mixing potassium with other minerals like phosphorus has the potential to enhance soybean production and improve nutrient utilisation efficiency (Awuni *et al*., 2024).

Research over an extended period has shown that applying too much potassium can lead to nutrient imbalances, such as reduced levels of calcium and magnesium. When formulating a fertilisation technique, it is important to make sure it is well-balanced, a point the study highlighted (Bossolani *et al*., 2022).

2.8.10 Influence of Inorganic Nutrient Supplementation on Growth Parameters and Grain Yield

Nitrogen (N), phosphorus (P), and potassium (K) play a major role in the growth and development of soybeans.

Phosphorus is vital for cell growth and the overall development of plants. Research indicates that plants lacking phosphorus show reduced growth compared to those with sufficient phosphorus levels. For instance, the impact of phosphorus on plant height was significantly positive, achieved through enhanced dry matter production and the creation of an enabling environment for symbiotic activities, under poor moisture conditions (Fredeen *et al*., 1990; Rotaru, 2010).

The relationship between nitrogen and phosphorus is crucial. The interaction between nitrogen and phosphorus is a positive one, and this is demonstrated by the effect of phosphorus on how effective nitrogen influences the vegetative growth of soybean. In the case of *Stylosanthes humilis*, the correct use of nitrogen and phosphorus fertilisers encouraged both growth and nodulation, leading to taller plants (Gates and Wilson, 1974). Cell tugor and elongation are important processes in plant cell development, processes which are crucial for vertical for plant growth are affected by the key role of potassium. It helps to sustain osmotic potential within cells, enabling their expansion and contributing to increased plant height (Amtmann and Rubio, 2012; Kumar *et al*., 2022).

In soybean cultivation, adequate potassium supply has been shown to substantially enhance plant height. A study conducted in Kenya revealed that applying 67.5 kg K_2O per hectare resulted in taller soybean plants compared to those that received lower potassium levels (Kibet *et al*., 2023).

Potassium also influences plant height indirectly by regulating stomatal conductance and facilitating photosynthesis. Improved photosynthesis supports greater carbon assimilation, which in turn can promote shoot elongation and taller plant (Jay *et al*., 2012; Wasaya *et al*., 2021).

Chlorophyll content, which is a key photosynthetic efficiency indicator, is closely related to nutrient availability, particularly nitrogen (N), phosphorus (P), and potassium (K). The role of nitrogen is key in chlorophyll synthesis, its deficiency often results in low chlorophyll levels, which can impair photosynthesis and lower yields (Fredeen *et al*., 1990;

Hellal and Abdelhamid, 2013). Phosphorus deficiency can hinder chlorophyll synthesis by affecting key enzymes in the Carbon Cycle, thereby reducing carbon fixation (Fredeen *et al*., 1990).

Potassium deficiency also results in decreased chlorophyll content, which is an observation across various crops, including cotton (Bednarz *et al*., 1998; Kumar *et al*., 2022). In soybean, potassium fertilisation has been shown to improve chlorophyll content, with foliar potassium treatments in wheat, for instance, leading to higher chlorophyll levels, and similar positive responses have been reported in soybean when available potassium is sufficient (Taha *et al*., 2020; Yadav *et al*., 2024). Moreover, potassium enhances chlorophyll retention in stress conditions. External application of potassium improved chlorophyll content of soybean in saline soils, by strengthening the plant's antioxidant defence system and minimizing oxidative damage (Taha *et al*., 2020).

The response to soybean fertlization depends on the type of cultivar. A study involving DPSB19, Gazelle, and SB24 found that chlorophyll content increased with 45 kg K_2O ha^{-1} in DPSB19 and SB24, while Gazelle showed optimal chlorophyll levels at a lower dose of 22.5 kg K_2O ha^{-1} (Kibet *et al*., 2023).

The application of nitrogen and phosphorus together has proven to be more effective at improving chlorophyll content than their single applications. Integrated nutrient management approaches such as using vermicompost in combination with NPK fertilizers have demonstrated significant increases in chlorophyll concentration in soybean leaves (Singh *et al*., 2014; Gangwar *et al*., 2023).

Nodulation plays a crucial role in soybean plants as it facilitates symbiotic nitrogen fixation, which is essential for their growth and productivity. Phosphorus acts as a vital regulator of nodulation. Insufficient phosphorus conditions significantly reduce both the formation and functionality of nodules, supported by studies indicating that Phosphorus fertilisation restored nodulation and improved nitrogen and phosphorus uptake, even in both well-watered and drought-stressed environment (Rotaru, 2010; Jin *et al*., 2022). Even though, nitrogen is essential for plant growth, excessive application can be harmful to nodulation, by reducing the demand for symbiotic nitrogen fixation. However, a correct nitrogen application, especially when applied together with phosphorus, has been shown to enhance nodulation and increase yields (Gates and Wilson, 1974).

The combination of rhizobial inoculants, like *Bradyrhizobium japonicum*, and phosphorus fertilisers has been shown to enhance nodulation and increase soybean yield. Research indicates that integrated nutrient management strategies using microbial inoculants significantly improve nodule dry weight and seed production (Farhad *et al*., 2017; Shome *et al*., 2022).

Potassium supplementation also plays a key role in supporting both the formation and efficiency of nodules in soybeans. Studies have found that better nodule development and nitrogen fixation are improved by higher soil potassium levels (Wojcieska and Kocoñ, 1997). From a study conducted by Premaratne and Oertli, (1994) more nodules mass and number were produced on soils with optimal P levels compared to those that where grown on P-deficient soils. Potassium and phosphorus interact to enhance nodulation and biological nitrogen fixation in soybean as evidenced by Saat (2014) and Bongiovanni *et al*. (2016) who found the use of potassium chloride with single superphosphate (SSP) to significantly improve nodule and biomass as well as overall yield.

Relationship Between Plant Height, Chlorophyll Levels, Nodulation, and Soybean Yield

The relationships between soybean nodulation, plant height, chlorophyll content and yield are important in evaluating the performance of soybeans. Tall plants undergo higher levels of photosynthesis due to their ability to intercept more light because of their height, resulting in increased yields. The response to nutrient supplementation results in tall plants and the production of more grains (Singh *et al*., 2014; Mshamu, 2015). High yield of above-ground dry biomass is associated with higher chlorophyll content and better photosynthesis. Nutrient formulations that improve plant chlorophyll content; also boost seed yield (Gangwar *et al*., 2023; Biswas *et al.*, 2024). Another important yield component is nodulation has a direct impact on nitrogen supply. Several studies reported that increased nodulation through microbial inoculation and balanced nutrition strategies improves seed yields (Farhad *et al*., 2017; Shome *et al*., 2022).

Rock Phosphate (RP) Substitution with Triple Superphosphate (TSP), Phosphorus (P) Sources and Their Efficiency in Soybeans Production

Soybean yield, nodulation and overall plant health and optimal growth are directly affected by phosphorus. The selection of P source for production, especially between TSP and RP, influences the movement of phosphorus in the soil and the effectiveness with which P is absorbed. The rate of 75 kg P_2O_5 ha^{-1}, which is usually recommended for the application of TSP, significantly increased soybean yields in areas, with high soil fertility (Santini et *al*., 2020). One limitation to the absorption and utilisation of P is P fixation, which is caused by the excessive use of TSP (Veneklaas *et al*., 2012; Gaind, 2017).

The slow release of P from RP makes it preserve the environment more than TSP, and the two P sources combine well or organic materials. Farmyard manure combined well with single superphosphate to significantly improve soybean yield and increase the levels of P, in a study conducted Meghalaya (Majumdar and Kumar, 2007). Regular fertilisation with P is minimized due to the gradual released of P from RP source (Franzini *et al*., 2009; Rosendo *et al*., 2018). P is made available for plant nutrition throughout the season, while the availability from TSP is immediate, making the availability of P from TSP not sustainable. The first year of a study conducted to compare sources of P revealed that the reactive natural phosphate (RNP) produced more grains than TSP, although TSP raised the soil's P more rapidly, suggesting that the two sources, when applied together, could enhance the balance of available P (Richart *et al*., 2006).

Strategies for Optimizing Rock Phosphate Utilization

The combined use of TSP and RP has made it easier for RP to be used as a substitute of TSP, ensuring the short- and long-term P needs of soybean plants. When Gafsa rock phosphate was tested in a greenhouse with TSP, the absorption of P was considerably improved, particularly when it was not directly applied to the plant roots (Franzini *et al.*, 2009). The approach ensures the available P is sustained through slow and instant releases of P from RP and TSP, respectively.

Residual Effects and Soil Fertility

Frequent P supplementation improves soil fertility and ensures regular and consistent yields from one growth season to another. To improve the overall soil conditions and soil fertility, the knowledge of the long-term implications of P fertilisation on the environment is vital for successful nutrient management.

Residual Effects of TSP

TSP does not always result in an increase in soil P levels in the long run, although its solubility enables quick absorption. In a sugarcane study, TSP applied by broadcasting did not increase total phosphorus in the 0-40 cm soil layer when compared to the untreated plots. This highlights the need for strategies to sustain P levels beyond the initial crop cycle (Rosendo *et al*., 2018).

Residual Effects of RP

RP's slow-release of P offers enduring benefits. Residual P from RP consistently increased soil P levels and soybean yields for a duration of up to five years, as evidenced by comprehensive research conducted in Meghalaya (Majumdar and Kumar, 2007). Similar findings were made in Brazil, where it was discovered that mixing RP and TSP helped make phosphorus available for soybean and oat (Richart *et al*., 2006).

Soil P Pools: Phosphorus sources influence the various pools of phosphorus in soil. TSP predominantly enhances labile (readily available) phosphorus, while RP contributes to both moderately labile and organic phosphorus fractions. In sugarcane systems, TSP was found to be more immediately effective, but RP demonstrated stronger residual advantages over time (Rosendo *et al*., 2018).

2.8.11 Benefits and limitations of using rock phosphate

Rock phosphate, a naturally occurring phosphorus source, has been widely studied for its potential in sustainable soybean farming. While it offers several benefits, there are also notable limitations.

Benefits of Rock Phosphate in Soybean Systems

Environmentally Sustainable Option: The RP is a non-synthetic, natural phosphorus source that supports environmentally friendly farming practices. It reduces reliance on energy-intensive chemical fertilisers, thereby lowering greenhouse gas emissions (Haniati *et al*., 2020; Huang and Hue, 2022).

Economical and Sustainable Fertility. In comparison to synthetic alternatives, RP is less expensive when combined with organic inputs or biofertilizers. Phosphate-solubilising bacteria (PSB) or farmyard manure (FYM) applied with RP has been shown to enhance available P and reduce the need for substantial fertiliser applications (Noor, 2005). The slow release of nutrients contributes to the enhancement of long-term soil fertility (Meena and Biswas, 2013).

Improve Soil Quality; The RP has the potential to increase pH levels and reduce harmful aluminium concentrations in acidic soil, thereby improving the growth conditions for soybeans (Huang and Hue, 2022). RP can improve soil organic matter and promote microbial activity when used with compost or green manure (Meena and Biswas, 2013).

Enhanced Nutrient Absorption and Crop Yield; When combined with organic materials or inputs such as NPK, RP can improve crop yield and nutrient uptake. Research indicates that the combination of RP, zeolite, and manure enhances soybean productivity in Alfisols (Haniati *et al*., 2020). Co-inoculation of *Bradyrhizobium japonicum* and PSB enhances yield and increases available P (Singh and Singh, 1993; Dubey *et al*., 1997). The interaction of biofertilisers, such as vesicular-arbuscular mycorrhizae (VAM) and phosphate-solubilising bacteria (PSB), had a positive impact on P solubilization and plant absorption, especially when used with RP. This interaction supports seed quality, particularly protein content, alongside yields (Munda *et al*., 2001; Mahanta and Rai, 2008).

Residual Benefits for Subsequent Crops

The residual effects of RP can benefit subsequent crops in a crop rotation systems as evidenced by Tanwar and Shaktawat (2003) and Meena and Biswas (2013) who found that the application of RP to soybeans enhanced wheat production and improved available nutrients.

Limitations of Using Rock Phosphate in Soybean Cultivation

Low Solubility and Availability

Factors like soil's pH and microbial activities which may require extra changes to improve P solubilization, have a significant impact on the efficacy of RP (Brahim *et al*., 2017; Huang and Hue, 2022).

Limitations by Soil pH

Rock phosphate dissolves best in soils with pH range between 5.5 and 7.0 which is neutral to slightly acidic. In extremely acidic soils, its efficacy may reduce, and liming may be necessary to lower the soil pH to a more acceptable level (Chien *et al*., 1995; Huang and Hue, 2022). Because of its poor solubility in alkaline soils, RP may not attain its full potential in some environments (Tanwar and Shaktawat, 2003).

Variable Agronomic Effectiveness

The efficacy of RP in soybean farming is affected by its quality and availability. Research indicates that North Carolina Rock Phosphate (NCRP) frequently shows superior relative agronomic effectiveness (RAE) compared to other types, such as Udaipur Rock Phosphate (URP) and Mussoorie Rock Phosphate (Sharma *et al*., 2001; Sharma *et al*., 2003). Since different sources of P have varying degrees of solubility, choosing the right kind of rock phosphate for a given soil condition requires careful consideration.

Dependence on Microbial Activity

The release of P from RP is supported by the vital role of fungi and bacteria that solubilise phosphate. The activity of soil bacteria has a significant impact on the effectiveness of rock phosphate. To increase phosphorus availability in soils with low microbial activity, further inoculation with vesicular-arbuscular mycorrhizal fungus or phosphate-solubilizing bacteria may be necessary (Noor, 2005; Singh and Singh, 1993).

Potential for P Deficiency in High-Yielding Systems

High-yielding soybean crops may require more phosphorus than rock phosphate alone can supply, particularly in low-phosphorus soils. Comprehensive nutrient management techniques or additional phosphorus fertilisation may be required to prevent yield losses (Schoninger *et al*., 2013; Savini *et al*., 2016).

Long-Term Sustainability Concerns

Although rock phosphate occurs naturally, its limited supply and the effects of rock phosphate mining on the environment raise questions about its sustainability. If an excessive amount of rock phosphate is used and not replaced by organic matter or other sources, soil fertility may eventually deteriorate (Meena and Biswas, 2013).

2.8.12 Essential micronutrients for soybeans

Boron (B)

Transport of nutrients, membrane function, and cell wall stability all depend on boron. Additionally, it plays a role in the flower formation and seed development (Fageria *et al*., 2002). A lack of boron can result in the abortion of flowers, decreased pod development, and diminished seed production. It may also cause seeds to be distorted or misshapen (Fageria *et al*., 2002; Hellal and Abdelhamid, 2013). Applying boron through foliar methods, particularly during the reproductive phase, can enhance both yield and seed quality (Fageria *et al*., 2002; Patil *et al*., 2020).

