

**EFFECT OF PHOSPHORUS FERTILIZER AND CROPPING SYSTEMS ON
RICE BEAN (*Vigna umbellata*, L.) PRODUCTION IN WESTERN KENYA**

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DECLARATION

Declaration by the Candidate

This thesis is my original work and has never been presented for the award of an academic degree in any other university and should not be copied or reproduced in any format without written authority from the author and/or the University of Eldoret.

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DEDICATION

I dedicate this thesis to my fiancée Irine Akoth, my daughter (Maryvinne Linna), and dear family members; Dad (Alex Migaya), Mum (Caroline Atieno), Siblings (Victor Ochieng, Leon Otieno, Alice Anyanga, Emma Migaya, Alfonse Ouma, and Chrispine Obunga and Cousins (Kennedy Odero and Maurine Obunga), and friend Naomi Okoth for their encouragement, support, and prayers during my studies.

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ABSTRACT

Low soil phosphorus (P) remains a critical constraint to sustainable legume production in Western Kenya. Rice bean (*Vigna umbellata* L.), a resilient and nutrient-rich yet underutilized legume, offers opportunities for food security enhancement and soil fertility restoration. The crop productivity has been hindered by nutrient deficiencies and suboptimal cropping systems. This study evaluated the effect of phosphorus fertilizer and cropping systems on rice bean soil fertility dynamics, phenology and yields across three agroecological sites; Siaya, Rongo and Kaimosi over two consecutive seasons (September–December 2020 and March–August 2021). A split-plot design was used, with cropping system (monocrop, conventional intercrop and MBILI) as the main factor and P amendments (control at 0 kg P ha⁻¹, FYM at 5 kg P ha⁻¹, combined FYM + inorganic at 15.5 kg P ha⁻¹, and sole inorganic at 26 kg P ha⁻¹) as the subplot factor, replicated three times per site. Data on soil available P, phenological stages, pods per plant, grain yields, phosphorus agronomic efficiency (PAE) and harvest index (HI) were collected and analyzed using Analysis of Variance (ANOVA). Results showed that soil available P was highly responsive to P amendments, with 26 kg P ha⁻¹ application producing the highest levels (up to 8.88 mg kg⁻¹ at Rongo monocrop), while 15.5 kg P ha⁻¹ application maintained moderately high levels that balanced immediate nutrient supply with long-term fertility. Cropping system effects on soil P were less pronounced, but monocropping and MBILI showed slightly greater retention than conventional intercropping. Phenological responses were notable: 0 kg P ha⁻¹ plots matured 12–17 days later than 15.5 kg P ha⁻¹ or 26 kg P ha⁻¹ treatments, with delayed flowering and extended vegetative growth under P deficiency. Across sites and seasons, grain yields ranged from 0.24 t ha⁻¹ in conventional controls at Siaya to 1.72 t ha⁻¹ under monocrop with 15.5 kg P ha⁻¹ P in Rongo, highlighting the clear yield advantage of combined nutrient management in low-P soils. PAE varied widely, peaking at 63.42 kg kg⁻¹ under monocrop with fertilizer treatment of 15.5 kg P ha⁻¹ at Rongo. The PAE was higher under the fertilizer treatments of 5 kg P ha⁻¹ and 15.5 kg P ha⁻¹ treatments than under 26 kg P ha⁻¹, indicating superior nutrient use efficiency with organic amendments. Harvest index values reflected biomass partitioning, highest in conventional and MBILI systems (up to 11.10%) compared to 3–4% in monocrops. The study concludes that combining organic and inorganic phosphorus sources within site-specific cropping systems accelerates phenological development, improves nutrient use efficiency and maximizes yield in rice bean production. Extension programs should prioritize farmer training on integrated soil fertility management to promote organic–inorganic nutrient combinations. These findings provide a framework for sustainable intensification of underutilized legumes in phosphorus-deficient soils.

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LIST OF ACRONYMS, ABBREVIATIONS AND SYMBOLS

Al - Aluminium

AE - Agronomic Efficiency

AM - Amendments

ANOVA - Analysis of Variance

ATC - Agricultural Training Centre

BNF - Biological Nitrogen Fixation

CS - Cropping Systems

Ctrl - Control

FAO - Food and Agriculture Organization

FYM - Farmyard Manure

K - Potassium

KAFUCO - Kaimosi Friends University College

LM - Lower Midland zones

LSD - Least significant difference

MBILI - Managing Beneficial Interactions in Legume Intercrops

Mn - Manganese

N - Nitrogen

OM - Organic Matter

P - Phosphorus

PAR - Photosynthetically Active Radiation

pH - Potential hydrogen

RCBD - Randomized Complete Block Design

SA - South Asia

SSA - Sub-Saharan Africa

SFCC - Soil Fertility Capability Classification (SFCC)

t ha⁻¹ - tons per hectare

TSP - Triple Superphosphate

USA - United States of America

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Global food systems face mounting pressure due to rapid population growth, land degradation and the escalating impacts of climate change. By the year 2050, the world's population is forecast to reach approximately 9.7 billion, necessitating significant improvements in both agricultural productivity and long-term sustainability (Gu et al., 2021). Despite scientific and technological advancements, food insecurity remains a pressing global challenge, especially in marginal environments described by soil infertility and limited agricultural systems (Castellanos-Navarrete et al., 2015; Agene, 2024).

These multidimensional issues demand an extreme shift in attitude towards nutrient-rich climate resilient crops that may function under low-input conditions. Rice bean (*Vigna umbellata* L.) crop has superior agronomic importance combined with very high nutritional attributes. It's composed of 58-72% carbohydrate, 18-32% protein and 3-4.9% ash (Khadka & Acharya, 2009). This legume is capable of maturing within a short duration and it's also resistant to drought. It can be cultivated in soils which are acidic and degraded (Saini et al., 2020; Dahipahle et al., 2017). Rice bean's potential to give better yields while requiring very low external inputs makes it to be advocated for consideration by smallholder farmers in western Kenya. It's a promising crop capable of solving food and nutritional insecurities in the region. This crop has received very little consideration in major agricultural research programs and development initiatives (Kokwon et al., 2025). There is inadequate understanding of its full growth and yield potential in the region. Its

progress has been constrained by emphasis on more dominant crops like common bean, soybean, groundnut and maize (Onyanha et al., 2022).

Phosphorus is helpful in good establishment of the roots, improving biological nitrogen fixation (BNF) and facilitating energy transfer mechanisms (Syers et al., 2008.). In soils of the tropics, P availability is limited by iron and aluminum oxides fixation (Oloo, 2016). The structurally poor tropical soils have very low levels of organic matter. This also inhibits the nutrient uptake by crops and hence a reduction of the performance of the crop. P fertilizer application improve crop productivity. The high P cost combined with low P use efficiency of 10-30% have hindered their benefits to farmers in the region (Savini et al., 2016). Phosphorus management practices which encompasses precise rates of application, correct placement and incorporation with varying intercropping systems can increase the legume productivity in SSA (An et al., 2023). Regrettably, research on phosphorus relations with rice bean has been low. This has enabled escalation of knowledge gaps making it difficult to evaluate this important agronomic behavior in different soil fertility and crop management options. The high rates of food insecurity in SSA is as a result of inadequate soil fertility with the region experiencing heavy weathered and low nutrient soils (Kisinyo et al., 2019).

Very few smallholder farmers apply phosphorus fertilizers frequently in SSA (Otieno et al., 2018). These drawbacks negatively affect legume cultivation which is important for the improvement of food security and soil fertility restoration in the region. The production of legumes in SSA is very low because of degradation of soils, high labor-intensive management requirements, inferior seed quality, pests and diseases outbreaks and market inadequacy (Waldman et al., 2016). Rice bean can be used to restore degraded lands

through raising soil organic matter and enhancing nitrogen fixation processes in such nutrient poor soils (Khadka, 2009).

Intercropping systems improve nutrient cycling processes, limit weed populations and assist in the conservation of soil moisture (Mongare et al., 2020). Managing Beneficial Interactions in Legume Intercrops (MBILI) model has given promising results in improving resource use efficiencies (Thuita et al., 2011). The long-term successes and profitability of such systems depend on the effect of P and their associations with crop type and local characteristics of the soil.

In western Kenya, P deficiency can be explained by the poor crop management strategies which include over-cultivation and low usage of fertilizers leading to the emergence of grossly unfavorable nutrient ratios in farms. The research on rice bean is highly insufficient, yet this crop is adequately supplemented with unique features like the early maturity and the general resistance to abiotic and biotic stress factors and the high-nutritional value. There is scanty agronomic evidence on the impact of phosphate fertilizers on the crop in multi cropping regimes. These are the areas of weakness that have slowed its marketing and dissemination of its knowledge to farmers (Saini et al., 2020).

Poverty rates i.e. 47.56% recorded in Siaya County together with erratic weather patterns limit crop productivity in the region (MoALF, 2017). Intercropping systems practiced in western Kenya have focused widely on major legumes. The region's agricultural productivity is hindered by fertilizers unaffordability and low extension services. There is a need for diversified cropping systems which aim to improve management of nutrients in acidic soils. Soil health and crop output are enhanced by organic and inorganic fertilizers application (Oloo, 2016). The growth and yield responses of rice bean production under

different phosphorus rates and cropping systems in western Kenya need to be assessed. The crop's tested resilience to both biotic and abiotic stressors with its rich nutritional status enable it to be a strong legume acceptable to smallholder farmers. Research is also required to provide visualized and farmer-accepted recommendations on phosphorus rates and cropping systems for the crop. The study seeks to evaluate the effect of four phosphorus fertilizer rates and three cropping systems in regards to the rice bean phenological development and yield in western Kenya. The outcome will inform management decisions in soil fertility and hence the mainstreaming of rice bean into smallholder farming practices.