Zinc (Zn)

Many of the physiological processes that plants go through depend on zinc. The biosynthesis of tryptophan, a precursor to auxin, is necessary for cell elongation. For plants to produce chlorophyll normally, zinc is necessary (Tisdale and Nelson, 1984). Application of zinc enhanced nodule nitrogenase activity and nodulation efficiency (Zhang and Yang, 1996). Zinc is an essential element for enzymes and a healthy plant's metabolism in soybeans. Yellow mottling between leaf veins, which initially develops in the upper leaves, is one sign of a zinc shortage. Just like cobalt, copper, manganese, and nickel, zinc (Zn^{2+}) is taken up by soybeans from the soil.

Zinc is crucial for the synthesis of proteins, the stability of membranes, and the functioning of enzymes. Additionally, it contributes to the detoxification of superoxide radicals and supports the health of plants (Fageria *et al*., 2002).

A lack of zinc can lead to slowed development, reduced leaf dimensions, and lower crop production. An irregular storage of P might also occur in the worst-case scenario, which is harmful to plants (Parker, 1997; Dell *et al*., 2006). Focusing mainly on the growth stages V6 and R, the direct application of zinc to the leaves enhanced seed quality and yield. This method of application would require several repetitions to successfully solve the inadequate levels of zinc (Gettier *et al*., 1985; Científicas, 2012).

Molybdenum (Mo)

Nitrogenase and nitrate reductase are some of the nitrogen metabolism-related enzymes which are essential for nitrogen fixation and require molybdenum to become fully functional (Fageria *et al*., 2002). One of the functions of molybdenum is to support nitrogen fixation and increase crop yield, and it is usually used with lime to change soil pH, mostly in acidic soils (Anderson and Mortvedt, 1982; Bhat *et al*., 2020). The amount and the effectiveness of nitrogen fixation is negatively impacted by molybdenum deficiency, leading to poor seed quality and grain yield; an issue mostly persistent in acidic soils (Anderson and Mortvedt, 1982; Bhat *et al*., 2020).

Copper (Cu)

Lignin synthesis and photosynthesis are among the several processes that are influenced by copper and also helps to protect plants against antioxidants (Fageria *et al*., 2002). Reduced leaf area, plant height and seed production are all associated with low levels of copper (Fageria *et al*., 2002; Hellal and Abdelhamid, 2013). Despite the rarity of copper deficiencies in soybeans, balanced fertilisation methods can help maintain adequate soil copper levels (Raghuveer and Keeerti, 2017; Gangwar *et al*., 2023).

2.8.13 Impact of NPK Fertilization on Soybean Quality

In terms of protein and oil content, soybeans have 40–42 % protein, depending on the amount of nitrogen applied. Increasing the nitrogen content of soybeans can increase their protein levels (Hellal and Abdelhamid, 2013; Shome *et al*., 2022).

Phosphorus fertilisation is associated with higher soybean oil content. Effective phosphorus management has been shown to enhance oil quality in particular and crop yield (Lara *et al*., 2018; Tewari, 1965).

Seed Quality and Absorption of Nutrients. It can be verified that potassium use improves seed quality by increasing seed density, electrical conductivity, and moisture content. These factors are essential for maintaining seed viability and overall quality (Lara *et al*., 2018).

When applied properly, NPK fertilisation can affect the uptake of micronutrients like iron and zinc, improving seed quality even though it primarily supplies macronutrients (Meshram *et al*., 2019; Shome *et al*., 2022).

2.9 The Effect of Nutrient Deficiencies on the Health of Soybeans

2.9.1 Nitrogen (N) Deficiency

Effects on Growth and Yield

For soybeans, nitrogen is an essential nutrient that supports chlorophyll content, leaf growth, and total plant biomass. Growth can be hampered by a nitrogen deficiency, which results in fewer leaves and less shoot mass (Lemaire, 1997; Hellal and Abdelhamid, 2013). A nitrogen deficiency can cause a 10 % drop in soybean yields since nitrogen is necessary for the synthesis of seed proteins and the overall productivity of the plant (Hellal and Abdelhamid, 2013).

Role in Nodulation and Nitrogen Fixation

The Nitrogen Use Efficiency (NUE) is used to evaluate legumes, especially soybeans. Soybeans are able to thrive under adverse weather conditions and inadequate soil water conditions due to high NUE. The kind of mutualistic relationship rhizobia have on root nodules is essential for soybeans to fix nitrogen. Nitrogen deficiency retards nodules' growth and lowers the effectiveness of nitrogen fixation, worsening the other effects of the deficiency (Jin *et al*., 2022; Shome *et al*., 2022).

Physiological Responses

A lack of nitrogen can reduce the effectiveness of photosynthesis by influencing chlorophyll synthesis and varying its form (Lemaire, 1997; Sun *et al*., 2018).

Under nitrogen deficiency, levels of ureides in nodules and roots increase, indicating a potential disruption in nitrogen fixation (Rotaru, 2010).

Management Schemes

Timely and proper nitrogen fertilisation is essential to avoid shortages and minimise environmental impact (Yan-ming, 2011; Hellal and Abdelhamid, 2013). Inoculating soybeans with nitrogen-fixing bacteria such as Rhizobium japonicum can improve nitrogen absorption and increase yields, particularly in conditions where nitrogen is lacking (Shome *et al*., 2022).

2.9.2 Phosphorus (P) Deficiency

Effects on Growth and Yield

A lack of phosphorus restricts the growth of soybeans by decreasing both cell division and expansion. Consequently, this leads to shorter plants that have smaller leaves (Fredeen *et al*., 1990; Jin *et al*., 2006). A lack of phosphorus can lead to considerable reductions in yield, varying between 29 % and 45 %, based on how severe and prolonged the deficiency is (Hellal and Abdelhamid, 2013).

Impact on Photosynthesis and Assimilate Partitioning

A lack of phosphorus decreases the function of enzymes in the Calvin cycle, resulting in lower CO_2 fixation and reduced photosynthetic efficiency (Foyer and Spencer, 1986; Fredeen *et al.*, 1990). Plants that lack phosphorus tend to produce more starch in comparison to sucrose, which may restrict the energy accessible for their growth and development (Foyer and Spencer, 1986).

Role in Drought Tolerance

A phosphorus deficiency intensifies drought stress by decreasing the accumulation and transport of phosphorus to seeds. Applying phosphorus fertilizer can improve drought resilience by increasing both phosphorus and nitrogen accumulation (Jin *et al*., 2006; Rotaru, 2010).

Management Schemes

Phosphorus application, especially in phosphorus-deficient soils, can significantly improve soybean growth, boost nodulation, and increase overall yield (Rotaru, 2010; Mshamu, 2015). Breeding soybean varieties with high phosphorus uptake efficiency can help minimize yield losses under phosphorus-deficient conditions (Mshamu, 2015; Zhang *et al*., 2021).

2.9.3 Potassium (K) Deficiency

Effects on Growth and Yield

Several enzymes require potassium to become active; cell tugor maintenance and osmotic pressure all depend on potassium (Firmano *et al*., 2020). Potassium deficiencies can lead to soybean yield losses ranging between 16% - 36%; this yield loss is, however, dependent on the levels of the deficiency (Hellal and Abdelhamid, 2013).

Role in Cation Balance and Nutrient Uptake

Potassium deficiency lowers the available calcium (Ca) and magnesium (Mg) in the leaves, which also makes ions in the soil and plant tissues imbalanced (Firmano *et al*., 2020). In the same study, Firmano *et al.* (2020) observed that certain micronutrients, which are crucial, including boron, are influenced by the lack of potassium.

Management Schemes

Potassium improves soybean growth and yield, while helping to restore lost potassium nutrients from the soil; excessive supply of K, however, causes nutrient imbalance in the soil (Firmano *et al*., 2020).

2.9.4 Combined Effects of Nutrient Deficiencies

Interactive Effects of N and P Deficiencies

The deficiency of both P and N causes a decline in nodulation and nitrogen fixation, leading to poor yields (Jin *et al*., 2022; Rotaru, 2010). The deficiencies of both nutrients, N and P, is much more severe than those of the individual nutrients (Hellal and Abdelhamid, 2013).

Interactive Effects of Drought and Nutrient Deficiencies

Drought aggravates the negative impacts of P deficiency by hindering the transport of P to the seeds, causing poor yields and low protein content (Jin *et al*., 2006; Rotaru, 2010). Higher nitrogen applications can help soybeans tolerate drought stress by increasing morphological, physiological characteristics and yield component (Basal and Szabó, 2020).

Interactive Effects of Temperature and P Deficiency

The P deficiency significantly influences photosynthesis in soybeans at cold temperatures (22-26 ^{0}C). Higher temperatures (30-34 ^{0}C), however, have little impact on photosynthesis with P deficiency (Singh *et al*., 2019).

2.9.5 Management Practices to Mitigate Nutrient Deficiencies

Balanced Fertilisation

Balanced fertilisation of phosphorus and potassium is key to prevent nutrient deficiencies and to promote optimal soybean growth and yield (Yan-ming, 2011; Hellal and

Abdelhamid, 2013). The QUEFTS model can optimize fertiliser application by estimating nutrient requirements based on specific yield targets (Yang *et al*., 2017).

Use of Microbial Inoculants

Phosphate-solubilizing bacteria (PSB) and nitrogen-fixing bacteria, such as *Rhizobium japonicum*, can be used to inoculate soybeans to significantly enhance growth and nutrient uptake (Shome *et al*., 2022). The activities of microorganisms, that are beneficial to the soil, reduce the reliance on synthetic fertilisers by making more nutrients easily available to plants (Shome *et al*., 2022). Traits like improved phosphorus uptake and nitrogen use efficiency are the point of reference for breeding nutrient-efficient soybean cultivars, which can compensate for the yield losses in nutrient-deficient soils (Mshamu, 2015; Jin *et al*., 2022). The rise in yields in both phosphorus-rich and phosphorus-deficient soils was achieved with great success by orthodox breeding techniques, there is a need for more investigation into the soybean plants' consistent performance in conditions with poor nutrients (Zhang *et al*., 2021). It is essential to conduct soil and tissue analysis to determine available nutrients and formulate a balanced nutrient strategy needed to boost production (Firmano *et al*., 2020). Leaf tissue analysis provides critical information that helps remedy the particular deficiency observed quickly (Adu-Gyamfi *et al*., 1989; Lemaire, 1997).

2.10 Technological Innovations, for Improving Soil Fertility and Soybean Cultivation

Soybeans have become an important crop globally due to their high protein and oil content. It is therefore important to take measures that promote soil fertility and increase productivity. New techniques that sustain effective nutrient management are achieved through modern advanced technologies.

2.10.1 AI and Machine Learning for Phosphorus Management

Among the new technological tools that are helping soybean farmers in decision-making are machine learning and artificial intelligence. They have significantly changed phosphorus application techniques. Unlike the conventional methods that focus mainly on soil test phosphorus (TSP), contemporary machine learning models, such as Random Forest (RF), incorporate a broader array of variables, including soil pH, texture, organic matter, precipitation, and application techniques.

2.10.2 Accurate Sensor-Based Irrigation and Nutrient Management

In precision agriculture, sensor technologies have become essential instruments. Devices such as soil moisture sensors enable optimal irrigation, and chlorophyll meters (SPAD) measure the amount of chlorophyll in leaves to determine when nitrogen top-dressing is required to improve photosynthesis and productivity. It has been shown that employing these techniques for real-time crop health monitoring can increase seed yields by up to 35.4 % when compared to conventional methods (Sachin *et al*., 2023).

2.10.3 Biofertilizers and Microbial Inoculants

Examples of sustainable microbial treatments that enhance root development and nutrient uptake, particularly phosphorus, are arbuscular mycorrhizal fungus (AMF) and plant growth-promoting bacteria (PGPB). For instance, co-inoculation of AMF and Bacillus increased soybean yields by 813 kgha^{-1} (Leite *et al*., 2022). *Rhizobium*, *Bradyrhizobium* and *Bacillus* are among the commonly used bacteria to inoculate legumes to boost nodule count and make nutrients easily available to facilitate absorption (Basavesha *et al*., 2023).

2.10.4 Decision Support Systems for Site-Specific Nutrient Management

Nutrient Expert and other digital tools help recommend fertilisation techniques that are crop and soil-specific. By this, nutrients are used more effectively and the environmental impact of fertilisation is minimised. Studies have shown the importance of nitrogen in promoting yield by up to 1352 $kgha^{-1}$ (Khanda *et al*., 2020).

2.10.5 Bioengineered Microbes for Soil Health

Microbes that are genetically modified enhance soil structure, nitrogen and available phosphate and also support the breakdown of soil pollutants. Yields are multiplied, and better crop health is achieved through the modern technologies of hormone creation (Sharma *et al*., 2024).

2.10.6 Smart Tools for Real-Time Soil Monitoring

Farmers are now able to measure the levels of nitrogen and phosphorus because of the introduction of modern-day gadgets that provide fast and reliable on-field data. The incorporation of these technologies into farming, helps to manage nutrients more sustainably using data that makes fertilisation more precise (Singh *et al*., 2023).

2.10.7 Co-Fertilization Techniques

Slow-release formulations containing nutrients such as phosphorus and sulfur from struvite have shown positive outcomes. Through improved nutrient utilization and stronger root systems, these blends raise soil fertility and productivity (Valle *et al*., 2022).

2.10.8 Bacterial Consortia and Endophytic Microbes

Potential advantages are being investigated through the study of bacterial consortia and endophytic bacteria, which colonize plant tissues and produce hormones and enzymes to promote growth. These microbial communities have been shown to increase soybean yield by up to 2.63 tha^{-1} (Ngosong *et al*., 2022; Moretti *et al*., 2024).

2.10.9 Cluster-Based Biofertilizer Application

With this technology, microbial inoculants are applied either locally or regionally. In free trials, this strategy can raise soybean seed yields by 14 % when compared to traditional methods (Anbessa and Temene, 2024).

2.11 Importance of Region-Specific Fertility Management

Because soil types, climates, and farming practices vary, it is crucial to optimise soybean yield using area-specific strategies.

2.11.1 Adaptation to Local Soil and Climate Conditions

The optimal application rates for nitrogen, phosphorus, potassium, magnesium, and zinc varied between the Sudanean and Sudano-Guinean zones, according to Benin's nutrient recommendations (Faki *et al*., 2021). Both the application of compost and ammonium nitrate in Ukraine's forest-steppe zone and the integration of rhizobium, sulfur, and vermicompost in India's alluvial soils significantly enhanced soil quality and soybean yields (Kotlyarova *et al*., 2021; Balram *et al*., 2022).

2.11.2 Yield Response to Fertility Improvements

By increasing soil pH and reducing aluminium toxicity, lime and phosphogypsum were utilised in Brazil's tropical no-till systems to increase root development and readily available nutrients, thereby increasing soybean yields (Bossolani *et al*., 2022). Also, the experiment that involved the use of lime and manure applied with phosphorus saw a boost in the quality of the soil, which improved yield in the Central Highlands of Kenya.

Staggered application of potassium in Goias located in Brazil improved soybean production in a crop rotation system of maize and soybeans (Xavier *et al*., 2019).

2.11.3 Integrating Organic and Inorganic Nutrient Sources

Chemical and organic fertilisers are combined to enhanced soil health and productivity. This strategy increased in the levels of organic carbon and essential nutrients such as nitrogen, phosphorus and potassium in India (Lohar and Hase, 2022). The intercropping system of soybean and maize has been effective in the Democratic Republic of Congo in enhancing both production and financial returns by the Integrated Soil Fertility Management (ISFM) (Muyayabantu, 2013).

2.11.4 Economic and Environmental Sustainability

After testing the soil, a nutrient management strategy with a cost-benefit ratio of 4.05 in India suggests that the nutrient management strategy formulated was more advantageous in terms of cost than the usual fertilisation technique (Dwivedi *et al*., 2015). When potassium was applied in parcelled form, in Brazil, it resulted in better soil reserve protection and enhanced environmental conditions and subsequently lowered the requirements of inputs (Xavier *et al*., 2019). Another method that is effective in terms of cost, tested in Kenya, involved the use of lime and manure together, which positively influenced soil fertility and recorded good yields (Serafim et *al*., 2013).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study site

The research was conducted in Kpalsogu, a community located in the Tolon district of the Northern region of Ghana, in the 2023 rainy season. The district lies between latitudes $9^{o}15^{1}$ and $10^{o}02^{1}$ north and longitudes 00 53`and 10 25` west. The two main air masses influencing the climate at the study site are the monsoon and harmattan. While the monsoon brings humid air from the Atlantic Ocean, the harmattan brings dust and dry air from the Sahara Desert. During the harmattan, which runs from November to April, temperature ranges from 18 °C at night to 42 °C during the day. From May to October, the monsoon wind is felt. This results in an average annual rainfall of 950 mm in the affected area, with a monomodal distribution that typically starts in May, peaks in August or September, and then declines sharply in October. A protracted dry season follows, lasting from November until the end of April (GSS, 2014). The predominant vegetation type is grassland, with sporadic Guinea Savannah woodland. Except for the lowlands, where alluvial deposits are present, the soil is mostly sandy loam. The soil is extremely susceptible to gully and sheet erosion. Most of the topsoil has been lost due to years of constant erosion, which has also reduced the soil's organic matter.

3.2 Experimental design and treatment

The study was a two-factor experiment and was laid out in a split-plot experimental design replicated four times. The main plot factor was Rhizobium inoculation at two levels (Rhizobium and no-Rhizobium). The subplot factor was made up of fifteen fertilizer regimes (Table 1). Subplot sizes were 5 m x 5 m with 2 m alleys between main plots and replications, and a meter between subplots.

Table 1: Fertilizer used as subplot treatments

	Treatments	Amount of fertilizer (kg/ha)
T1	Control	Untreated
T2	NPS+TE (14:31:5+B, Zn)	193.5
T3	NPK(14:18:18+B, Zn)	333.3
T4	TSP	131 TSP
T5	TSP + K	131 TSP + 100 MoP
T6	TSP + K + TE (4ZnO, $4B_2O_3$)	131 TSP + 100 MoP + 11.4Zn +7.1 B
T7	80%TSP + 20%RP	105 TSP +86 RP
T8	80%TSP + 20%RP + K	105 TSP +86 RP + 100 MoP
T9	80%TSP + 20%RP + K + TE (4ZnO, $4B_2O_3$)	105 TSP +86 RP + 100 MoP+11.4 Zn + 7.1 B
T10	60%TSP + 40%RP	79 TSP +174 RP
T11	60%TSP + 40%RP + K	79 TSP +174 RP + 100 MoP
T12	60%TSP + 40%RP +K + TE (4ZnO, $4B_2O_3$)	79 TSP +175 RP + 100 MoP+11.4 Zn + 7.1 B
T13	100% RP	200 RP
T14	100%RP + K	200 RP+ 100 MoP
T15	100%RP + K + TE (4ZnO, $4B_2O_3$)	200RP + 100 MoP+11.4 Zn + 7.1 B

3.3 Cultural practices

Treatments with inoculation were treated with Rhizobium using the recommended processes of inoculant application before planting. The soybean Favour variety was used, and the seeds were coated with a slurry solution of the Rhizobium (SARIFIX soybean rhizobium inoculant from SARI) prepared with water and sugar at 5 g of inoculant per 1 kg of seeds. They were air-dried and sown on the 26th of July by drilling at an inter-row row distance of 75 cm and within row spacing of 5 cm. Rock Phosphate treatments were applied on the same day that planting was done for plots earmarked for rock phosphate.

The other fertilizer treatments were applied 14 days after planting. All fertilizers were applied by side drilling. Pre-emergence herbicides, Vezir 240 SL and Agil 100 EC, produced by Adama company were mixed and sprayed on August 21, 2023.

3.4 Data collection

Data were collected on the following parameters;

3.4.1 Chlorophyll content

Leaf chlorophyll content was taken as SPAD meter reading. Five plants were selected and tagged. Three SPAD readings on two fully grown leaves, from the top and the next below, were taken from each of the five tagged plants. Thirty SPAD meter readings were collected from the five plants, and their average value was recorded for each plot. The data were taken at two-week intervals from 4-10 weeks after planting (WAP)

3.4.2 Plant height

The height of the main stem was measured using a meter rule set at the base of the plant to the apex. This was repeated for the other four tagged plants on each experimental unit. The data were taken at two-week intervals from 4-10WAP.

3.4.3 Earliness to maturity

This was measured as days to 50% flowering and full maturity. The number of days it took from the planting for each plot to achieve 50% flowering was recorded for each treatment, as days to 50% flowering. The number of days it took from the planting for each of the plots to achieve maturity was recorded. Maturity was taken as the yellowing of the husks of the pods.

3.4.4 Average number of pods per plant

At harvest, five plants were selected randomly from each plot and the number of pods on each plant was removed, counted and recorded. Their average was calculated and recorded as the number of pods per plant.

3.4.5 Pod weight

In each plot, fifty pods were randomly selected and weighed using a digital scale. The total weight was divided by fifty to obtain the average pod weight.

3.4.6 Nodule and effective nodule number

Five plants on each plot were selected randomly and uprooted eight weeks after planting by digging around the base of the plant using a spade. The roots were washed under running water to remove soil and other debris from the roots and nodules. The nodules on each plant were detached, counted and recorded. The total number of nodules was divided by five to obtain an average of the nodules per plant.

The nodules counted were cut open using a blade to observe the inner colour. The effective nodules showed a pink colour. The total number of effective nodules counted was also divided by five to obtain the average number per plant.

3.4.7 Biomass and Grain Yield

Border rows were discarded, and 20 cm was left out of each end of a row. At planting 20 cm were left at the beginning and end of each plot. The effective harvested area was 4.6 m x 3 m= 13.8m^2. Harvesting was therefore done in 13.8 m^2 plot. The crops were cut at the base from the harvested area. The biomass was determined by weighing all the material from the harvested area. The pods were manually threshed on plot-wise. The grains were air-dried in the sun and stored in labelled bags. The dried grains were weighed using a digital scale. The weighed grains were then converted to kg per hectare.

3.4.8 1000 seed weight

Pods from each plot were threshed separately, and 1000 seeds from each plot were randomly selected and weighed using a digital scale.

3.5 Partial Budget Analysis of Soybean

In order to conduct a comprehensive economic analysis of the various treatments, a range of analytical techniques including partial budget analysis, dominance analysis, and marginal analysis were employed to narrow on the treatment that will bring better returns. Partial budget specifically computes the variable costs and net benefits associated with each treatment within an experimental framework. Subsequent to the partial budget analysis, a dominance analysis was carried out. This procedure excluded treatments that result in greater additional costs with lesser net benefits in comparison to treatments that incur the same or lower additional costs from further consideration. Marginal analysis encompasses the evaluation of marginal (incremental) benefits against marginal (incremental) costs associated with transitioning from one treatment to an alternative one. It requires the computation of the following:

Net Benefit Analysis

The net benefits were determined through the following calculations:

$$Net\ Benefits\ (NB) = Gross\ Benefits\ (GB) - Total\ Variable\ Cost\ (TVC) \quad .... (1)$$

Where GB = Output (Yield) × Output price, and TVC =Sum of variable cost.

Marginal Rate of Return (MRR)

Change in net benefits (ΔNB) and change in total variable costs (ΔTVC) were computed and were used to compute the marginal rate of return (MRR) as shown:

$$MRR = \frac{\Delta NB}{\Delta TVC} \times 100 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

$Where\ \Delta NB = change\ in\ net\ benefits\ (marginal\ benefits)\ and\ \Delta TVC = change\ in\ total\ costs\ that\ vary\ (marginal\ variable\ cost)$.

3.6 Data analysis

All data collected from the field were subjected to the analysis of variance (ANOVA) in GenStat Statistical Software 12th Edition. The data were analyzed based on the split-plot design used. The main plot and sub-plot interaction as well as the main effect, were examined. Where a factor was significant, the treatment means were separated and compared using the Duncan Multiple Range test at a 5% probability level. Tables and graphs were made using an Excel spreadsheet. Relationships among grain yield, yield parameters and other parameters collected were established using linear regression analysis.

CHAPTER FOUR

RESULTS

4.1 Plant height

Inoculation and fertilizer interaction did not affect plant height at the four periods plant height was measured (Appendix 1). Inoculation impacted on plant height only at six weeks after planting (P=0.040) where inoculated plants recorded an average plant height of 33.84 cm and non-inoculated plants recorded an average plant height of 34.81 cm. Fertilisation affected plant height significantly from 6-10 WAP (P<.001) (Appendix 1). The compound fertilisers NPS+TE (14:31:5+B, Zn) and NPK(14:18:18+B, Zn) induced higher heights throughout the study period, with NPK(14:18:18+B, Zn) consistently producing the tallest plants from 6-10WAP, with plant heights of 39.20 cm, 57.34 cm, and 79.62cm, respectively (Figure 1). The unfertilized control treatments consistently recorded the lowest plant heights, 32.58 cm, 45.37 cm, and 54.43 cm, respectively, from 6-10WAP, indicating a significant gap between the tallest and the shortest producing treatments. At 10 WAP, the two compound treatments remained outstanding. The TSP-based treatments and their partial substitution with rock phosphate scattered around the same height, notably up to 8WAP. At 10WAP, TSP-based treatments and their partial substitution with rock phosphate significantly improved plant height relative to control, but could not match the plant heights produced by the compound fertilizers. The 100% rock phosphate treatments were of the same height as the untreated control (Figure 1). However, the inclusion of K and TE to 100% Rock phosphate helped to improve its performance, the increase in plant heights were however, not significant and was not statistically different from the control.

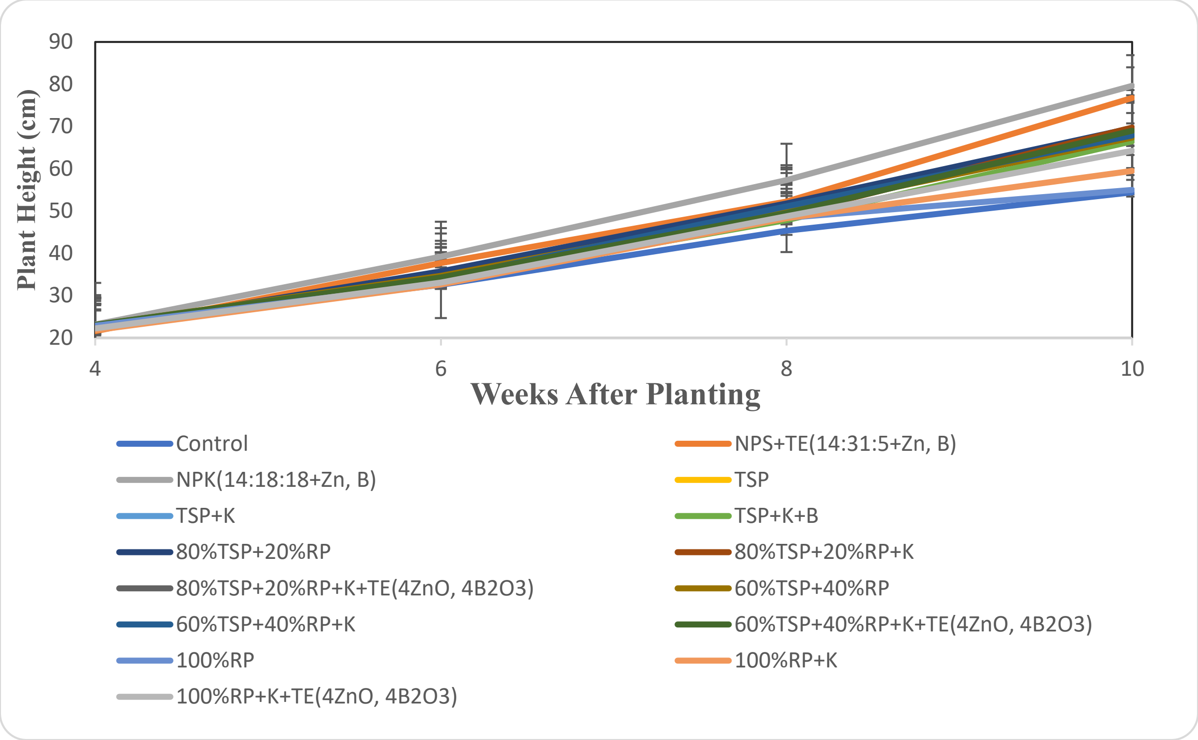

Figure 1: **Influence of primary nutrients, phosphorus source and some essential elements on soybean plant height. Error bars represent (SEM)**

4.2 Chlorophyll content

Fertilization and inoculation interaction did not significantly influence (P>0.05) leaf chlorophyll at all the weeks, SPAD readings (Appendix 1). Inoculation also did not have significant effect on the greenery of the soybean (P>0.05) (Appendix 1). Fertilization did not affect leaf chlorophyll at 4 WAP (P=0.481); however, by the 6th week after planting, fertilizer treatments significantly affected (P<0.01) the greenery of the plants (Appendix 1). The differences in the chlorophyll content among the treatments were significant, especially at 10WAP, where the fertilized treatments maintained higher chlorophyll levels compared to the unfertilized control. At 10 WAP, three scatter points were observed, which were (i) the two compound fertilisers, (ii) the TSP and its substitution with rock phosphate and (iii) the 100 % rock phosphate plus the untreated control. While greenery increased from week 8 to 10 in the first two groups, it declined in the third group (Figure 2).

As observed in the plant height, the compound fertilisers NPK (14:18:18+B, Zn) and NPS (14:31:5+B, Zn) caused higher chlorophyll development throughout the period than the other treatments with NPS (14:31:5+B, Zn) consistently producing the highest chlorophyll content from 6-10WAP with corresponding SPAD values of 42.61, 45.98, and 46.06, respectively. The lowest chlorophyll content was, however, diverse among the fertilizer treatments, TSP+K, 60%TSP+40RP, and control, producing SPAD values of 35.74, 38.81, and 37.43, respectively from 6-10WAP, the changes in SPAD readings between the highest and lowest chlorophyll producing treatments was not significant.