1.2 Statement of the problem

Agricultural productivity in western Kenya is increasingly limited by soil acidity and phosphorus (P) deficiency (Kisinyo et al., 2019.). The soil acidity has been caused by leaching of basic cations while phosphorus deficiency is due to fixation of phosphorus by aluminum and iron oxides (Njoroge et al., 2017). Small scale farmers in the region have tried to ameliorate these setbacks by applying inorganic and organic fertilizers either independently or in combination to improve crop yields. However, only 10-30% of applied phosphorus is annually available for use by the plants (Savini et al., 2016). Existing data indicate that the common bean yields are less than 1 t ha⁻¹ in western Kenya against a yield potential of 2 t ha⁻¹(Opala et al., 2020). In addition, in the same region, soy bean yields stand at less than 1 ton ha⁻¹ against a yield potential of 3 ton ha⁻¹(Oluoch et al., 2024). The green grams yields currently stand at between 0.5-0.6 t ha⁻¹ despite a yield potential of 1.5 t ha⁻¹ (Muchomba et al., 2023). There is a need to promote other legumes which can do competitively well in the region for the improvement of food

nutrition and security. Rice bean can produce yields of 1.3-2.75 t ha⁻¹ (Dahipahle et al., 2017). The crop adapts well and can produce better yields in such acidic soils with minimal external inputs. It can also biologically fix nitrogen (Muoni et al., 2022). Its cultivation in the region has been hampered by a lack of knowledge on its production patterns and agronomic qualities hindering its promotion. There is therefore a call to promote its production in the region with a sole focus on improving food security through legume diversification approach. Cropping systems have also been diversified in western Kenya (Mongare et al., 2020). However, little or no focus has been on how these cropping systems influence rice bean production. There is therefore a need to evaluate the effect of phosphorus fertilizer levels and cropping systems on rice bean production in western Kenya.

1.3 Justification of the Study

The dominant soils in western Kenya are Acrisols and Ferralsols which are highly weathered and deficient in phosphorus which inhibit sustainable agriculture (Owino et al., 2015; Njoroge et al., 2017). This study is justified in its aim to generate agronomic insights on how phosphorus application rates influence rice bean performance in such environments. The results will be useful in optimizing P use and give support to soil fertility improvement approaches in farms.

Rice bean has been greatly sidelined from Kenya's national agricultural research, extension and food security programs (Onyancha et al., 2022). Kenya has about 3.6 million legume farmers and over 4.4 million food-insecure people, while the national per capita protein intake has dropped to 61 g/day against the recommended 69 g/day. This therefore means, there is a need to reduce legume yield gaps which currently stands at 25-60% in

western Kenya (Michael et al., 2024). Legumes are high in plant proteins (Lisciani et al., 2024). The promotion of cultivation of drought resistant and highly nutritious legumes like rice bean could bridge the dietary and yield production gaps. This study addresses the critical knowledge gap on the crop's agronomic response to phosphorus under different cropping systems, thereby generating evidence that can inform its inclusion in sustainable farming practices and promote its broader adoption in western Kenya and similar agroecological zones. Such efforts concur with Sustainable Development Goals 1 and 2, which aim to end hunger and poverty by 2030 (UNESCO, 2018). Different cropping systems have shown promise in enhancing nutrient use efficiency and productivity in cereals and legumes (Mongare et al., 2020). However, rice bean integration into such systems remains untested. The research will also contribute to the scientific community by identifying the most suitable phosphorus management strategies and cropping systems to optimize rice bean productivity in acidic soils of western Kenya. These insights inform extension recommendations and shaping agricultural policy aimed at sustainable intensification, particularly for smallholder farmers managing marginal lands.

1.4 Research Objectives

Overall objective: To diversify legume production for improved food security in western Kenya.

1.4.1 Specific objectives

1. To evaluate the effect of phosphorus (P) fertilizer and cropping systems on soil available phosphorus under rice bean production in western Kenya.
2. To determine the influence of P fertilizer and cropping systems on the phenological development of rice bean in western Kenya.
3. To establish the effect of P fertilizer and cropping systems on the yield and yield components of rice bean in western Kenya.

1.5 Research Hypotheses

The hypotheses of the study were:

H₀₁: Phosphorus fertilizer and cropping systems have no significant effect on soil available phosphorus under rice bean production in western Kenya.

H₀₂: Phosphorus fertilizer and cropping systems have no significant influence on the phenological development of rice bean in western Kenya.

H₀₃: Phosphorus fertilizer and cropping systems have no significant effect on the yield and yield components of rice bean in western Kenya.

CHAPTER TWO

LITERATURE REVIEW

2.1 Background on Soil Fertility and Phosphorus Deficiency in Smallholder Systems

In smallholder farming systems across the tropics, the challenge of maintaining soil fertility continues to undermine agricultural resilience and productivity. These systems are predominantly rain-fed, low-input and reliant on marginal lands, making them vulnerable to degradation from continuous cultivation, nutrient mining and limited replenishment of soil nutrients (Agegnehu et al 2017). Soil fertility decline is compounded by socioeconomic constraints, such as limited access to fertilizers, inadequate extension services and labor shortages (Otieno et al., 2018). Although various interventions have been proposed, ranging from integrated soil fertility management (ISFM) to conservation agriculture, their adoption has been limited due to economic and knowledge barriers. Moreover, national programs often focus on major staples like maize and wheat, leaving underutilized legumes such as rice bean out of the mainstream research and development agenda, despite their resilience and nutritional advantages.

Globally, sustainable agricultural intensification is increasingly constrained by nutrient depletion, especially in low- and middle-income countries where farming inputs are scarce and land is overexploited. Soil fertility decline, marked by the depletion of critically essential macro- and micronutrients, has been recognized as a major barrier to productivity and food security (Opala et al., 2023).

Prolong cultivation, lack of adequate crop residue management and destruction of forests have reduced organic matter in the soil. This has destroyed the structure of the soil rendering them very less effective while supporting plants growth (Oloo, 2016). Nitrogen

deficiency has been the major focus by most researchers for decades, but of late much attention is now shifting to the deficiency of phosphorus research. P improves the root growth of the plants, initiates the energy transfer processes via the Adenosine Triphosphate (ATP) and controls the crucial processes of reproductive crops (Syers et al., 2008.). The main legumes that include common beans and soy beans have received attention in the whole world with minimal programs being paid on underutilized legumes (Dahipahle et al., 2017). The nutrient requirements of rice bean have not been significantly highlighted in spite of the fact that the crop can grow very well in acidic tropical soils. The soils of this region are highly weathered and very acidic hence they tend to fix phosphorus (Peter et al., 2018).

The high presence of aluminum (Al^{3+}) and iron (Fe^{3+}) in these soils results in strong binding of applied phosphorus, making it unavailable to crops (Opala et al., 2020). Phosphorus levels are typically below 10 mg kg^{-1} , and this is insufficient to maintain high crop production (Okalebo et al, 2002; Agriculture, 2014). Despite the limitations mentioned, the most widespread phosphorus management suggestions are generalized on the regional and various systems of cropping, which leaves lapses in crop-specific and soil-specific knowledge on phosphorus interactions. Use of ISFM practices has been promoted, its application is however declining due to the absence of resources and limited information that relates soil chemistry and crop response in diverse environments.

One of the major limitations of production in the Kenyan agricultural land is phosphorus shortage, and more so among the small holder systems that comprise the majority of food production. Vihiga, Migori, and Siaya counties have a pH level of less than 5.5 that accelerates phosphorus fixation and therefore inhibiting the occurrence of nutrients to crops

to be used (Njogo et al., 2018). The P fertilizers applied by the smallholder farmers in the area are lower than that of legumes which is not in accordance to phosphorus requirements. Some of the factors that contribute to this low use of P fertilizers include the high cost of the fertilizer and the difficult nature of the work of organic manure and low agricultural extension services (Otieno et al., 2018).

In western Kenya, the consequence of P deficiency is quickly visible in farms. The presence of Acrisols and Ferralsols associated with high P fixation and low organic matter hinder availability of soil nutrients, interfering with biological and microbiological soil processes (Aguyoh et al, 2019). Some smallholder farmers have documented very low legume yields even when adequate fertilizers are applied in the soil, suggesting immense soil quality setbacks and unresponsiveness that may not be effectively resolved by existing farming practices (Njoroge et al., 2017). Rice bean yield outcomes in such soil conditions may be poor despite a yield of 1.3-2.75 t ha⁻¹ under good ecological conditions (Dahipahle et al., 2017).

This legume crop cultivation is thought to have originated from Indo China areas and South Asia nations. The crop being originating from South and South East Asia, is cultivated widely in India, China, Nepal, Philippines, Laos, Vietnam, Korea, Thailand, West Bengal, Sri Lanka, Brazil, Malaysia, Fiji, Sierra Leone, Mauritius, Zaire, Ghana, Mexico, Tanzania, Jamaica and Haiti. Very minimal cultivation spreads to West Indies, Queensland (Australia), USA and East Africa (Ahmed & Jamil, 2024). The crop needs very minimal fertilizer requirements and can effectively perform well in soils which are deficient in phosphorus nutrient. The crop is highly nutritious and can reach the actual physiological maturity after a short duration of planting. It can fix nitrogen biologically into the soil hence

improving the fertility of the soil (Yadav et al., 2022). The studies on rice bean agronomy have been very limited with no recommended P requirements in western Kenya.

P deficiency address demands not only fertilizer additions but also expanded understanding of the interactions of crops and the soil together with available crop management strategies which can enhance P nutrient use efficiencies. Intercropping influence P availability through the changing of distribution of plant roots, the rhizosphere pH and overall activation of soil microbial processes (Gebru, 2015). Cropping systems productivity depend wholly on the variety of the crop chosen and the subsequent crop interactions (Nkhata *et al*, 2021). Mono cropping, conventional, and MBILI systems of intercropping have been widely adopted by the farmers in western Kenya (Kinyua et al., 2023). Mono cropping system lays emphasis on the planting of a particular type of crop within the same farm within the same period. The weaknesses usually related to this type of cropping system are the poor management of soil cover, concentration of pests and diseases in the farms, lack of methods of controlling weeds, loss of nutrients in soil and destruction of soil structure. The MBILI systems have maximized the nutrient capture by the plants and solar energy capture (Mongare et al., 2020). Rice bean has been minimally researched within such systems. How it responds to different cropping systems and varying phosphorus levels has not been researched. Intercropping systems are challenged by reducing main crop's yield production due to high labor requirements for the maintenance of the crop (Mupangwa et al., 2021). P deficiency implications for underutilized crops like rice bean remain poorly researched. Research efforts should focus on understanding the interaction between phosphorus amendments and cropping systems, particularly for adaptable, stress-

tolerant crops like rice bean that can contribute to both food security and soil restoration in smallholder agroecosystems.

2.2 Effect of Phosphorus Fertilizer and Cropping Systems on Soil available Phosphorus

Soil available phosphorus (P) refers to the portion of phosphorus that is available readily for the growth of plants, contributing to nutrient availability. This component performs a significant function in sustaining long-term soil fertility mechanisms. The quantities and qualities of soil available P depend on the type of fertilizer applied, existing soil characteristics, cropping system used and prevailing environmental conditions (Khan et al., 2018). The entire world has experienced a growing interest in P recovery and recycling in the farms because of the depleting nature of phosphate rock materials (Sarvajayakesavalu et al., 2018). The various types of P fertilizers possess different degrees of efficiencies with regard to the manner in which they interact and dissolve with soil colloids. The inorganic fertilizers such as triple superphosphates (TSP) and diammonium phosphates (DAP) deliver immediate and easy P supply to the soil but get immobilized in the soils that are highly weathered that are common in the tropics (Savini et al., 2016). This could lower their effectiveness and efficiency sometime in the future. The effect of the use of rock phosphate in combination with organic fertilizers has some level of influence on the P available in soils. The biochar and compost fertilizers can also stabilize soil available P thereby reducing their fixation in acidic soils (Pouangam et al., 2023)..

The common conventional intercropping systems could reduce leaching of nutrients. However, they may not be very effective in optimizing legume photosynthetically active radiation because of the spacing. This can lead to incorporation of a more reliable cropping

systems like the MBILI intercropping systems into small holder farms (Kinyua et al., 2024).

In the Kenyan context, researches have demonstrated that manure-amended soils showed higher residual phosphorus levels compared to plots treated with TSP alone, suggesting the importance of integrated nutrient approaches (Oloo, 2016). Mainstream research and government extension programs still emphasize major legume productions in Kenya. It has been established that MBILI intercropping systems have the potential of improving availability of light and phosphorus uptake by plants in western Kenya (Thuita et al., 2011). Inadequate diversity in phosphorus research could bring missed opportunities while identifying alternative crops which may be very efficient in nutrient acquisition and nutrient recycling processes. The management of P remains a major obstacle in smallholder systems. In such circumstances, the soil available P is important, as crops must depend on past P applications and original soil P reserves. Cropping systems also complicate nutrient dynamics. The mono cropping removes nutrients rapidly while intercropping enhances nutrient use efficiency (Mongare et al., 2020). MBILI intercropping systems has been shown to lower nutrient losses and improve P uptake in maize-bean cropping systems. The application of such systems to rice bean crop remains under researched.

There is a gap in the literature of rice bean in studying its ability to enhance soil available P under various cropping systems (Dahipahle et al., 2017). The architecture of the roots, secretion chemistry and biological interactions are different across legume species thereby affecting P acquisition and retention (Saini et al., 2020). The common beans and soybeans have been the focus of most soil fertility programs neglecting rice bean in the region. Most farmers in Western Kenya integrate legumes like soybeans, cowpeas and groundnuts into

maize-based intercropping systems. There is inadequate experimental data that link rice bean growth performance with soil available phosphorus. This can prevent researchers to develop procedures for incorporating rice bean into soil fertility management strategies.

The soil available phosphorus plays a crucial role in sustaining productivity in phosphorus-deficient and low-input systems, but its dynamics are highly context-specific (Hussain, 2017). Soil type, cropping system and fertilizer source all interact to determine how much phosphorus remains available after crop harvest. For underutilized legumes like rice bean, which are increasingly recognized for their resilience and nutritional value, understanding these interactions is vital. Current research offers a general framework but falls short of providing crop-specific and site-specific insights. There is an urgent need for targeted studies examining how phosphorus amendments and cropping systems affect soil available phosphorus and availability in rice bean production in western Kenya.

2.3 Influence of Phosphorus and Cropping systems on Legume Phenology

Phenology, which includes stages such as germination, flowering and pod development, is sensitive to nutrient availability, particularly phosphorus. Phosphorus enhances early root development, accelerates flowering and facilitates assimilate partitioning, all crucial for short-duration legumes like rice bean (Zaidi et al., 2010). Inadequate phosphorus levels lower plant phenological stages and number of pods and seeds per plant. While these effects are pronounced for all legumes, limited research on how rice bean responds phenologically to P fertilizers exist. Rice bean has a short-lived semi erect to erect vine structures with a height of 30–200 cm. Its taproot system is 100–150 cm deep with finely haired branches (Onyancha et al., 2022). The plant is sensitive to light with a determinate

habit of growth. It produces occasional and non-simultaneous flowering. It produces trifoliolate leaves with 6–9 cm hairy leaflets and yellow flowers which are clustered on 5-20 cm racemes. The sizes of the pods range between 7.5–12.5 cm and can hold 6–10 oblong seeds which are different in color from green to yellow to black, yellow and brown (Pattanayak et al., 2019). These unique characteristics state a potentially different phenological response curve compared to commonly studied legumes.

Worldwide, studies on P and phenology in legumes focus on large-scale crops like soybean, chickpea and cowpea. P availability affects the flowering time and maturity duration in legumes. These generalizations are not always transferable to unique crops like rice bean (Saini et al., 2020). Most of those studies occur under controlled experimental conditions which do not reflect the realities in small scale farming. The phenological patterns got from these studies do not adequately inform localized adaptation strategies or fertilizer recommendations for rice bean. Its occasional and staggered flowering habit combined with highly exposed pods, elongated and slightly curved seeds with beaked ends, rice bean may exhibit phenological responses that require more context specific research studies. The improvements in legume phenological attributes is associated with the cropping systems patterns (Mongare et al., 2020). The MBILI systems enhances the solar energy penetration to allow adequate photosynthetic active radiation which can improve flowering and development of pods.

In Africa, effect of phosphorus levels on crop phenology has been studied in ground nuts and common beans in Nigeria, Uganda and Tanzania (Dikr & Abayechaw, 2022). These researches reiterates that P nutrient improves early plant growth vigour. Crop phenology determines the timing of crop harvest, scheduling of labor activities and assessing the

compatibility to intercropping systems which is a critical consideration in rice bean production. Rice bean's twining growth habit and the occasional requirement for staking in order to improve vegetative growth has necessitated the urge to understand its phosphorus cropping systems (Saini et al., 2020). Increasing P rates have been demonstrated to increase common bean's phenology in Ethiopia (Amanuel et al., 2018). There exists scanty phenological data of rice bean in various cropping arrangements in western Kenya (Michael et al., 2024). The available literature emphasizes on phenological traits of major legumes. This is expected to be integrated to rice bean production fully without taking any consideration that the crop has specific gene types and unique physiological make up. In western Kenya, the intercropping systems have not also documented the effect on crop phenology in rice bean production (Michael et al., 2024). Specific studies should evaluate how P fertilizer and cropping systems improve crop phenological development. These studies should be able to be adopted by smallholder farmers. The studies should also consider local soil types, available rainfall patterns and preferred farmer crop management strategies.

2.4 Effect of Phosphorus Fertilizer and Cropping Systems on the Yield of Legumes

Yield and yield components such as pod number, seed weight, harvest index, and phosphorus use efficiency (PUE) are directly influenced by nutrient availability and cropping design (Otieno et al., 2018). P improves the crop flowering, the formation of pods and filling of the seeds. It also helpful in accumulation of biomass (Zaidi et al., 2010). Yield and yield components are due to seed variety planted and the date of planting, the

cropping system used by the farmer, agro ecological region and crop agronomic management approaches.

In the whole world, P has been demonstrated to facilitate legume productivity (Khan et al., 2023). Field experiments have indicated that P increases legume root expansion, root nodule development and aiding the process of partitioning assimilate. These activities increase the number of pods and the resultant improvement seed weight (Billah et al., 2019). The efficiencies are realized when the P nutrient is placed in required quantities needed and when the crop nutrient demand is at its peak level. These results are derived from established research systems which prevent their transferability for their utilization by the smallholder farmers in SSA. Research from Ghana, Nigeria, Ethiopia and Tanzania shows that phosphorus deficiency not only reduces crop yield but also leads to inefficient phosphorus utilization due to fixation by iron and aluminum oxides (Fosu-Mensah et al., 2016). Legumes in these contexts benefit most from integrated nutrient management strategies that combine inorganic phosphorus fertilizers with organic amendments such as compost or farmyard manure. These practices improve soil structure, buffer acidity, stimulate microbial activity, and reduce phosphorus losses through leaching and fixation (Opala et al., 2020). However, in many smallholder systems, limited access to inputs, high labor costs, and weak extension support often prevent the widespread adoption of such integrated approaches (Kisinyo et al., 2019.). In Ethiopia, the increasing rates of phosphorus improved the common bean yields and further hastened its crop phenology parameters (Tesfaye & Balcha, 2015). General legume trials tend to focus on common beans, soybeans and groundnuts while rice bean remains largely ignored in largescale studies.