TSP, partially substituted with 20%RP and 40%, and the sole application of rock phosphate showed a steady increase up to 8WAP. At 10WAP, these treatments generally had lower SPAD values than the compound fertilizers.

The SPAD values of 100RP peaked at 8WAP with a value of roughly 41, and declined slightly at 10WAP. The supplementation with K and trace elements followed similar trend as 100%RP and did not cause a significant change in the chlorophyll content

At the pod filling stage, the greenery of the plants was not different from what was observed three weeks earlier at the 10 WAP (Figure 3). All fertilized treatments produced chlorophyll levels higher than the unfertilized control, with significant difference. The control treatment showed the lowest chlorophyll level at pod filling with a SPAD value of 33.01. Three groups were established, just like what was observed at the 10 WAP, with the two compound fertilisers showing superiority in chlorophyll development, with NPS (14:31:5+B, Zn) maintaining its dominance with the highest SPAD values of 46.84 at pod filling. The TSP and its substituted form with rock phosphate performed better than the application of rock phosphate, with a significant change in chlorophyll levels, but could not match the compound fertilizers. The addition of trace elements to the rock phosphate did not lead to significant change in greenery as was also observed in TSP (Figure3).

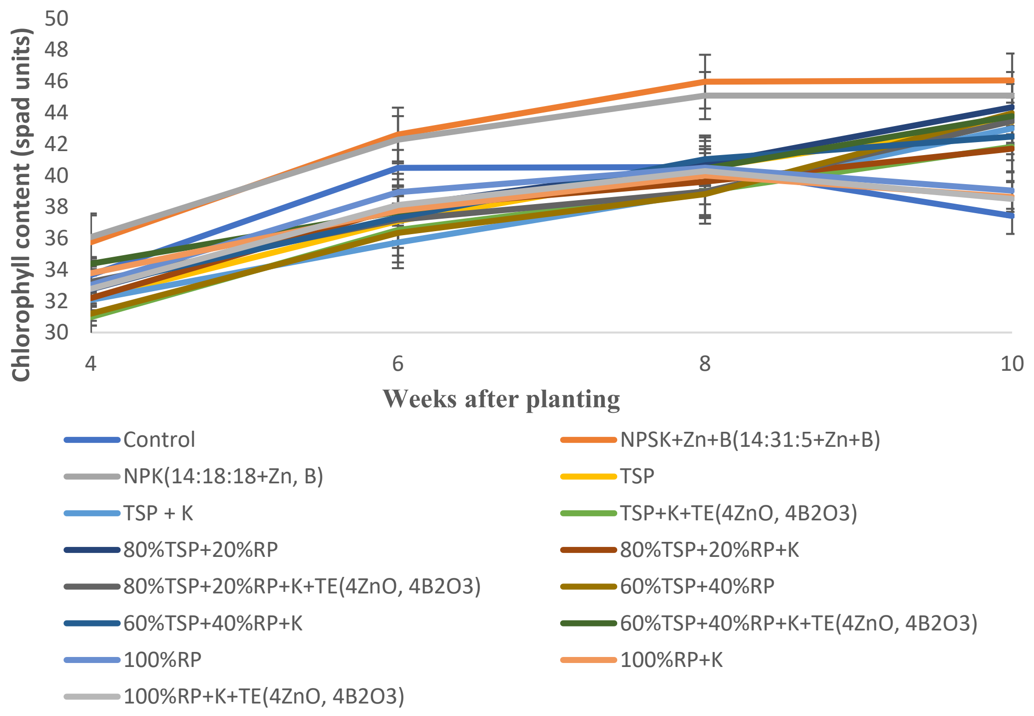

Figure 2: **Influence of primary nutrients, phosphorus source and some essential elements on soybean chlorophyll content. Error bars represent (SEM)**

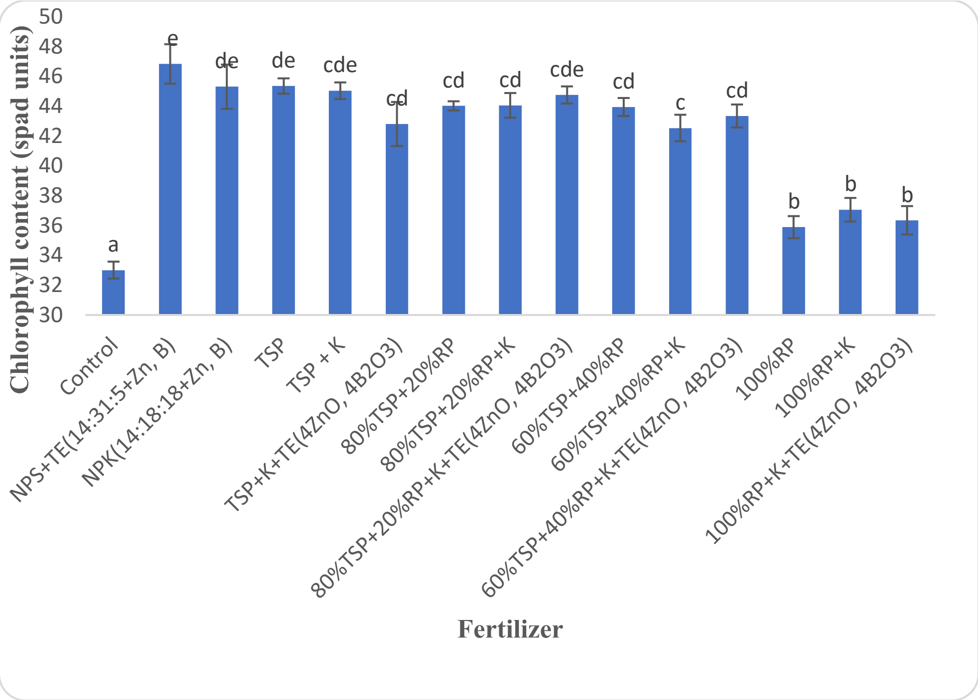

Figure 3: **Influence of primary nutrients, phosphorus source and some essential elements on soybean chlorophyll content at pod filling. Error bars represent (SEM)**

4.3 Earliness to maturity

4.3.1 Days to 50% flowering

Inoculation (P=0.092) and fertilizer interaction (P=0.162) did not have a significant effect on days to 50% flowering. In contrast, the impact of fertilisation on the days to 50% flowering was highly significant (P< 0.001) (Appendix 2).

The compound fertilizers NPK(14:18:18+B, Zn) and NPS+TE(14:31:5+B, Zn) delayed flowering, with NPS+TE(14:31:5+B, Zn) the most among the fertilized treatments taking 49 days to mature, and NPK(14:18:18+B, Zn) coming close, maturing a day earlier. The unfertilized control, induced flowering significantly earlier than the the compound fertilizers, taking almost 48 days to mature. (Figure 4). All other fertilizers, including the control, induced flowering significantly earlier than NPS+TE(14:31:5+B, Zn), all those treatments having similar flowering periods ranging between 47 and 48 days.

The single nutrient fertilizer, superphosphate (TSP), caused plants to flower earlier (almost 48days) than the control, although the difference in days was not statistically significant. The addition of K to TSP did not demonstrate any noticeable change in flowering between plants. The partial substitution of TSP with RP did not significantly alter days to flowering. The incorporation of TE to 100% Rock phosphate and its combination with K caused the earliest flowering of 47 days (Figure 4). The untreated control was not significantly different from TSP and its substituted forms.

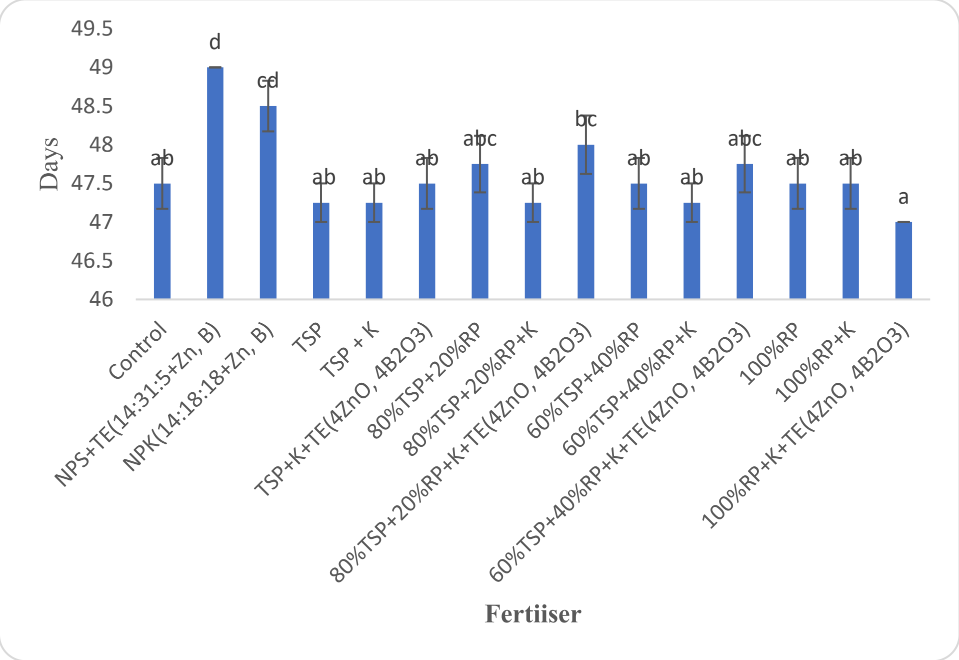

Figure 4: **Influence of primary nutrients, phosphorus source and some essential elements on soybean number of days to flower (50%). Error bars represent (SEM)**

4.3.2 Days to 100% maturity

Inoculation (P=0.468) and fertilizer interaction (P=0.978) did not affect soybean plant at full maturity (Appendix 2). However, the influence of fertilisation on the duration to achieve full maturity was found to be highly significant (P< 0.001) (Appendix 2).

Treatments that included rock phosphate were the earliest to mature, and they were not significantly different from the untreated control (Figure 5). The least number of days it took to mature was 98 and this was achieved by the control, rock phosphate and its supplementation with K. The addition of trace elements to RP with K delayed maturity by a day more with the change in the number of days not significantly different from the treatments earliest to mature. The effect of the compound fertilizers, NPK (14:18:18+B, Zn) and NPS+TE(14:31:5+B, Zn) on maturity was outstanding; they prolonged maturity, with the NPK (14:18:18+B, Zn) having the strongest impact on maturity. NPK (14:18:18+B, Zn) took 121 days to mature and the maturity days produced was not significantly different from that of NPS+TE(14:31:5+B, Zn). The impact of the compound fertilizers on maturity was not significantly different from the impacts of TSP, TSP+K and 60%TSP+40%RP.

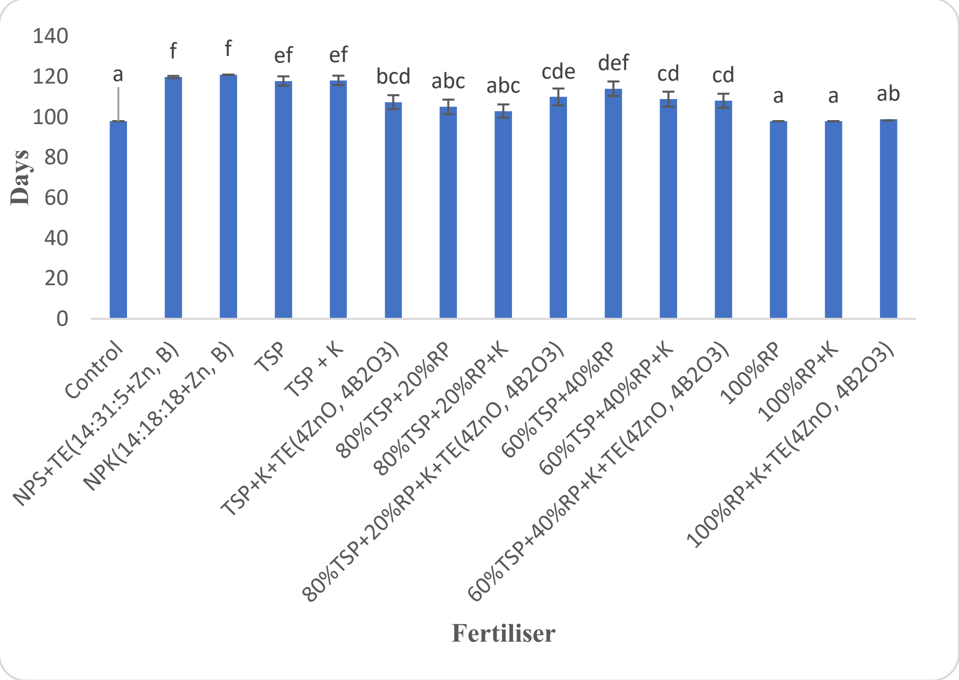

Figure 5: **Influence of primary nutrients, phosphorus source and some essential elements on soybean maturity days. Error bas represents (SEM)**

4.4 Nodule count and effective nodule count

Inoculation (P=0.666) and fertilizer interaction (P=0.443) did not affect nodulation. The effect of fertilisation on nodulation was highly significant (P =0.001) (Appendix 2). Compound fertilizer NPS+TE(14:31:5+B+Zn) caused the least nodulation, producing approximately 26 nodules that was not significantly different from the untreated control. The effect of NPK (14:18:18+B, Zn) and TSP on nodulation was statistically similar and nominally above the untreated control, both treatments producing nodules counts between 41 and 42. The TSP+K blend caused nodulation that was outstanding among the fertilizers tested, recording the highest nodule count (52). The nodule count produced by TSP+K was significantly superior to the control (~29) and most of the rock phosphate-based treatment (28-32 nodule counts), with their nodule counts statistically different from each other (Figure 6). Further inclusion of the trace elements into TSP+K blend notably impaired nodulation as shown in Figure 6, with a significant decline in nodulation, producing nodule count that was lower than TSP+K without the trace element. In terms of effective nodulation, the addition of trace elements to TSP+K caused a decline in nodule count but was statistically similar to that of TSP+K.

The partial substitution of TSP with 40%RP did not significantly change nodulation more than what was observed when 20%RP substitution was used. Generally, when K was added to TSP or its substituted form (80%TSP +20% RP) there was appreciation of nodulation though not at significant levels. When the trace elements were further added, the nodulation declined (Figure 6). The 100%RP and its amends had similar effect on nodulation as the untreated control. The effective nodule count followed the same pattern as the main nodule count, with TSP+K still leading in effective nodulation, producing the highest effective nodules of 26 and the compound fertilizer NPS+TE(14:31:5+B+Zn) producing the lowest effective nodule count of almost 13. The difference between the nodulation and the effective nodulation trends is the reduction in the effective nodules number by 48%-51%. (Figure 7).