P deficiency and soil acidity are significant agronomic challenges in western Kenya (Njoroge et al., 2017). Efforts to improve legume P use efficiency and yield should focus on promoting alternative cropping systems. Intercropping systems in SSA are widely practiced for yield sustainability by small holder farmers (Gitari et al., 2020). The MBILI systems improve resource use efficiency (Mongare et al., 2020). When compared with the traditional intercropping systems like the conventional which hinder growth and development of understory crops as a result of heavy shading and competition for nutrients, the MBILI intercropping systems enhance solar radiation interception, soil moisture capture and the P uptake hence improving the crop yield (Thuita et al., 2011). The MBILI layout facilitates better penetration of light, reduced nutrient leaching and improvement of rhizosphere interactions which are very essential for P acquisition and BNF. Most of the MBILI trials have centered on common bean researches. The emerging data suggest that rice bean exceptionally do well in this system due to its climbing habit, improved photosensitivity and deep tap root system which could allow it to exploit both light and subsurface P more efficiently. The rice beans can produce a yield of 1.3-2.75 t ha⁻¹ when it is given correct nutrient requirements (Yadav et al., 2022). In western Kenya, the small scale farmers use low-quality seeds with limited extension services available which have continued to ignore rice bean cultivation (Kokwon et al., 2025). Integrating yield indicators like PUE, the seed weight systems and the HI with agronomic practices can improve P fertilizer use efficiency in rice bean production.

2.5 Theoretical framework

This study is anchored in two complementary theoretical constructs: the Soil Fertility Capability Classification (SFCC) system and the Theory of Agronomic Efficiency of Nutrient Use. These theories give a perfect explanation of the soil properties, the dynamics and crop response to nutrients in smallholder farms dominating in the western Kenya. The SFCC classifies the soils based on their reliance on their fertility and physico-chemical characteristics like texture, depth, drainage, acidity, P fixation and organic matter content (Sanchez et al., 1982). In western Kenya, SFCC can assist in assessing factors which could diminish soil fertility so as to estimate appropriate soil amendments options (Kisinyo et al., 2019.). SFCC is more focused on the conditions of the soil and does not dwell much on the cropping systems involved. Other theories which focus on behavioral traits of plants should then be considered. The Theory of Agronomic Nutrient Use Efficiency (AE) postulates that the response of the yield is determined by not just the nutrient availability in the soil but also by crop type, management options and existing climatic conditions (Muindi et al., 2017). Agronomic efficiency is defined as the yield increase per unit of nutrient applied. It is a key component in evaluating the sustainability of fertilizer use (Fixen et al., 2012). In western Kenya, maximizing AE is important for improving productivity while minimizing input costs (Nduwimana, 2020). The challenge of AE is that it relies on response of yields in the short term. The working assumptions of this study are informed by both frameworks. First, phosphorus availability is assumed to be a limiting factor in acidic soils due to high fixation by aluminum and iron oxides. Second, rice bean is hypothesized to possess inherent traits such as efficient rooting patterns and biological nitrogen fixation that may enable it to utilize both applied and residual phosphorus more

effectively than other legumes. Third, intercropping systems, especially the MBILI model are assumed to improve phosphorus agronomic efficiency by enhancing light interception, reducing competition and improving rhizosphere interactions. The integration of SFCC and the AE offers a robust framework for analyzing how phosphorus fertilizer rates and cropping systems influence soil nutrient dynamics, crop phenology and yield performance. This dual-theory approach is particularly well-suited for assessing rice bean in phosphorus-deficient, smallholder systems and serves as a foundation for evidence-based recommendations aimed at sustainable intensification and improved food security in western Kenya.

2.6 Research Gap

Although phosphorus fertilization and intercropping practices have been widely studied in relation to legume performance, there remains a notable gap in empirical data when it comes to underutilized legumes such as rice bean, especially in the context of phosphorus-deficient, acidic soils like those prevalent in western Kenya. Current legume researches focus on major legume crops which have already been integrated into nation food programs, ignoring the probable potential of rice bean. In addition, little is known concerning rice bean phosphorus nutrient requirements and how it interacts with different cropping systems given its unique qualities in Kenya. With this shortage of data, its promotion has been considered very difficult and cannot be justified easily. Hence the findings from this research will serve as a basis for tailoring soil fertility management options and cropping strategies suited to acid soils associated with inadequate resources.

CHAPTER THREE

METHODOLOGY

3.1 Description of the Study Areas

The study was conducted in Western Kenya across three representative sites over two cropping seasons, beginning with the short rainy season from September to December 2020 and concluding with the long rains from March to August 2021 (Figure 1). Western Kenya experiences a bimodal rainfall pattern, with the long rains typically occurring between March and June and the short rains between September and December (Oloo, 2016).

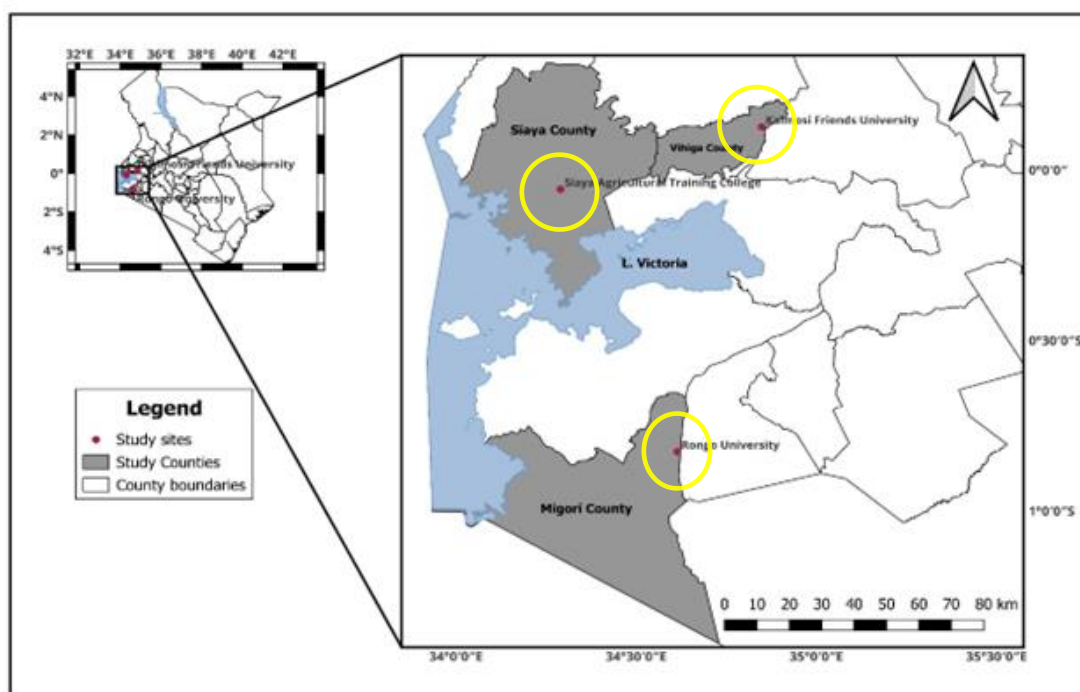


Figure 3.1: A map of study sites in western Kenya

The sites were purposively selected to capture contrasting agro-ecological zones, specifically lowland and midland areas, allowing for an assessment of rice bean performance under diverse environmental conditions. In all three sites, cereal and legume cultivation through sole cropping or intercropping is a common agricultural practice.

Additionally, the three partnering universities provided land for this research as part of broader efforts to strengthen food security in the region.

Site 1: *Siaya Agricultural Training College (ATC)* farm in Siaya County is located at latitude $00^{\circ} 03' 23''$ N and longitude $034^{\circ} 17' 25''$ E, with an altitude of 1,500 m above sea level. The area receives an annual rainfall of 1,000–1,750 mm, with temperatures ranging between 15°C and 30°C . The dominant agro-ecological zone is the lower midland (LM1) with isolated pockets of upper midland zones. The predominant soils are Acrisols (Owino et al., 2015)

Site 2: *Rongo University School of Agriculture Research and Teaching Field* in Migori County is located at latitude $00^{\circ} 49' 33''$ S and longitude $034^{\circ} 36' 53''$ E, at an altitude of 1,522 m above sea level. The area receives 1600 mm of annual rainfall, with a mean annual temperature of 20.6°C . The site lies within the LM1 agro-ecological zones and is characterized by orthic Ferralsol soils (Aguyoh et al, 2019; Jaetzold et al., 2009).

Site 3: *Kaimosi Friends University College (KAFUCO)* farm in Vihiga County is situated at latitude $0^{\circ} 07' 36''$ N and longitude $34^{\circ} 50' 55''$ E, with an altitude of 1,679 m above sea level. Kaimosi falls within the upper midland agro-ecological zone and receives an annual rainfall of 1,900 mm. The mean temperatures range from 14°C to 32°C , and the dominant soil type is Acrisols (Njogo et al., 2018; Jaetzold et al., 2009).

Overall, the selection of these sites ensured the study could capture the response of rice bean to phosphorus management under varied agro-climatic conditions, contributing critical insights for smallholder farming systems across Western Kenya.

3.2 Field Design and Treatment Structure

The field experiment was implemented as a split-plot design with twelve treatment combinations, each replicated three times at the experimental sites. The main plot factor consisted of three cropping systems: monocropping (a pure stand of rice bean), conventional intercropping (one row of maize alternating with one row of rice bean), and the MBILI system (an improved intercropping arrangement featuring two rows of maize alternating with two rows of rice bean) as described by Thuita et al. (2011). Within each main plot, four phosphorus (P) amendment treatments were applied as subplots. The first treatment was a control, receiving no phosphorus input (0 kg P ha^{-1}). The second treatment was farmyard manure (FYM only) to supply 5 kg P ha^{-1} . The third treatment was an integrated amendment, combining organic and inorganic sources to deliver $15.5 \text{ kg P ha}^{-1}$ through 13 kg P ha^{-1} from triple superphosphate (TSP) and 2.5 kg P ha^{-1} from FYM ha^{-1} . The fourth treatment was inorganic only, applying 26 kg P ha^{-1} entirely from TSP. These phosphorus levels and sources were informed by recommendations from Pramanik et al. (2009.) for the Indo-Gangetic Plains and Kenya's National Accelerated Agricultural Input Access Programme (Ministry of Agriculture, 2014), which emphasize targeted phosphate fertilizer use to improve legume yields in the region's acidic soils. Apart from the control plots in each site, all the other plots were applied with 22 kg N ha^{-1} as blanket treatments from Calcium Ammonium Nitrate (CAN). The split-plot design was selected for its practicality, with cropping systems assigned as main plots and phosphorus fertilizer treatments randomized within each main plot as subplots. Each main plot was subdivided into four subplots, each receiving a distinct P amendment. Treatments were randomized within blocks and replicated three times per site to account for site variability and ensure

robust statistical comparison. **Table 3.1** summarizes the twelve treatment combinations, specifying the cropping system, P amendment description, phosphorus rate and fertilizer source. For example, Treatment 1 under monocropping was the control with no inputs, while Treatment 4 used an inorganic-only input of 26 kg P ha⁻¹ from TSP plus 22 kg N ha⁻¹. This same structure was consistently applied to the conventional and MBILI systems, ensuring clear comparisons across all factors.