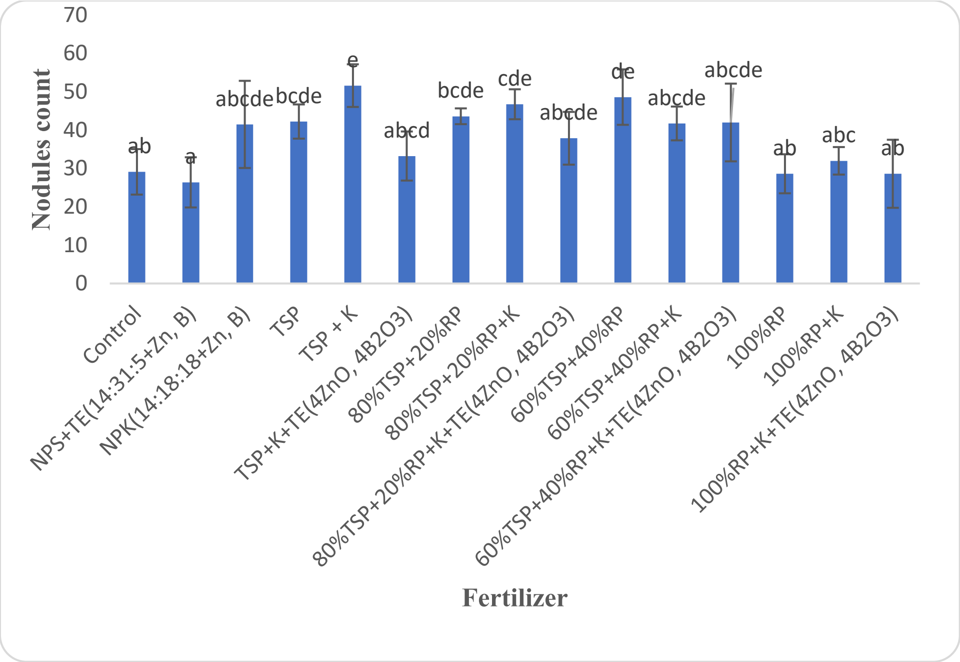

Figure 6: **Influence of primary nutrients, phosphorus source and some essential elements on soybean nodulation. Error bars represent (SEM)**

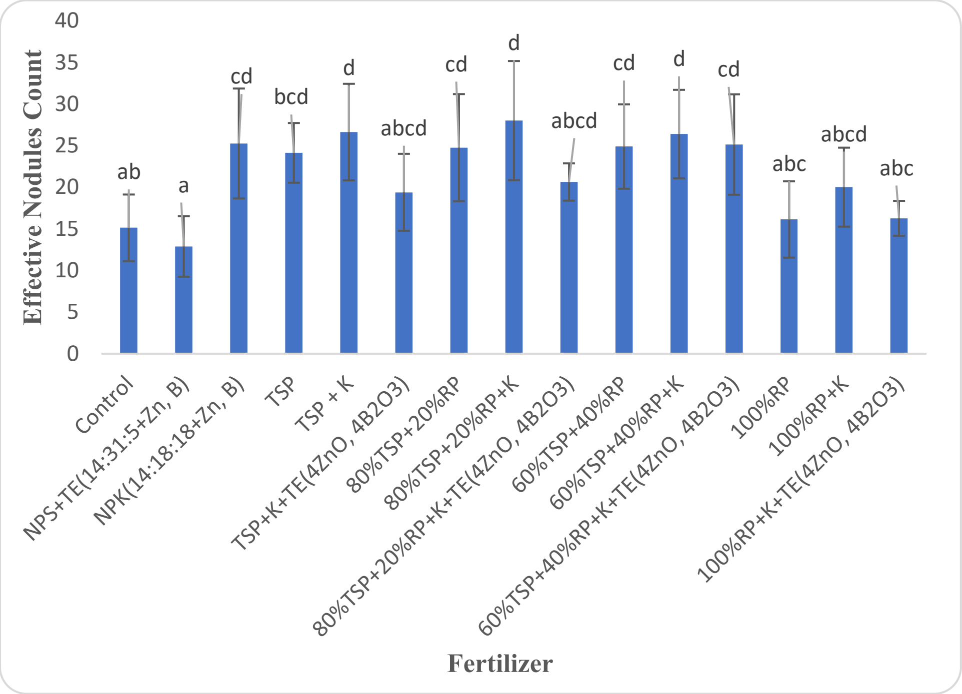

Figure 7: **Influence of primary nutrients, phosphorus source and some essential elements on effective nodulation of soybean. Error bars represent (SEM)**

4.5 Pod weight and pod number

4.5.1 Pod weight

Inoculation (P=0.249) and fertiliser interaction (P=0.214) did not affect pod weight. Fertilisation, however, had a significant effect on pod weight (P=0.038) (Appendix 2).

All fertilisers performed better than the untreated control which produced the lowest pod weight (15.2g). The control pod weight was not significantly different from that of the sole application of rock phosphate and its amends. Compound fertilisers NPK (14:18:18+B+Zn) and NPS+TE(14:31:5+B+Zn) had pronounced and comparable effects on pod weight, with the difference in their pod weights not significantly different from the untreated control. TSP and the compound fertilisers had similar effects on pod weight (22.18g). the blend of K and TSP improved pod weight, causing an outstanding performance among the tested fertilisers. This performance produced the highest pod weight (25.82g), which was significantly different from the untreated control. The inclusion of TE to the TSP+K treatment caused a decline in pod weight, though not significantly different from the untreated control (Figure 8). The effect of partial substitution of TSP with 20%RP and 40%RP on pod weight was statistically similar, and both had performance similar to the untreated control. The addition of K to 80%TSP+20%RP marginally improved pod weight, while further addition of the trace elements to the blend caused a marginal decline in pod weight, showing changes that were not significant. The same pattern was observed when 40 % substitution was considered (Figure 8).

100% RP with K and TE inclusion was not statistically different from the untreated control.

The change in pod weight between the highest (TSP+K) and the lowest (control) performing treatment was significant, however, the pod weight changes among the fertilized treatments were not significant and they produced pod weights that were statistically similar.

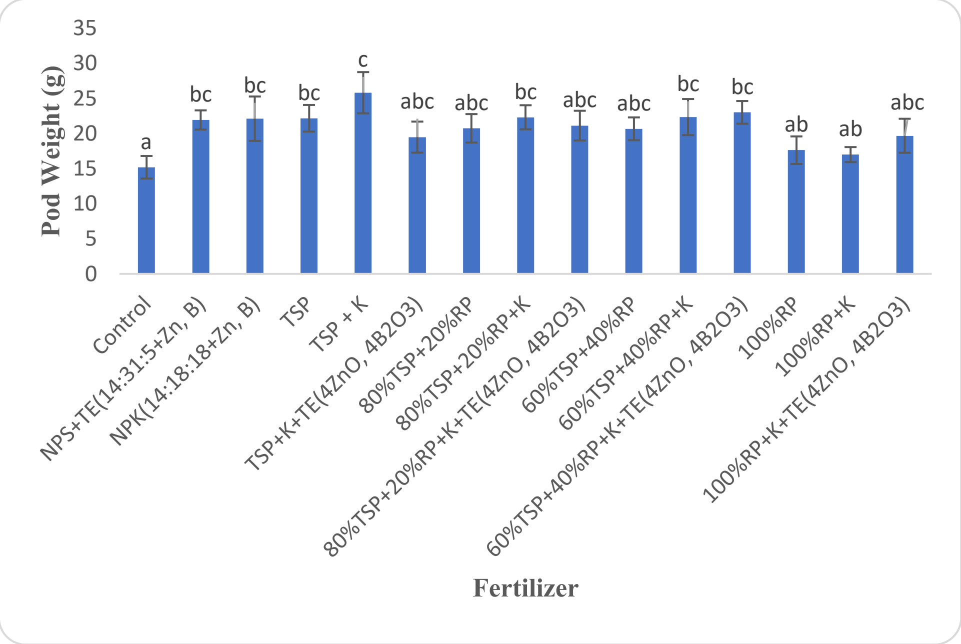

Figure 8: **Influence of primary nutrients, phosphorus source and some essential elements on pod weight of soybean. Error bars represent (SEM)**

4.5.2 Inoculation and fertiliser effect on podding

Inoculation did not affect podding (P=0.141). However, the fertiliser interaction had a significant effect on podding (P=0.030). The effect of fertilisation on podding was highly significant (P <0.001) (Appendix 2).

Figure 9 illustrates the influence of the interaction between inoculation and fertilisation on podding. Podding in the control plots was not affected by the inoculation, though non-inoculated plants produced nominally more pods. (Figure 9). Inoculation interaction with the compound fertilisers NPK (14:18:18+B, Zn) and NPSK+TE(14:31:5+B+Zn) had a pronounced positive effect on podding, causing their respective inoculated plants to significantly outperform their non-inoculated counterparts, with difference in their pod number not significant.

NPK (14:18:18+B, Zn) produced more pods than NPS+TE (14:31:5+B, Zn), though the difference was not significant (Figure 9). Podding was positively influenced by TSP (Figure 9) for the control. When K was combined with TSP (TSP+K), the non-Rhizobium inoculated plots produced more pods than the inoculated plots with their difference not significant. When TE was added to the TSP+K, the pod number did not significantly improve; however, the inoculated plots performed better than the non-inoculated counterparts, producing pod numbers that were statistically similar. (Figure 9). Except for 60%TSP+40%RP+K+TE, the 20% and 40% substitution of TSP regimes did not improve podding in both inoculated and non-inoculated plots indicating that the partial substitution of TSP with RP (either 80%:20% or 60%:40) did not cause any significant difference in podding between the inoculated and non-inoculated (figure 9). Indeed, the inoculated 60%TSP+40%RP+K+TE had the most positive influence on podding and produced the highest number of pods (102). However, it was the TSP+K that produced the highest number of pods among the non-inoculated treatments (98). The difference in podding between the highest inoculated and the non-inoculated was not significant. The application of rock phosphate in isolation limited podding, resulting in the lowest pods produced in both inoculated (48) and non-inoculated (63). Though the non-inoculated 100%RP produced more pods than the inoculated one, their difference, however, was not significant, the use of inoculant in plots where rock phosphate was applied in isolation and with potassium did not significantly improve podding when compare with control. The addition of TE to 100% RP+K brought pod number to the level of TSP and substituted forms.

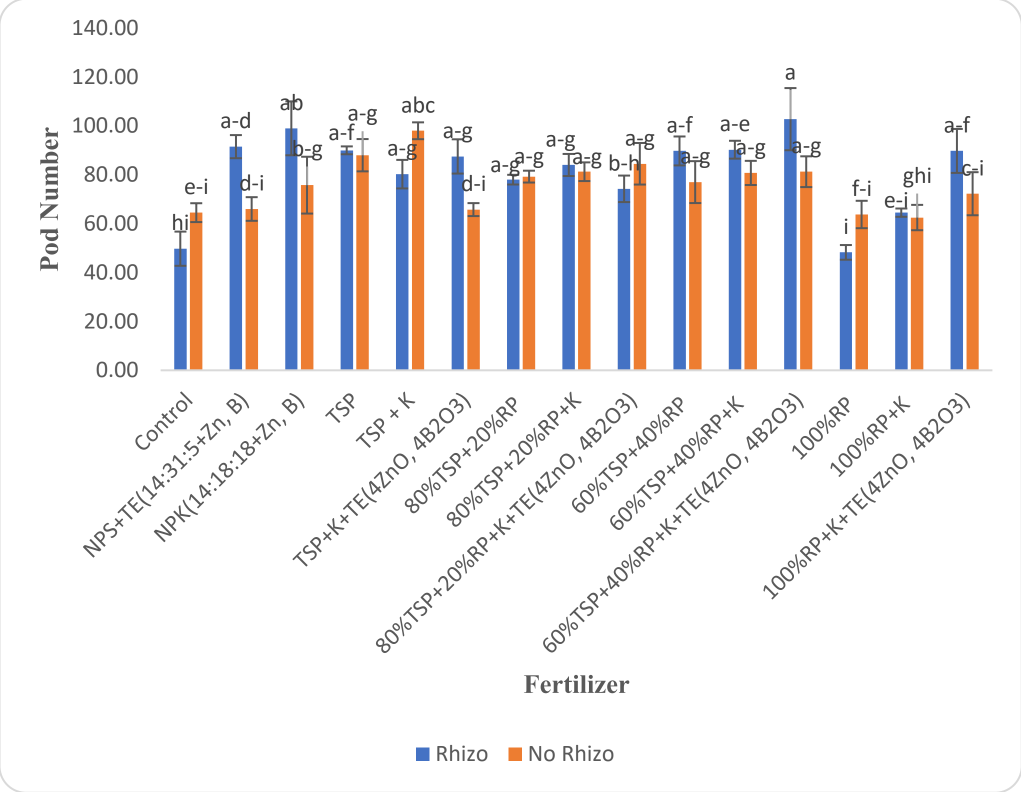

Figure 9: **Influence of primary nutrients, phosphorus source and some essential elements and their interaction with Rhizobium on soybean podding. Error bars represent (SEM)**

4.6 Grain yield

Inoculation (P=0.730) and fertiliser interaction (P=0.636) did not affect grain yield. Fertilisation, however, had a significant effect on grain yield (P<0.001) (Appendix 2). The untreated control produced the lowest grain yield of 500 kgha^{-1}. The performance of NPS+TE (14:31:5+B, Zn) was lower than that of NPK (14:18:18+B, Zn) but was still significantly higher than the control. NPK (14:18:18+B, Zn) was at par with TSP and

TSP+K, producing grain yields that were statistically similar (Figure 10). The inclusion of the trace elements brought the yield down, though not significantly. The 20% substitution of TSP with RP (80%TSP+ 20%RP) led to the highest grain yield in the trial, about 2 tonha^{-1}. The addition of K and the trace elements, Zn and B, to 80%TSP+ 20%RP did not improve grain yield, marginally reducing the grain yield but still perform better than the untreated control with a significant increase in grain yield (Figure 10). The 40% substitution of TSP with RP (60%TSP+40% RP) reduced yield, but not significantly when compared with 20% substitution of TSP. When the trace elements were added to 60%TSP+40% RP+K the grain yield rose to its equivalence of 20% substitution of TSP, producing grain yield that was not statistically different from TSP+20%RP. The use of rock phosphate in addition to K and the trace elements produced grains about double of that of the untreated control (Figure 10). The 100%RP and its amends produced grain yields that were significantly higher than the control but were still considerably inferior compared to the TSP-based and the compound fertilizers treatments.