Table 3.1: Field Fertilizer Treatment Combination Structure

Treatment No.	Cropping System	P Amendment Description	kg P ha⁻¹	kg N ha⁻¹(CAN)	P Fertilizer Source
1	Monocropping	Control	0	0	Nil
2		FYM only	5	22	FYM
3		Combined	15.5	22	TSP + FYM
4		Inorganic	26	22	TSP
5	Conventional	Control	0	0	Nil
6		FYM only	5	22	FYM
7		Combined	15.5	22	TSP + FYM
8		Inorganic	26	22	TSP
9	MBILI	Control	0	0	Nil
10		FYM only	5	22	FYM
11		Combined	15.5	22	TSP + FYM
12		Inorganic	26	22	TSP

Monocropping-sole rice beans, conventional- one row rice beans, one row maize, MBILI- two rows rice beans, two rows maize, FYM- Farmyard manure, TSP- Triple Super Phosphate, CAN-Calcium Ammonium Nitrate. The chemical content of the farmyard manure used was 0.43% P and 1.83% N based on laboratory analysis using procedures set by Okalebo et al (2002).

3.3 Field Experimental Layout

At each site, the experimental area was divided into three blocks (replicates) to account for spatial variation in soil and topography. A buffer zone of 1m from each block was maintained as shown in **Figure 3.2**.

3.4 Field agronomic Practices

Just before setting up the experiment plots, the three experimental sites were conditioned to a month-long natural fallow. The plots were then prepared to a fine tilth using hand hoes, and boundaries were marked with pegs. The rice bean variety used was derived from the Rongo location land race. The TSP provided inorganic P while nitrogen nutrient was derived from CAN. The hybrid variety of maize, H513, used to test intercropping systems was purchased from Kenya Seed Company, Eldoret, for the two seasons. The plot sizes were measuring 3.0 m × 3.0 m (9 m²). In the mono-cropping systems, rice bean seeds were spaced at 30 cm by 10 cm. This gave 600 stems per plot, which could be extrapolated to 333,333 stems ha⁻¹. In each hill, two seeds were planted, but were later subjected to thinning to one seed after two weeks of planting. This was to ensure correct planting density throughout the growing season. In regards to conventional intercropping systems, H513 maize seed was planted at a spacing of 75 cm by 25 cm. This yielded 96 maize stems per plot, which, when extrapolated, could give 53,333 maize stems ha⁻¹. Likewise, in every hole, two seeds were planted and later subjected to thinning to leave one per hole. Between the rows of maize, rice bean seeds were planted at a spacing of 10 cm inter rows. This yielded 133,333 stems ha⁻¹ of rice bean after thinning, which was done after two weeks.

Lastly, in the MBILI systems, the pairs of maize rows were spaced 30 cm apart, with a spacing of 1m between the neighboring pairs of maize. Within the 1m spacing, two rows of the rice bean seeds were planted in an interrow and intra-row spacing of 34 cm and 10 cm, respectively. The rice bean plants were later thinned to one plant per hill after two weeks of planting. Fertilizer was applied using the banding method within furrows. In all cropping systems, 22 kg N ha⁻¹ was applied at planting, except in the control plots. For maize in intercrops, an additional 53 kg N ha⁻¹ was top-dressed six weeks after planting to reach a total of 75 kg N ha⁻¹. Fertilizers were thoroughly mixed with soil before seed placement to avoid direct contact with seeds, and seeds were covered with a thin layer of soil. Manual weeding was done every two weeks to keep plots weed-free. Spraying for termites, stalk borers, and other pests and diseases was done biweekly using Aqua Wet 15SL (Nonylphenol ethoxylate), Prove 1.92 EC (Emamectin benzoate), and Mistress Fungicide (Cymoxanil).

3.5 Soil Sampling and Analysis

Soil samples were collected at the beginning and end of each cropping season. Three samples per plot were taken from each site using a soil auger, then thoroughly mixed to form a composite sample for each plot. The samples were air-dried in a greenhouse at the University of Eldoret and Rongo University, sieved through a 2 mm sieve, and subsamples were prepared for analysis following the standard procedures described by Okalebo et al (2002).

3.5.1 Soil pH (2.5:1 Water)

Fifty (50) ml of deionized water was added to 20 g of soil. The mixture was stirred for 10 minutes, left to stand undisturbed for 30 minutes, then stirred again for 2 minutes. The pH was measured using a calibrated pH meter as described by Okalebo et al (2002).

3.5.2 Soil Available Phosphorus

Available phosphorus was determined using the Olsen method. Air-dried soil (2.5 g) was mixed with 50 ml of Olsen's extracting solution (0.5 M NaHCO₃, pH 8.5) in a 250 ml polyethylene bottle. The mixture was shaken for 30 minutes on an orbital shaker and filtered through Whatman No. 42 filter paper. The filtrate was used for colorimetric measurement of phosphorus as described by Okalebo et al (2002). The initial soil available phosphorus (P) in the experimental sites is shown in **Table 3.2**.

Table 3.2: Initial Site Characterization of the On-Station Field Trials in Western Kenya.

Soil parameters	Kaimosi	Rongo	Siaya	Range
pH (1:1 soil water)	4.9	5.2	5.6	5.0-6.0
Available P (mg P kg ⁻¹)	4.4	5.4	6.1	< 10.0
Organic C (%)	1.3	1.2	1.6	< 4.0
Total N (%)	0.1	0.1	0.1	< 0.25
Exchangeable Ca (mg kg ⁻¹)	108.5	64	294.5	
Exchangeable K (mg kg ⁻¹)	202	194.8	211.5	

3.6 Crop Growth and Phenology Measurements

For each treatment plot, key phenological observations were recorded to determine the effect of phosphorus fertilizer amendments and cropping systems on rice bean.

- a) Specifically, the number of days from sowing to when 75% of the plants in each plot reached flowering (75% flowering) was monitored through regular visual inspections. The number of days to 75% flowering was recorded as the number of days after sowing (DAS) when approximately 75% of the plants in each plot had at least one fully opened flower. Observations were conducted every 2–3 days beginning from 40 DAS to ensure accurate determination of the flowering window, with phenological development assessed from a random sample of ten tagged plants per plot in an effective harvest area ($2.25 \times 1.6 \text{ m}^2$).
- b) Number of days to physiological maturity was determined as the period from sowing to the point when approximately 75% of the plants in a plot had pods that had turned brown and dry, indicating that seed filling was complete and the crop had reached physiological maturity. This stage was marked when the pod color transitioned fully from green to brown. Both flowering and maturity dates were recorded at the plot level and averaged across replicates per treatment. This was determined from a random sample of ten tagged plants per plot in an effective harvest area.
- c) At harvest, the number of pods per plant was determined by sampling ten randomly selected plants within the effective harvest area ($2.25 \times 1.6 \text{ m}^2$). This provided a reliable estimate of pod production as a yield component under different phosphorus management strategies and cropping systems across sites and seasons.

3.7 Yield and Biomass Measurements

At physiological maturity, rice bean plants were manually harvested from each effective plot area, excluding the border rows to minimize edge effects. All above-ground biomass was cut at ground level and separated into grain and non-grain components (straw, leaves, and pods where applicable). The harvested biomass was weighed fresh in the field and then air-dried under shade to constant weight. Sub-samples were taken and oven-dried at 65°C for 72 hours to determine precise dry matter content. Grain yield was then determined after threshing, cleaning, and adjusting the moisture content to a standard 12% using the oven-dry method. The clean grain weight per plot was converted to yield in tons per hectare ($t\ ha^{-1}$). Total above-ground biomass yield was calculated as the sum of grain and straw dry weights per plot, also expressed in $t\ ha^{-1}$. The harvest index (HI) was computed as the ratio of economic yield (grain yield) to total above-ground biomass yield, expressed as a percentage using the formula:

$$HI(\%) = \frac{(\text{Grain yield})}{\text{Total above ground biomass yield}} \times 100 \quad \dots\dots\dots \text{Eq 1}$$

All yield and biomass measurements were taken separately for each treatment replicate to allow accurate comparison of phosphorus fertilizer effects and cropping system differences across sites and seasons. Analysis of PAE was achieved by using incremental grain yield (from all fertilized plots) above a control divided by the amount of P fertilizer applied, as shown in the Eq (2).

$$AEP = \frac{\text{Grain yields with PA} - \text{Grain yields without PA}}{\text{Amount of P applied}} \quad \dots\dots\dots \text{Eq 2}$$

Where:

AEP = Agronomic Efficiency of Phosphorus, (kg grain / kg P)

PA = phosphorous application

These measurements provided the basis for analyzing yield response, nutrient use efficiency, and biomass partitioning, which are key indicators of the performance of rice bean under varying phosphorus management practices and cropping systems.

3.8 Statistical Model and Data Analysis

All field data, including rice bean yield, soil available phosphorus, phenological observations (number of days to 75% flowering, number of days to physiological maturity and number of pods per plant), biomass, harvest index and phosphorus agronomic efficiency, were analyzed using a mixed-effects model suitable for a split-plot design. In this design, Cropping System was assigned to main plots and randomized within complete blocks at each site, while Phosphorus Amendment levels were randomized within subplots nested inside each main plot. This two-stage randomization accounted for main-plot and subplot variation according to a standard split-plot layout in a randomized complete block design (RCBD).