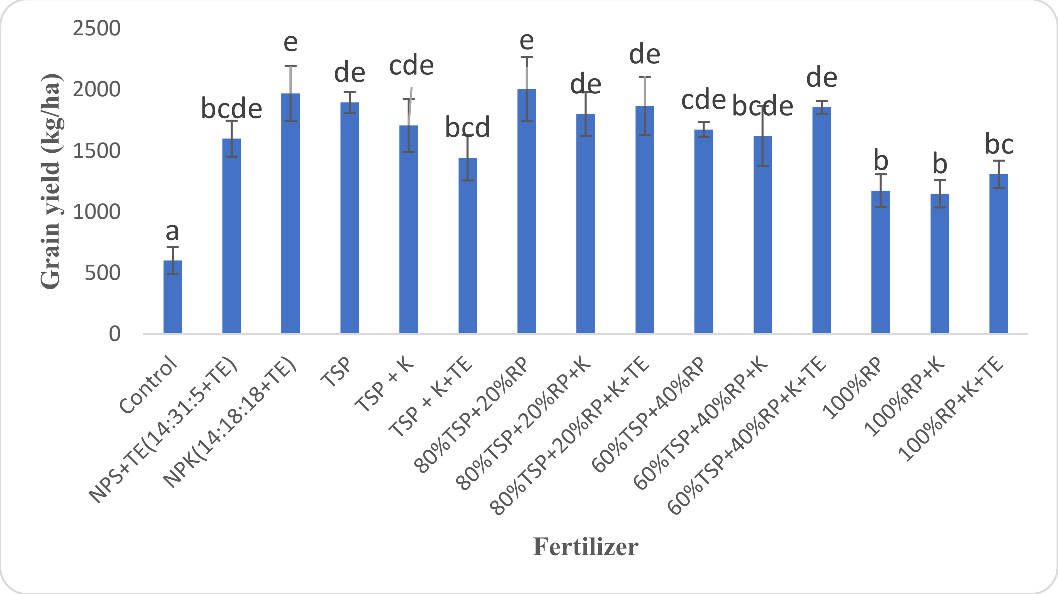

Figure 10: **Influence of primary nutrients, phosphorus source and some essential elements on grain yield of soybean. Error bars represent the (SEM)**

4.7 The above-ground dry biomass

Inoculation (P=0.116) and fertiliser interaction (P=0.614) did not affect the above-ground dry biomass. The influence of fertilisation on the above-ground dry biomass was significant (P=0.003) (Appendix 2). The untreated control produced less biomass than all other fertilizers.

The compound fertilisers NPK (14:18:18+B, Zn) and NPS+TE(14:31:5+B, Zn) had the most pronounced effect, causing an outstanding performance of the above-ground dry biomass (Figure 11). NPK (14:18:18+B, Zn) produced more biomass than NPS+TE (14:31:5+B, Zn), recording the most above-ground biomass of 6 tonsha^{-1} though the difference was not significant. The control treatment produced the least amount of above-ground dry biomass of 2.7 tonsha^{-1} which is significantly lower than the compound fertilizers and the TSP-based fertilizers. The effect of TSP on the biomass was not as pronounced as the compound fertilisers. The difference in the biomass produced by NPK (14:18:18+B, Zn) and TSP was significant, however the biomass produced by TSP and NPS+TE (14:31:5+B, Zn) were statistically similar; TSP performed notably better than the untreated control producing 4.3 tonsha^{-1} of biomass. The supplementation of TSP with K and trace elements resulted in a marginal change in biomass.

The above ground dry biomass produced by the partial substitution of TSP with RP either in the ratio of 80%:20% or 60%:40% produced biomasses that were not statistically different from each other. The difference in the biomass when TSP was partially substituted with 20%RP and 40%RP was not significant; however still considerably above the untreated control.

The biomass produced by the 100%RP was similar to the untreated control. The supplementation of RP with K resulted in an increase that was not significant. The performance of the 100% RP was better than the untreated control only when K and TE were added and was not significantly different from the high biomass producing treatments.

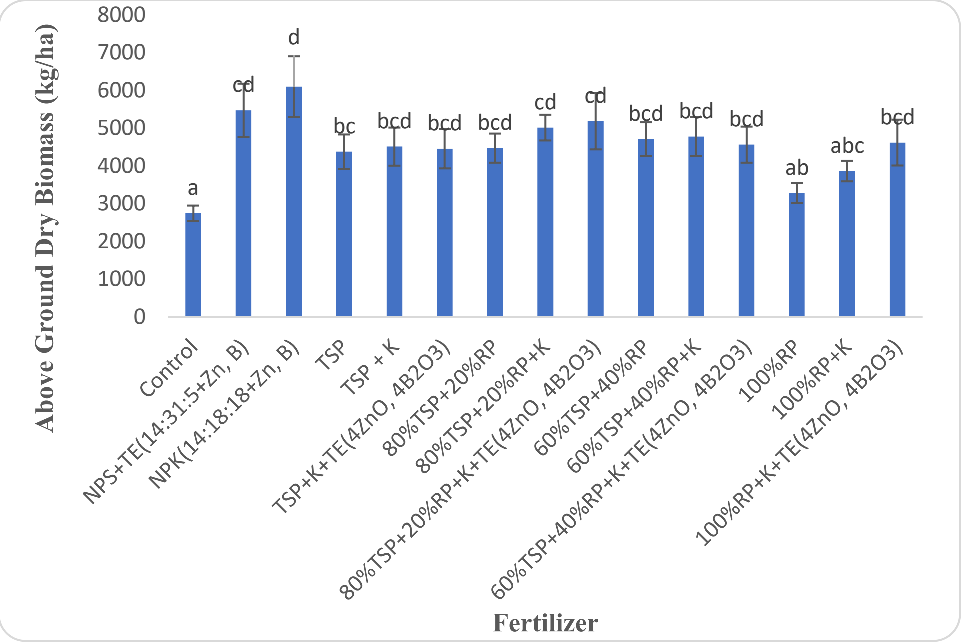

Figure 11: **Influence of primary nutrients, phosphorus source and some essential elements on above-ground dry biomass of soybean. Error bars represent (SEM)**

4.8 Regression Analysis

The regression analysis of some selected parameters has shown that grain yield had a positive linear relationship with the above-ground dry biomass, pod weight, pod number and the effective nodule count (Figure 12).

The regression analysis has also shown that grain yield had a positive linear relationship with chlorophyll content level and chlorophyll level at pod filling and plant height (Figure 13). Change in these parameters affects yield and vice versa, with linear regression equations and r^2 values shown on each graph in Figure 13.

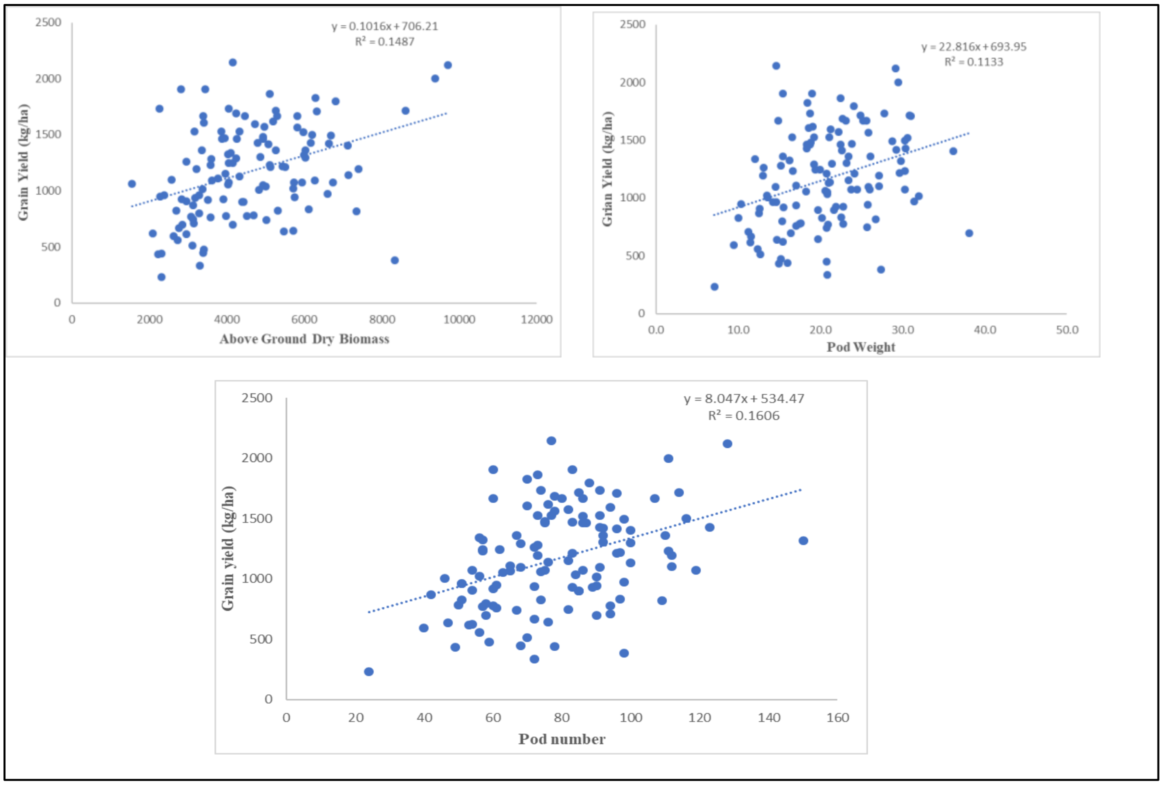

Figure 12:**Regression analysis indicating the relationship between yield parameters and grain yield**

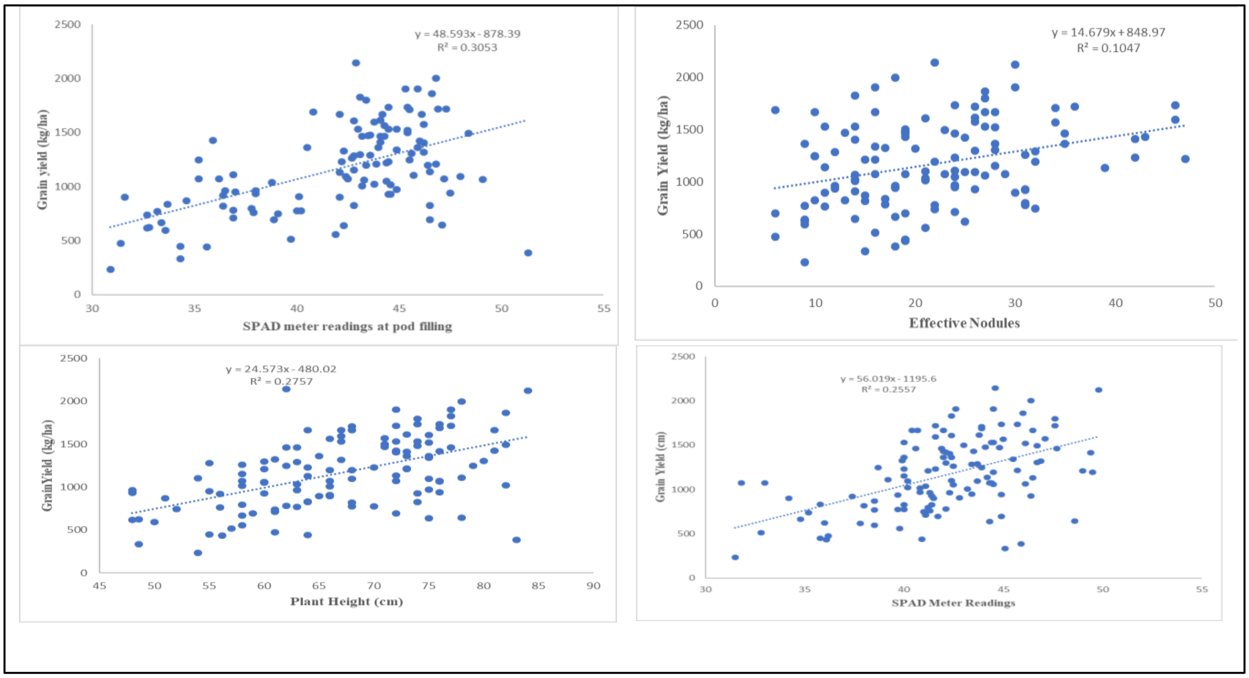

Figure 13: **Regression analysis indicating the relationship between growth parameters and grain yield**

4.9 Partial Budget Analysis

Table 2 shows the prices of fertilizers that were used to derive the Total Variable Cost. Table 3 shows that all the treatments applied in the soybean trial were dominated except three: 100% RP, 80% TSP+20% RP and TSP. These were treatments that contained only phosphorus without Potassium and the trace elements. The marginal rate of return were very good (Table 3).

Table 2: **Prices of fertilizer used in computation of partial analysis**

Fertilizer prices in 2023	Price (GH₵) per 50 kg
Triple super phosphate (TSP)	472
Rock Phosphate (RP)	320
NPK 14-18-18 +TE	496
NPS 14 -31- 5	528
Muriate of Potash (K)	416
Borate (B)	608/kg
Zinc sulphate	610/kg

Table 3: **Partial budget analysis of treatments used in soybean showing marginal rate of return. Net benefit highlighted were dominated and were excluded in subsequent marginal analysis**

Treatment	TVC	Net benefit	ΔTVC	ΔNB	MRR
Control	0	3601.4			
100%RP	1280	5763.5	1280.00	2162.0	168.9
TSP	1935.2	9441.6	655.20	3678.1	561.4
80%TSP+20%RP	2102.1	9934.1	166.90	492.5	295.1
60%TSP+40%RP	2281.8	7761.7			
100%RP+K	2580	4304.1			
NPS+TE(14:31:5+B+Zn)	3194.4	6399.8			
TSP + K	3235.2	7011.2			
80%TSP+20%RP+K	3402.1	7402.2			
60%TSP+40%RP+K	3581.8	6142.8			
NPK(14:18:18+B+Zn)	5164.6	6647.0			
100%RP+K+TE	13862.96	-6015.1			
TSP + K+TE	14518.16	-5851.5			
80%TSP+20%RP+K+TE	14685.06	-3489.4			

CHAPTER FIVE

DISCUSSION

5.1 Plant height

The fertilization greatly enhanced the growth of the soybean. TSP and up to 40% substitution with rock phosphate improved height growth better than 100% rock phosphate. The inclusion of K and the trace elements to rock phosphate improved its performance to be in the status of TSP and its substitution forms. The treatments that greatly enhanced height growth were the two compound fertilizers, NPK (14:18:18+B, Zn) and NPS+TE (14:31:5+B, Zn). They both contained nitrogen, phosphorus and the trace elements. While the later substituted K with S. This fertilizer's composition, rich in nitrogen and phosphorus, promoted growth. Studies indicate that plant height can significantly rise with the use of NPK fertilisers; some investigations have shown that utilising particular NPK formulations can result in heights of up to 75.50 cm (Lisdayani *et al*., 2021). Other research also indicates that using these compound fertilizers significantly increases plant height and biomass, demonstrating their effectiveness in encouraging robust growth (Eni *et al*., 2015: Cahyono *et al*., 2024).