The general statistical model for each measured response variable was:

$$Y_{ijklm} = \mu + S_i + S_{ej} + C_k + P_l + (C \times P)_{kl} + B_m(S_i) + \varepsilon_{ijklm} \dots\dots\dots \text{Eq 3}$$

Where:

Y_{ijklm} = Observed value of response variable (e.g., yield, available P, days to 75% flowering, number of days to physiological maturity, number of pods, harvest index or PAE)

μ = overall mean

S_i = random effect of the sites (n = 1, 2, 3)

S_{ej} = fixed effect of season (j = short rain, long rain)

C_k = fixed effect of cropping system (k = monocrop, conventional, MBILI)

P_l = fixed effect of phosphorus amendment level (l = control, FYM, Combined, inorganic)

$(C \times P)_{kl}$ = interaction between the cropping system and phosphorus amendment

$B_m(Si)$ = random effect of block nested within site (m = 1, 2, 3)

ε_{ijklm} = residual error term

All data were coded and cleaned in Microsoft Excel, then subjected to Analysis of Variance (ANOVA) using GenStat v20 Edition. Treatment means were compared using Tukey's Honest Significant Difference (HSD) test at a significance level of $p \leq 0.05$ to identify significant differences among treatments. This combined approach ensured robust estimation of treatment effects and their interactions while properly accounting for site and seasonal variability inherent to field conditions in Western Kenya.

CHAPTER FOUR

RESULTS

4.1 Effect of Phosphorus (P) Fertilizer and Cropping Systems on Soil Phosphorus under Rice Bean

Phosphorus (P) fertilizer and the adoption of different cropping systems significantly influenced soil available phosphorus (P) concentrations across sites and seasons (**Table 4.1**). The mean soil available P values exhibited considerable variability between sites, with Siaya generally maintaining higher P levels compared to Rongo and Kaimosi under similar treatments. Across all sites, P concentrations ranged from as low as 4.20 mg kg⁻¹ under the conventional control plot at Kaimosi to as high as 8.88 mg kg⁻¹ under the monocrop inorganic P treatment at Rongo. Averaged across seasons, the inorganic P amendment (26 kg P ha⁻¹) consistently produced the highest available P values, with means of 7.68 mg kg⁻¹, 7.77 mg kg⁻¹, and 7.25 mg kg⁻¹ in Siaya, Rongo, and Kaimosi respectively under monocropping. The combined treatment (15.5 kg P ha⁻¹ from FYM and inorganic fertilizer) produced moderately high P values, with means ranging from 6.33 mg kg⁻¹ to 7.48 mg kg⁻¹ across cropping systems and sites. Conversely, control plots without P fertilizer recorded the lowest soil P concentrations.

Statistical analysis revealed that phosphorus amendments had a highly significant effect on soil P across all sites ($p < 0.001$), while the effects of cropping system alone were not significant ($p > 0.05$), although a trend toward higher P retention under monocropping and MBILI systems was observed. Seasonal effects were significant at all sites ($p < 0.05$), with slightly higher soil P levels recorded in the long rains. Significant interactions between cropping system and amendments (CS × AM) were observed in Siaya ($p < 0.001$).

Table 4.1: Soil Available Phosphorus (mg kg⁻¹) under different cropping systems and phosphorus amendments across sites and seasons (short rains of 2020 and long rains of 2021)

Cropping system		Siaya			Rongo			Kaimosi		
	Amendment	short rains	long rains	Mean	short rains	long rains	Mean	short rains	long rains	Mean
Monocrop	Control (0 kg P ha ⁻¹)	6.04	6.34	6.19 ^{ab}	5.45	5.61	5.53 ^a	4.58	4.88	4.73 ^{ab}
	FYM (5 kg P ha ⁻¹)	6.25	6.52	6.39 ^{abcd}	6.00	6.30	6.15 ^{abc}	5.90	5.75	5.83 ^{bc}
	Combined (15.5 kg P ha ⁻¹)	7.43	6.93	7.18 ^{bcd}	8.02	6.95	7.48 ^{cd}	6.97	6.45	6.71 ^{cd}
	Inorganic (26 kg P ha ⁻¹)	6.70	8.67	7.68 ^d	6.66	8.88	7.77 ^d	6.20	8.30	7.25 ^d
	mean	6.61	7.11	6.86	6.53	6.93	6.73	5.92	6.34	6.13
Conventional	Control (0 kg P ha ⁻¹)	5.50	5.69	5.60 ^a	5.43	5.69	5.56 ^a	4.20	4.37	4.28 ^a
	FYM (5 kg P ha ⁻¹)	6.02	6.22	6.12 ^{ab}	5.97	6.28	6.12 ^{abc}	5.55	5.85	5.70 ^{bc}
	Combined (15.5 kg P ha ⁻¹)	6.25	6.42	6.33 ^{abc}	7.98	6.88	7.43 ^{cd}	7.80	6.75	7.28 ^d
	Inorganic (26 kg P ha ⁻¹)	6.60	8.54	7.57 ^{cd}	6.64	8.42	7.53 ^d	6.25	7.48	6.86 ^{cd}
	mean	6.09	6.72	6.41	6.51	6.81	6.66	5.95	6.11	6.03
MBILI	Control (0 kg P ha ⁻¹)	5.88	6.18	6.03 ^{ab}	5.35	5.65	5.50 ^a	4.53	4.75	4.64 ^{ab}
	FYM (5 kg P ha ⁻¹)	6.32	6.62	6.47 ^{abcd}	5.84	6.08	5.96 ^{ab}	5.56	5.86	5.71 ^{bc}
	Combined (15.5 kg P ha ⁻¹)	7.18	6.79	6.99 ^{bcd}	6.53	6.60	6.56 ^{abcd}	6.87	6.40	6.64 ^{cd}
	Inorganic (26 kg P ha ⁻¹)	6.52	7.32	6.92 ^{abcd}	6.51	7.88	7.20 ^{bcd}	6.49	8.60	7.54 ^d
	mean	6.47	6.73	6.60	6.06	6.55	6.31	5.86	6.40	6.13
<i>P values</i>	Cropping system	0.076			0.086			ns		
	Seasons	0.006			0.018			0.011		
	Amendments	<.001			<.001			<.001		
	CSx S	ns			ns			ns		
	CSxAM	<.001			ns			0.18		
	SxAM	ns			<.001			<.001		
	CSxSxAM	0.026			ns			ns		
	s.e.	0.68			0.70			0.61		
	CV%	13.30			12.60			13.90		

Values represent mean P values per treatment combination. Different superscript letters within the same column indicate significant differences ($p < 0.05$). Statistical significance of main effects and interactions (cropping system, season, and amendment) is provided along with standard error (SE) and coefficient of variation (CV%), CS-Cropping systems, S- Seasons, AM-Amendments

4.2 Effect of phosphorus (P) fertilizer and cropping systems on rice bean phenology

4.2.1 Effect of Phosphorus Fertilizer and Cropping Systems on Number of Days to 75% Flowering in Rice Bean

The number of days to 75% flowering in rice bean in Siaya varied considerably across phosphorus (P) fertilizer amendments and cropping systems, reflecting both the influence of nutrient availability and the effect of cropping arrangements on crop phenology (**Figure 4.1a**). Control plots without P fertilizer generally exhibited delayed flowering, with monocrop, conventional and MBILI systems reaching 75% flowering at 84, 109, and 87 days, respectively, during the short rains, and slightly longer durations (93–98 days) during the long rains.

Application of FYM at 5 kg P ha⁻¹ produced modest improvements in flowering, with days to 75% flowering reduced to 81–88 days across cropping systems. The combined phosphorus treatment (15.5 kg P ha⁻¹ from FYM + inorganic fertilizer) consistently accelerated flowering, with the shortest durations recorded in monocrop plots (67–72 days). Inorganic P application at 26 kg P ha⁻¹ also enhanced earliness, inducing flowering within 72–92 days across the three cropping systems. Analysis of variance revealed that cropping system ($p < 0.001$) and phosphorus treatment ($p < 0.001$) significantly influenced flowering time, while seasonal effects were not statistically significant ($p > 0.05$). No significant interactions were observed among cropping system, season, and amendment factors, indicating a consistent response pattern across treatments.

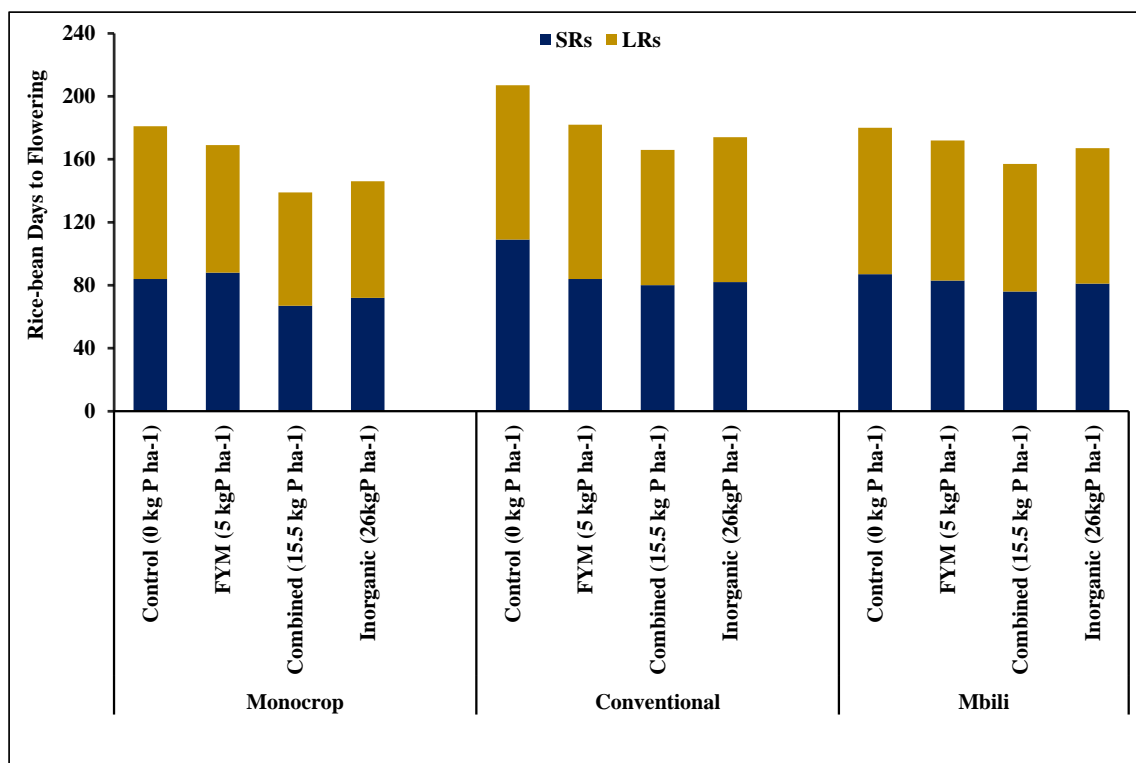


Figure 4.1a: Effect of phosphorus fertilizer and cropping systems on rice bean days to flowering across short rains (SRs) of 2020 and long rains (LRs) of 2021 in Siaya.