TSP increased soybeans more when combined with K and then trace elements Zn and B than when TSP was applied alone. According to this study, applying TSP by itself is a more efficient method of promoting plant development than combining K and micronutrients. Research by Sutradhar *et al*., (2017) and Culpan, (2022), indicate that specific parameters such as podding and seed yield were enhanced by micronutrients like B, the effect of boron however, on plant height was marginal. The foliar application TSP, boron, and other micronutrients produced a good yield, but their impact on plant height was minimal (Pasala *et al*., 2021; Dass *et al*., 2022). The different sources of P have different effects on plant height as observed when TSP was partly replaced with RP, resulting in a slight change in plant height. While different fertilisers such as TSP and RP pairings, may influence growth, the recommended ratios of combinations produce distinct effects on plant height (Vangervihi and Obasi, 2022). Using 80% TSP+20% RP with K and TE included did not cause significant change in plant height. This is explained by the high phosphorus content of 20% RP and 80% TSP, which made the impact of K and trace elements negligible. This observation may be explained by the technique and timing of application. In contrast to foliar application, Patil *et al*., (2020) noted that soil application of K, Zn, and B may not result in the anticipated height increases. Gowthami and Rao (2014) observed that nutrients application during key growth phases can enhance growth results; however, the minimal height increase indicates that the timing or technique for K and B application in this instance might not have been ideal.

The study shows that the substitution of TSP with RP had minimal effects on plant height, as evidence by various research such as a research conducted in Brazilian Cerrado, using Arad phosphate rock (PR) with TSP led to soybean yields similar to those achieved with TSP alone, indicating the impact of this substitution on plant height was not significant (de Oliveira *et al*., 2011). While RP can enhance overall growth when combined with other amendments, its standalone application yields limited improvements. This finding was also observed by Sithamparam and Seran (2014), who examined RP with cattle manure and observed that when RP was applied alone, the height of soybean plants did not noticeably increase, even though it helped with root and shoot growth.

5.2 Leaf chlorophyll content measurements

The influence of the compound fertilisers NPK (14:18:18+B, Zn) and NPS+TE (14:31:5+B, Zn) on soybean plant greenness is significant, as evidenced by the high SPAD meter readings they recorded with time. The two compound fertilisers produce more chlorophyll, which plays a crucial role in photosynthesis, due to their balanced ratios of N, P, K, and S (Manu *et al*., 2020). The influence of TSP only, TSP+K and 80% TSP with 20% RP on plant greenness were not as pronounced as those of the compound fertilisers. This is attributable to two factors that are key to chlorophyll maintenance and overall plant health, factors which are variations in available P and nitrogen deficiency in those fertilisers. Phosphorus affects chlorophyll synthesis and photosynthesis. Low chlorophyll content, which causes inefficient or reduced amount of photosynthesis and low chlorophyll fluorescence, are a result of P deficiency, according to a study conducted by Singh and Reddy (2015).

When RP was raised from 20% to 40%, plant greenness somewhat declined. This result is probably related to the direct effects of phosphorus on photosynthesis and chlorophyll fluorescence. A lack of phosphorus can change measurements linked to chlorophyll, such as electron transport rate and quantum efficiency, and decrease the absorption of carbon dioxide (Singh and Reddy, 2015). The reduced phosphorus availability in the 60% TSP+ 40% RP treatment may have been insufficient to support optimal greenness.

However, adding potassium to the TSP + 40% RP treatment enhanced plant greenness at 8 weeks after planting (WAP). This improvement is important, as greener leaves indicate better photosynthetic activity, which supports greater biomass and yield. Liu (2012) found that potassium application significantly increases chlorophyll content in soybean, especially during reproductive stages, mainly through increasing chlorophyll, an essential for photosynthesis. Integrated nutrient management practices involving potassium have also been shown to improve plant height, root growth, and biomass accumulation in soybeans, all associated with enhanced chlorophyll content (Gangwar *et al*., 2023).

At the pod-filling stage, NPS+TE (14:31:5+B, Zn) produced more greenness than NPK (14:18:18+B, Zn) with a significant change. Higher photosynthetic efficiency and potential production are probably the cause of this increase in greenness. According to Khalili *et al.* (2024), the use of NPS+TE enhanced the uptake of N and S during crucial growth stages, which are essential for the development and greenness of soybeans. Compared to the orthodox NPK, NPS+TE improves nutrient consumption efficiency by making nutrients available in required quantities (Khalili *et al*., 2024). During the stage of pod filling, NPS+TE maintains high chlorophyll levels, which leads to increased levels of photosynthesis and crop production (Bondarenko *et al*., 2022).

The study found that, TSP generally increased soybean plants' greenness at the pod filling stage of development. Greenness, however, decreased with the addition of K and boron. This finding aligns with Farhan and Muhawish (2022), who found that during vegetative growth stages, TSP improved chlorophyll levels by making more phosphorus available, phosphorus which plays a critical role in plant energy transfer and photosynthesis.

5.3 Crop Maturation Time

The compound fertilisers NPK (14:18:18+B, Zn) and NPS+TE (14:31:5+B, Zn) had similar influence on the days to flowering of soybean plants. The number of days it took to reach 50% flowering for TSP, and when it was substituted with RP and other variations, was similar to the untreated controls. Mazur *et al*. (2022) concluded that the favour variety of soybean typically flowers within 40 to 60 days, taking into consideration the environmental conditions. Egli, (2005) observed that early flowering is often linked to higher reproductive success, as compared with prolonged flowering phase beyond 40 days. However, the application of NPK and NPS+TE treatments slightly delayed flowering compared to the control and TSP-based treatments. This delay may be attributed to the balanced nutrient supply from compound fertilisers, which supported prolonged vegetative growth evident through increased plant height and chlorophyll content and thus extended the time to flowering. A similar trend was observed in the time to full maturity, where plants treated with compound fertilizers matured late compared to those treated with single fertilizers. Research by Ahmed *et al*. (2015) suggests that while TSP may promote earlier maturity due to its phosphorus-driven stimulation of root development and early flowering, NPK can extend the vegetative phase, leading to delayed flowering and maturity.

The NPS+TE (14:31:5+B, Zn) fertilizer has a higher phosphorus content compared to NPK (14:18:18+B, Zn), which can influence soybean maturity differently. Particularly crucial for root growth and internal energy transfer, phosphorus can influence when a plant reaches maturity (Xiang *et al*., 2012). Nutrient availability to the plants influences days to maturity. It was seen that available P in the 100% RP was low, and the crops in those plots were the first to mature, taking 98 days, while the compound fertilizers that provided nitrogen and phosphorus took 120 days to mature, which is 10 days late compared to the 110 days (Legacy Crop Improvement Center) the breeder reported. According to studies, soybean plants given rock phosphate reached maturity earlier, and this is probably because there was less phosphorus available, which can cause earlier reproductive development (Sithamparam and Seran, 2014). In contrast, NPK fertilizers provide easily accessible phosphorus, which speeds up development but may postpone maturation because of the increased vegetative growth (Lamyaa *et al*., 2019). Because phosphorus availability and soybean development are inversely correlated, lower phosphorus levels may cause the plant to mature early as it adjusts to nutrient scarcity (Valadão *et al*., 2008).

The presence of nitrogen and phosphorus in NPS+TE (14:31:5+B, Zn) and NPK (14:18:18+B, Zn) facilitated an enhanced root growth and energy accumulation; however, this may also result in a postponement of flowering as the organism allocates more resources towards root and energy development at the expense of reproductive growth (Kaur *et al*., 2024). Bhosale and Pacharne (2017) and López *et al*. (2022) assert that fertilizers such as NPK and NPS+TE application can significantly improve growth attributes such as plant height and pod formation. The findings of this study refute their assertion. These impacts may reduce the time to maturity, facilitating a more efficient growth cycle. Additionally, plants treated with triple superphosphate showed a similar extension in maturity period as those treated with compound fertilizers. This finding is contrary to other studies, which found that TSP generally promotes early maturity rather than prolonging it, although specific conditions and interactions with other factors can influence this outcome. Anani *et al*. (2021) found that triple superphosphate (TSP), particularly when utilized in conjunction with rhizobia inoculants, markedly enhanced soybean productivity and facilitated earlier maturation in the Guinea savannah.

5.4 Nodulation and pod development

The compound fertilizer NPS+TE (14:31:5+B, Zn) performed worse than NPK (14:18:18+B, Zn) in nodulation and its counterpart effective nodules. The research shows that TSP combined with K fertilizer positively influenced nodulation the most among the fertilisers tested. Except for 60% TSP+40% RP, the addition of K to all the treatments showed an increment in nodules and effective nodules, though the difference may not be significant. The inclusion of Zn and B in the nutrients did not impact nodulation. The compound fertiliser NPS+TE (14:31:5+B, Zn) recorded an abysmal performance in nodulation, and this might be due to the absence of K in the compound. A pattern is therefore established that K inclusion in fertiliser is paramount in improving nodules and their effectiveness. Potassium, in addition to phosphorus mostly impact on nodulation. This impact could be attributed to the importance of K and P in soybean plants' growth and development. Given that it facilitates improved energy transfer and root development, phosphorus is necessary for nodulation. Numerous studies have demonstrated that applying phosphorus from TSP sources to soybeans greatly boosts nodulation and nitrogen fixation. When assessing the success level of nodulation, it is important to consider the nodules' dry weight, which increases at different rates of TSP application (Marcos, 2013; Shabnam *et al*., 2021). Plants' resistance to stress and metabolic capacities are improved by the application of muriate of potash, which is a good source of K vital for nodulation. Yield and nodulation are increased by TSP and muriate of potash applied together (Saat, 2014). Effective nodulation was affected by TSP more than by TSP with K, the study revealed. The interaction between P and K can explain this claim, the interaction which promotes important factors of legumes' nitrogen fixation, like nodulation and plant growth. Roni *et al*. (2011) further supported this assertion by indicating that nodulation was better enhanced by the application of K and P together than by K applied alone, leading to increased vegetative growth and overall nutrient assimilation. For example, nodules' dry weight and pod weight witnessed a significant rise by the application of single superphosphate (SSP) and potassium chloride (KCL), leading to the conclusion of improved nodulation (Saat, 2014). In the same study, it was observed that the absence of potassium in the process of nodulation did affect the process, however, potassium supported the soybean plants' overall health and vitality. It facilitates the effective utilization of phosphorus and various other nutrients, thus indirectly bolstering nodules formation (Saat, 2014). It has been noted that the synergistic application of TSP and Rock Phosphate (RP) results in a well-rounded phosphorus supply, wherein TSP provides immediate phosphorus availability while RP offers a gradual release mechanism. This strategic combination has the potential to optimize phosphorus accessibility throughout the entirety of the growing season, thereby facilitating the sustained development of nodules (Kabiru *et al*., 2024). The substitution of TSP with RP demonstrated the least beneficial impact on the effective nodulation, with the disparity in the effective nodules between 100% RP and the untreated control not being statistically significant. This is attributed to the low solubility of rock phosphate. This assertion was also confirmed by Wang. *et al*. (2005) who noted that rock phosphate is classified as a fertilizer with low phosphorus efficiency when utilized directly within soil matrices, attributable to its limited solubility, which consequently restricts its immediate bioavailability to plant systems.

The application of inoculant did not give splendid nodulation as expected. Apart from the compound fertilizers which caused inoculated plants to produce more nodules the inoculation effect was the same as non-inoculated among most of the fertilizer treatments. The application of rhizobium with TSP +K did not result to any benefit in podding, as the inoculated and non-inoculated plants produced a similar number of pods. This observation is attributed to rhizobium not being able to synergize well with the chemical fertilizers, potentially due to nutrient imbalances not supporting *Rhizobia* activity. This finding aligns with other studies such as that of Anani *et al*., (2021) and Dabesa and Tana (2021) who found that the combined application of TSP and inoculants did not yield a statistically significant rise in pod number, and this can be due to nutrient competition or soil conditions that were not favourable for effective nodulation. The application of TSP with inoculants in a Ghanaian study reported increased growth and yield; however, the particular interaction effects on podding were not always positive, indicating that the difference was impacted by local soil and environmental conditions. (Anani *et al*., 2021).

5.5 Grain Yield

The study showed that the compound fertilisers produced more grain yield than the untreated control. The highest grain yield was achieved by TSP partly substituted with 20% RP, with only the compound fertiliser NPS+TE being close. The solubility levels of TSP and RP explain this observation. TSP, the more soluble P source among the two, releases P promptly, while the release of P from RP is gradual. This P availability dynamics between TSP and RP plays to the advantage of the soybean plant, resulting in improved yield and growth. This observation is confirmed by the findings of Abbasi *et al*. (2012), who concluded that TSP and RP have a good interaction, which increases the availability of P. The interaction between the phosphorus sources under study, TSP and RP, enhance nitrogen fixation, efficient nodulation, and healthy root development, which results in improved growth and development (Abbasi *et al*., 2012). The slow release of P from RP, minimises phosphorus leaching when TSP and RP are applied together. The 20% RP part substitution of TSP with K, and the inclusion of trace elements into the 20% RP part substitution of TSP with K did not enhance grain yield. This is attributed to the role of K and trace elements in soybean growth and yield. The results of (Domingos *et al*., 2019), who pointed out that adding trace elements in addition to K may have contradictory effects on soybean yields, provide some support for this assumption. For instance, it has been shown that foliar K application combined with phosphate and boron can occasionally increase production; the specific outcomes, however, rely on site-specific factors (Domingos *et al*., 2019). This study found that using TSP by itself produced more grains than using TSP with K and TE. Although boron and zinc are acknowledged as critical micronutrients for soybean growth, the cultivar and application rate have different effects on yield. Studies suggest that boron may improve soybean growth, development, and yield in specific situations, but this advantage is not as strong as that of P and K. This observation might be due to the fertility level of the soil. Muriate of potash had minimal impact in extremely fertile soils, indicating that TSP application alone might be sufficient (Rampim *et al*., 2014).

The NPK (14:18:18+B, Zn) outperformed NPS+TE (14:31:5+B, Zn) in terms of grain yield among the compound fertilizers. This claim is explained by the balanced nutrient composition in suitable ratios, which promotes plant growth and development. The trace elements that are part of the NPK compound fertiliser help in the plant's nutrient uptake. Faraon *et al*. (2023) and Shaaibu and Rabiu (2023) observed that the nitrogen, phosphorus and potassium that make up the NPK fertiliser are supplied in the right amounts for plant growth and development due to their well-balanced ratio during formulation. The 14:18:18 used in NPK ensures a more equitable supply of nutrients compared to the disproportionate ratio of 14:31:5 used on the NPS+TE. The overall nutrient make-up and productivity are enhanced by the trace elements included in NPK fertilisers formulation (Dozet *et al*., 2022). The 14:31:5 ratio used in the formulation of NPS+TE, contains a high level of P, which may limit productivity. High levels of phosphorus prevent other essential nutrients uptake causing nutrient imbalance (Popescu *et al*., 2023).

The low K concentrations in NPS+TE may limit its capacity to promote the best possible development and growth of soybean plants (Kumah-Amenudzi *et al*., 2024). The regression analysis of grain yield against some parameters showed that biomass, pod weight, pod number and the effective nodule count influenced grain yield. An increase in these parameters increased grain yield. Jaradat *et al* (2006) found that one of the most important factors affecting yield is plant dry weight; higher dry weights lead to higher grain yield. Since larger plants usually produce more pods and seeds, higher plant biomass is linked to higher grain yields (Jaradat *et al*., 2006). Research shows that Ideal pod weight and number are crucial characteristics for breeding programs since they directly increase total production (Han *et al*., 2021). With an R2 value of 0.884, the quantity of pods per plant ranks third in terms of its contribution to yield, making it another crucial factor (Aduloju, 2014). It has been demonstrated that the practice of nutrition management techniques increases nodule mass and count, which in turn raises grain yield (Khanal *et al*., 2023).

5.6 Above-ground dry biomass production

The compound fertilizers NPK (14:18:18+B, Zn) and NPS+TE (14:31:5+B, Zn) produced similar amount of biomass. This is attributed to the effectiveness of the compound fertilizers in enhancing soybean growth, culminating in above-ground biomass yield. This finding, supported by Shaaibu and Rabiu (2023), indicates that NPK fertilizers significantly improve several plant growth indicators such as height, leaf area, and dry shoot mass, which are directly related to biomass production. The NPS fertilizer, which bears a resemblance to NPK, has demonstrated considerable influence on the yield of above-ground biomass; however, the particular composition and nutrient equilibrium within NPK may provide a more holistic nutrient provisioning (Oljirra and Temesgen, 2019).

This finding is also confirmed by Wantai. *et al*. (2006) who noted that the ratio of key nutrients in NPK fertilizers (14:18:18+B, Zn) and NPS+TE (14:31:5+B, Zn) fertilizers supply soybean plants critical nutrient in right proportions, thereby facilitating optimum growth and biomass generation.

From the study, the biomass generated by TSP and its application with trace elements and phosphorus, was comparable. This is attributed to the specific role of phosphorus in promoting biomass generation. In a research carried out in western Kenya, the application of TSP considerably enhanced the overall biomass production of soybean compared to the untreated control (Savini *et al*., 2016). The TSP applied in isolation produced more biomass than when TSP was mixed with potassium, boron and zinc. Roni *et al*. (2011) noted that the combination of TSP with K and boron may attenuate the influence of phosphorus, given that the alternative nutrients may not exhibit limiting characteristics in the soil, thereby resulting in a diminished contribution to the increase of biomass. In certain instances, the incorporation of potassium and the TE may augment various growth parameters; however, their influence on biomass may not be as significant as that of phosphorus in isolation (Jay *et al*., 2012; Bangar. *et al*., 2014).

5.7 Partial Budget Analysis

The marginal rate of return of the treatments that were not dominated were 168.9, 295.1 and 561.4 for 100% RP, 80%TSP+20% RP and TSP, respectively. Only phosphorus treatments, TSP and RP were economically viable treatments. Assuming that every farmer expects 100 % return in addition to the interest on the loan taken for farming, in Ghana about 45%, then Marginal Rate of Return above 145% will be acceptable to farmers. Rodrigues *et al*. (2023) reported high internal rate of return of 155% for two soybean cultivars. A marginal rate of return above 100% indicates that investments in soybean production yield substantial profits, encouraging farmers to invest more in these cultivars. All the three treatments (100% RP, 80%TSP+20% RP and TSP) exceeded the expected 145% marginal rate of return. But the marginal rate of return from the use of TSP was about twice the substitution of 20% TSP for rock phosphate. In Soybean production TSP application was extremely beneficial. The trace elements, B and Zn were costly. The addition of trace elements separately to single nutrients formulated fertilizers increased cost without appreciable increase in net benefit leading to negative Net Benefit. Therefore, the use of the trace elements not formulated with compound fertilizer is not beneficial.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The study was aimed at investigating the impact of rhizobium inoculation, NPK fertilization, essential nutrient supplementation and rock phosphate substitution for triple superphosphate on soybean field performance.

The following conclusions were drawn during the study;

- Rhizobium inoculation did not directly influence the yield of soybeans. Rhizobium inoculation, however had a notable influence on podding which is an essential yield component.
- NPK (14:18:18+B, Zn) and NPS+TE (14:31:5+B, Zn) are new introduced compound fertilizer by OCP. From the study, these two fertilizer regimes improved growth, chlorophyll development and grain yield.
- Triple superphosphate was a better source of phosphorus to soybean compared to rock phosphate. The supply of phosphorus by rock phosphate was inadequate for the growth and yield of soybean
- The ratio of 80% triple superphosphate and 20% rock phosphate improved yield better than 60% triple superphosphate and 40% rock phosphate
- Triple superphosphate combined with K enhanced growth and yield of soybean better than triple superphosphate applied in isolation
- The application of boron and Zn in combination with triple superphosphate and K did not improve the growth and yield of soybean.
- The supplementation of soybean with potassium improved growth and yield.

- The partial budget analysis showed that utilization of TSP gave highest Marginal rate of return (MMR). The 20% substitution of TSP for rock phosphate (80%TSP+20%RP) will reduce cost and give appreciable MRR next to that of TSP. If TSP cannot be used RP can be adopted and it will give marginal rate of return of 168.9%

6.2 Recommendations

The following recommendations are made based on the study findings:

- The application of NPK (14:18:18+B, Zn) and NPS+TE (14:31:5+B, Zn) are essential to maximize yield that will balance the cost of input.
- Triple superphosphate should be applied to soybean to provide phosphorus to soybean.
- Rock phosphate should not be applied in isolation due to being a poor source of phosphorus. Rock phosphate should be applied in combination with triple superphosphate or other phosphorus sources. When combining triple superphosphate with rock phosphate, the ratio of triple superphosphate to rock phosphate should be 80% TSP to 20% RP or 60% TSP to 40% RP.
- In order to maximize yield and profit, potassium should be added to soybean
- Application of Boron and Zn along with triple superphosphate and potash is not necessary.

OCP compound fertilizers NPK (14:18:18+B, Zn) and NPS+TE (14:31:5+B, Zn) are recommended to be applied to soybean to improve yield

In terms of the marginal rate of return, TSP is the fertilizer that should be applied to soybeans.

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APPENDICES

Appendix 1: Analysis of variance for growth parameters of soybean as influenced by fertilization, inoculation and interaction effects during the 2023 cropping season

		F probability (0.05)					
		Plant Height			Chlorophyll Content (SPAD readings)		
Sources of variation	df	6WAP	8WAP	10WAP	6WAP	8WAP	10WAP
Rhizobium (R)	1	0.04	0.322	0.589	0.542	0.426	0.791
Fertilization (F)	14	>0.001	>0.001	>0.001	>0.001	>0.001	>0.001
R x F	14	0.160	0.212	0.755	0.520	0.173	0.051
Residual	84						
Total	119						
SE		1.359	2.043	3.114	1.657	1.241	1.371
CV%		7.92	8.16	9.29	8.66	6.10	6.50

*SE= Standard Error; *CV%= Coefficient of Variation

Appendix 2: Analysis of variance for growth parameters of soybean as influenced by fertilization, inoculation and interaction effects during the 2023 cropping season

		F probability (0.05)							
Sources of variation	df	50% Flowering	Maturity	Nodules count	Effective nodules	Pod number	Pod weight	Grain yield	AGDB
Rhizobium (R)	1	0.092	0.468	0.666	0.960	0.141	0.249	0.730	0.116
Fertilization (F)	14	>0.001	>0.001	0.001	0.002	>0.001	0.038	>0.001	0.003
R x F	14	0.162	0.978	0.443	0.561	0.030	0.214	0.636	0.614
Residual	84								
Total	119								
SE		0.402	3.920	6.710	4.142	7.571	2.729	158.335	708.266
CV%		1.69	7.23	35.04	38.17	19.24	26.30	27.14	31.19

*SE= Standard Error; *CV%= Coefficient of Variation; *AGDB= Above Ground Dry Biomass

Appendix 3: ANOVA Table Plant Height at 4WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	76.000	25.333	2.24	
Rhizobium	1	3.633	3.633	0.32	0.610
Residual	3	33.854	11.285	3.43	
Fertilizer	14	29.713	2.122	0.65	0.820
Rhizobium.Fertilizer	14	71.889	5.135	1.56	0.108
Residual	84	276.349	3.290		
Total	119	491.438			

Appendix 4: ANOVA Table for Plant Height at 6WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	258.948	86.316	36.48	
Rhizobium	1	28.519	28.519	12.05	0.040
Residual	3	7.099	2.366	0.32	
Fertilizer	14	406.488	29.035	3.93	<.001
Rhizobium.Fertilizer	14	147.316	10.523	1.42	0.160
Residual	84	620.873	7.391		
Total	119	1469.243			

Appendix 5: ANOVA Table for Plant Height at 8WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	123.60	41.20	3.47	
Rhizobium	1	16.59	16.59	1.40	0.322
Residual	3	35.57	11.86	0.71	
Fertilizer	14	792.61	56.62	3.39	<.001
Rhizobium.Fertilizer	14	309.11	22.08	1.32	0.212
Residual	84	1402.06	16.69		
Total	119	2679.54			

Appendix 6: ANOVA Table for Plant Height at 10WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	420.73	140.24	3.36	
Rhizobium	1	15.12	15.12	0.36	0.589
Residual	3	125.05	41.68	1.07	
Fertilizer	14	5187.05	370.50	9.55	<.001
Rhizobium.Fertilizer	14	387.67	27.69	0.71	0.755
Residual	84	3258.89	38.80		
Total	119	9394.52			

Appendix 7: ANOVA Table for SPAD Readings at 4WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	2373.0	791.0	1.02	
Rhizobium	1	928.0	928.0	1.19	0.354
Residual	3	2332.0	777.3	1.01	
Fertilizer	14	10507.9	750.6	0.98	0.481
Rhizobium.Fertilizer	14	11230.1	802.1	1.05	0.417
Residual	84	64391.5	766.6		
Total	119	91762.4			

Appendix 8: ANOVA Table for SPAD Readings at 6WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	184.41	61.47	6.49	
Rhizobium	1	4.45	4.45	0.47	0.542
Residual	3	28.40	9.47	0.86	
Fertilizer	14	461.35	32.95	3.00	<.001
Rhizobium.Fertilizer	14	144.57	10.33	0.94	0.520
Residual	84	922.05	10.98		
Total	119	1745.22			

Appendix 9: ANOVA Table for SPAD Readings at 8WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	201.932	67.311	23.34	
Rhizobium	1	2.437	2.437	0.84	0.426
Residual	3	8.654	2.885	0.47	
Fertilizer	14	494.699	35.336	5.74	<.001
Rhizobium.Fertilizer	14	120.282	8.592	1.40	0.173
Residual	84	517.117	6.156		
Total	119	1345.120			

Appendix 10: ANOVA Table for SPAD Readings at 10WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	52.088	17.363	1.74	
Rhizobium	1	0.833	0.833	0.08	0.791
Residual	3	29.891	9.964	1.33	
Fertilizer	14	774.014	55.287	7.36	<.001
Rhizobium.Fertilizer	14	188.514	13.465	1.79	0.053
Residual	84	631.226	7.515		
Total	119	1676.567			

Appendix 11: ANOVA Table for SPAD Readings at Pod Filling

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	21.581	7.194	0.28	
Rhizobium	1	1.564	1.564	0.06	0.820
Residual	3	76.423	25.474	4.81	
Fertilizer	14	2015.179	143.941	27.19	<.001
Rhizobium.Fertilizer	14	126.970	9.069	1.71	0.068
Residual	84	444.624	5.293		
Total	119	2686.340			

Appendix 12: ANOVA Table for Days to 50% Flowering

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	2.5333	0.8444	2.37	
Rhizobium	1	2.1333	2.1333	6.00	0.092
Residual	3	1.0667	0.3556	0.55	
Fertilizer	14	30.8667	2.2048	3.40	<.001
Rhizobium.Fertilizer	14	12.8667	0.9190	1.42	0.162
Residual	84	54.4000	0.6476		
Total	119	103.8667			

Appendix 13: ANOVA Table for Days to 100% maturity

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	227.36	75.79	2.60	
Rhizobium	1	20.01	20.01	0.69	0.468
Residual	3	87.43	29.14	0.47	
Fertilizer	14	7732.97	552.35	8.98	<.001
Rhizobium.Fertilizer	14	323.37	23.10	0.38	0.978
Residual	84	5164.47	61.48		
Total	119	13555.59			

Appendix 14: ANOVA Table for Nodule Count at 8WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	2642.1	880.7	3.76	
Rhizobium	1	53.3	53.3	0.23	0.666
Residual	3	703.0	234.3	1.30	
Fertilizer	14	7314.5	522.5	2.90	0.001
Rhizobium.Fertilizer	14	2567.7	183.4	1.02	0.443
Residual	84	15124.9	180.1		
Total	119	28405.5			

Appendix 15: ANOVA Table for Effective Nodule Count at 8WAP

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	455.93	151.98	1.52	
Rhizobium	1	0.30	0.30	0.00	0.960
Residual	3	300.30	100.10	1.46	
Fertilizer	14	2613.95	186.71	2.72	0.002
Rhizobium.Fertilizer	14	865.45	61.82	0.90	0.561
Residual	84	5763.27	68.61		
Total	119	9999.20			

Appendix 16: ANOVA Table for Pod Number

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	9808.2	3269.4	15.50	
Rhizobium	1	832.1	832.1	3.94	0.141
Residual	3	632.9	211.0	0.92	
Fertilizer	14	14178.2	1012.7	4.42	<.001
Rhizobium.Fertilizer	14	6328.4	452.0	1.97	0.030
Residual	84	19258.9	229.3		
Total	119	51038.7			

Appendix 17: ANOVA Table for Pod Weight

Sources of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replication	3	479.52	159.84	5.16	
Rhizobium	1	63.12	63.12	2.04	0.249
Residual	3	92.90	30.97	1.04	
Fertilizer	14	790.23	56.45	1.89	0.038
Rhizobium.Fertilizer	14	550.41	39.32	1.32	0.214
Residual	84	2502.87	29.80		
Total	119	4479.06			

Appendix 18: ANOVA Table for Above Ground Dry Biomass

Sources of variation	d.f.	s.s.	m.s.	v.r.	F pr.

Replication	3	13085294.	4361765.	2.04	
Rhizobium	1	10271817.	10271817.	4.81	0.116
Residual	3	6406317.	2135439.	1.06	
Fertilizer	14	74545696.	5324693.	2.65	0.003
Rhizobium.Fertilizer	14	23890365.	1706455.	0.85	0.614
Residual	84	168551159.	2006561.		
Total	119	296750647.			

Appendix 19: ANOVA Table for Grain Yield

Sources of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Replications	3	341118.	113706.	0.39	
Rhizobium	1	41989.	41989.	0.14	0.730
Residual	3	879739.	293246.	2.92	
Fertilizer	14	9724998.	694643.	6.93	<.001
Rhizobium.Fertilizer	14	1164458.	83176.	0.83	0.636
Residual	84	8423517.	100280.		
Total	119	20575819.			