Bars represent the duration to 75% flowering under different P amendment

The number of days to 75% flowering in rice bean in Rongo varied significantly across phosphorus (P) fertilizer amendments, cropping systems and seasons (**Figure 4.1b**). Control plots without P fertilizer exhibited the longest time to flowering, with monocrop, conventional and MBILI systems reaching 75% flowering between 78–88 days during the short rains and extending to 84–97 days during the long rains.

Application of 5 kg P ha⁻¹ through FYM modestly reduced flowering duration to 74–80 days in the short rains and 76–90 days in the long rains. The combined phosphorus treatment (15.5 kg P ha⁻¹ from FYM + inorganic fertilizer) consistently produced the earliest flowering, with durations as low as 66 days in MBILI plots during the short rains

and 71–78 days across other systems. Inorganic P fertilizer at 26 kg P ha⁻¹ also induced earliness, with flowering occurring between 68–75 days in monocrop plots and 74–80 days in conventional systems.

Analysis of variance revealed that cropping system ($p < 0.001$), season ($p < 0.001$) and phosphorus amendment ($p < 0.001$) significantly influenced days to flowering. Notably, the seasonal effect was stronger in Rongo than in Siaya, with the long rains generally extending the vegetative period. Interaction effects among cropping system, season and amendment were not statistically significant ($p > 0.05$).

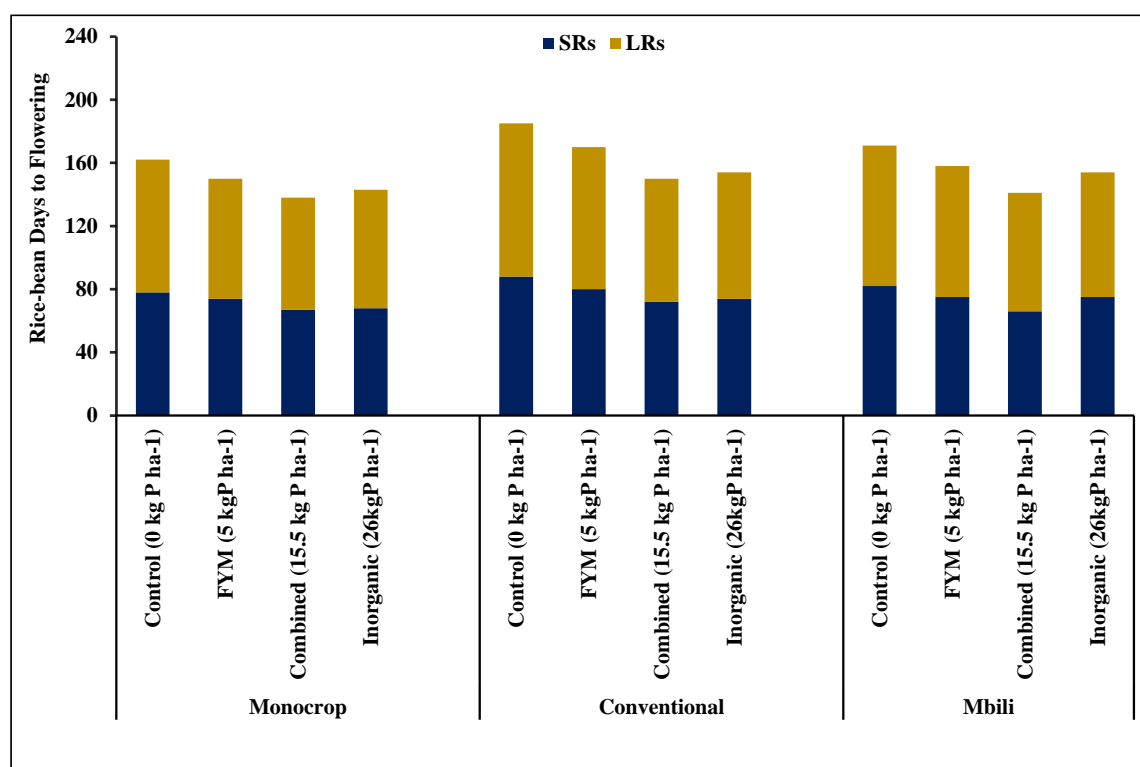


Figure 4.1b: Effect of phosphorus fertilizer and cropping systems on rice bean days to flowering across short rains of 2020 (SRs) and long rains of 2021 (LRs) in Rongo.

Bars represent the duration to 75% flowering under different P amendment treatments

In Kaimosi, the number of days to 75% flowering in rice bean was strongly influenced by phosphorus (P) fertilizer and cropping systems, while seasonal effects were minimal (**Figure 4.1c**). Control plots without P fertilizer generally exhibited the longest time to flowering, with monocrop, conventional and MBILI systems recording 103–107 days during the short rains and 90–104 days during the long rains. Application of 5 kg P ha⁻¹ through FYM moderately reduced flowering duration, with flowering observed at 85–101 days depending on the cropping system and season. Combined phosphorus application (15.5 kg P ha⁻¹ from FYM + inorganic) consistently produced the earliest flowering, with MBILI plots reaching 75% flowering in as little as 73 days during the long rains and 78 days in the short rains. Inorganic P fertilizer at 26 kg P ha⁻¹ also induced early flowering, though slightly later than the integrated treatment in some cases, with flowering occurring between 78–94 days across the systems.

Analysis of variance confirmed that phosphorus amendments ($p < 0.001$) significantly affected days to flowering, whereas season alone was not significant ($p > 0.05$). No significant interactions were detected among cropping system, season, and P amendment ($p > 0.05$), indicating that treatment effects were consistent across the seasonal conditions of Kaimosi.

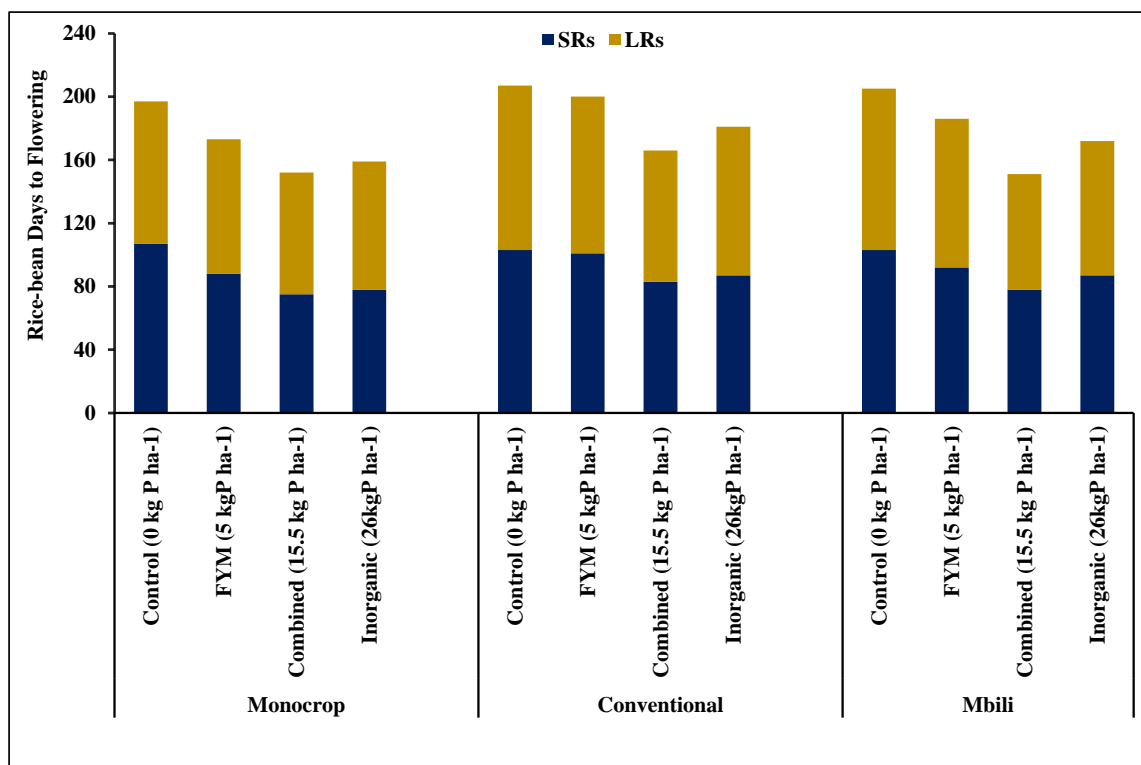


Figure 4.1c: Effect of phosphorus fertilizer amendments and cropping systems on rice bean days to flowering across short rains of 2020 (SRs) and long rains of 2021 (LRs) in Kaimosi.

Bars represent the duration to 75% flowering under different P amendment treatments

4.2.2 Effect of phosphorus (P) fertilizer amendments and cropping systems on rice bean number of days to attain physiological maturity

The number of days to physiological maturity of rice bean varied significantly across phosphorus (P) fertilizer amendments, cropping systems, sites and seasons (**Table 4.2**). In Siaya, the shortest mean days to physiological maturity (109 days) were observed under monocropping with the combined amendment of 15.5 kg P ha⁻¹ (FYM + inorganic), followed closely by the inorganic P treatment (113 days). Control plots recorded the longest days to physiological maturity (124–130 days) under all cropping systems. Rongo displayed a similar trend, where the combined P treatment resulted in the earliest days to

physiological maturity (109–112 days) across cropping systems, while the control plots under conventional and MBILI systems exhibited the most delayed days to physiological maturity (128–130 days). Kaimosi generally recorded slightly longer days to physiological maturity compared to Siaya and Rongo, with control plots under MBILI taking up to 132 days to reach physiological maturity. The application of $15.5 \text{ kg P ha}^{-1}$ significantly reduced the number of days to physiological maturity to as low as 111 days.

Statistical analysis indicated highly significant differences ($p < 0.001$) for the main effects of cropping system, amendment and season at all sites except for the seasonal effect at Kaimosi, which was marginally significant ($p = 0.047$). Cropping system \times amendment interactions (CS \times AM) were significant at Rongo and Kaimosi ($p < 0.001$). Seasonal variation influenced period of physiological maturity, with the short rains season generally producing slightly delayed period of physiological maturity compared to the long rains season. Overall, the combined FYM + inorganic P treatment consistently produced the shortest days to physiological maturity across all sites and cropping systems, followed by inorganic fertilizer alone, while control plots exhibited the longest vegetative phase.

Table 4.2: Effect of phosphorus fertilizer and cropping systems on rice bean days to physiological maturity across sites (Siaya, Rongo, and Kaimosi) and seasons (short rains of 2020 and long rains of 2021)

Cropping	Amendment	Siaya			Rongo			Kaimosi		
		short rains	long rains	mean	short rains	long rains	mean	short rains	long rains	mean
Monocrop	Control (0 kg P ha ⁻¹)	124	123	124 ^e	121	124	123 ^g	127	121	124 ^e
	FYM (5 kg P ha ⁻¹)	118	116	117 ^c	115	118	117 ^d	120	124	122 ^{de}
	Combined (15.5 kg P ha ⁻¹)	110	108	109 ^a	108	109	109 ^a	111	111	111 ^a
	Inorganic (26kg P ha ⁻¹)	114	112	113 ^{ab}	112	113	113 ^c	113	113	113 ^{ab}
	Mean	117	115	116	114	116	115	118	117	118
Convention	Control (0 kg P ha ⁻¹)	130	130	130 ^f	128	131	130 ^h	133	134	134 ^f
	FYM (5 kg P ha ⁻¹)	130	121	125 ^e	119	122	121 ^f	126	122	123 ^e
	Combined (15.5 kg P ha ⁻¹)	114	110	112 ^a	110	112	111 ^b	112	111	112 ^a
	Inorganic (26kgP ha ⁻¹)	121	116	119 ^{cd}	117	120	119 ^e	120	118	119 ^{cd}
	Mean	124	119	121	119	121	120	123	121	122
MBILI	Control (0 kg P ha ⁻¹)	130	128	129 ^f	126	130	128 ^h	132	132	132 ^f
	FYM (5 kg P ha ⁻¹)	122	121	122 ^{de}	122	124	123 ^g	124	122	124 ^e
	Combined (15.5 kg P ha ⁻¹)	111	111	111 ^a	112	111	112 ^{bc}	111	112	111 ^a
	Inorganic (26 kg P ha ⁻¹)	118	114	116 ^{bc}	115	116	116 ^d	117	116	117 ^{bc}
	Mean	121	118	119	119	120	120	121	121	121
<i>P values</i>	Cropping_system	<.001			<.001			<.001		
	Seasons	<.001			<.001			0.047		
	Amendments	<.001			<.001			<.001		
	CSx S	ns			ns			ns		
	CSxAM	0.059			<.001			<.001		
	SxAM	0.047			0.003			ns		
	CSxSxAM	0.079			0.027			<.001		
	s.e.	1.972			0.85			1.795		
	CV%	13.7			14.7			15.50		

Values represent mean days to physiological maturity per treatment combination. Different superscript letters within the same column indicate significant differences ($p < 0.05$). Statistical significance of main effects and interactions (cropping system, season, and amendment) are provided along with standard error (SE) and coefficient of variation (CV%), *CS-Cropping systems*, *S- Seasons*, *AM-Amendments*

4.2.3 Effect of Phosphorus Fertilizer Amendments and Cropping Systems on Number of Pods per Plant in Rice Bean

The number of pods per plant in rice bean was significantly influenced by phosphorus fertilizer, cropping systems and seasons in Siaya (**Figure 4.2a**). Across all cropping systems, pod production was lowest in the control plots without P application, while combined (15.5 kg P ha⁻¹; FYM + inorganic) and inorganic P (26 kg P ha⁻¹) treatments consistently produced the highest pod counts. In monocropping, pod numbers ranged from 53–57 pods per plant in the control to 90–96 pods per plant under the combined P treatment. FYM-only plots produced intermediate pod counts (71–86 pods).

Under conventional cropping, the control plots recorded the lowest pod counts (44–49), while the combined P treatment achieved 85–89 pods per plant, slightly higher than the inorganic treatment (75–79 pods). MBILI cropping exhibited a similar trend, with the control plots producing 41–46 pods per plant and combined P treatment yielding the highest counts (84–85 pods). Across all systems, FYM-only plots produced 60–86 pods.

Analysis of variance (ANOVA) confirmed that cropping system ($p < 0.001$), season ($p = 0.012$), and P fertilizer treatments ($p < 0.001$) all had significant effects on pod production. Interactions between season and P treatment were also significant ($p = 0.005$), indicating that the response to P fertilization varied between short and long rains. However, cropping system \times treatment interactions were not significant ($p > 0.05$), suggesting that the positive effects of P fertilizer were consistent across all cropping patterns. Overall, 15.5 kg P ha⁻¹ treatment resulted in the highest pod numbers across all cropping systems and seasons, followed by the inorganic treatment.

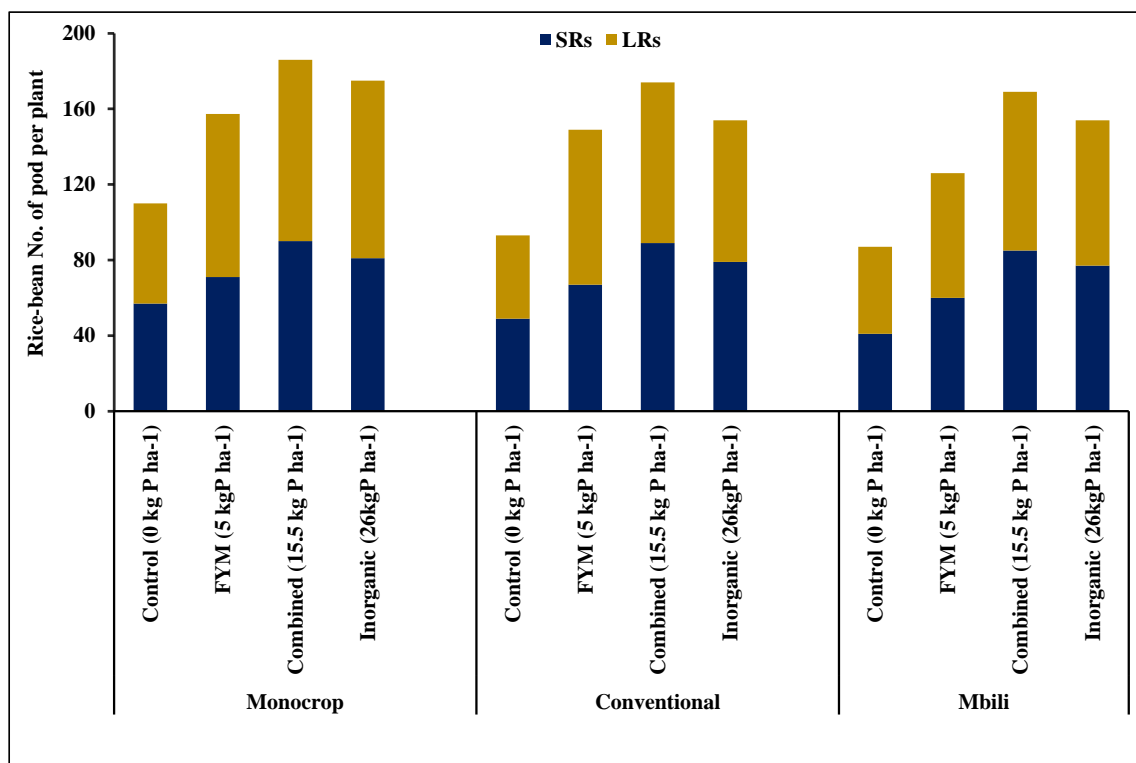


Figure 4.2a: Effect of phosphorus fertilizer amendments and cropping systems on the number of pods per plant in rice bean during short rains of 2020 (SRs) and long rains of 2021 (LRs) across three cropping systems in Siaya.

Bars represent the number of pods per plant under different P amendment treatments

The number of pods per plant in rice bean was significantly influenced by phosphorus fertilizer and cropping systems in Rongo, with a clear response to nutrient management across the short rains (SRs) and long rains (LRs) seasons (**Figure 4.2b**). The lowest pod numbers were consistently observed in the control plots without P application, which produced 49–55 pods per plant across the three cropping systems. Application of farmyard manure (FYM) alone moderately increased pod numbers, yielding 64–85 pods per plant depending on the cropping system and season. The combined P treatment (15.5 kg P ha⁻¹ from combined FYM and inorganic fertilizer) consistently produced the highest number of

pods, reaching 100 pods in monocropping and 82–87 pods in conventional and MBILI systems, respectively. Inorganic P alone (26 kg P ha⁻¹) also enhanced pod formation, though slightly less than the combined treatment, yielding 76–92 pods across the systems. Monocropping generally exhibited slightly higher pod counts than MBILI and conventional systems under high-P conditions.

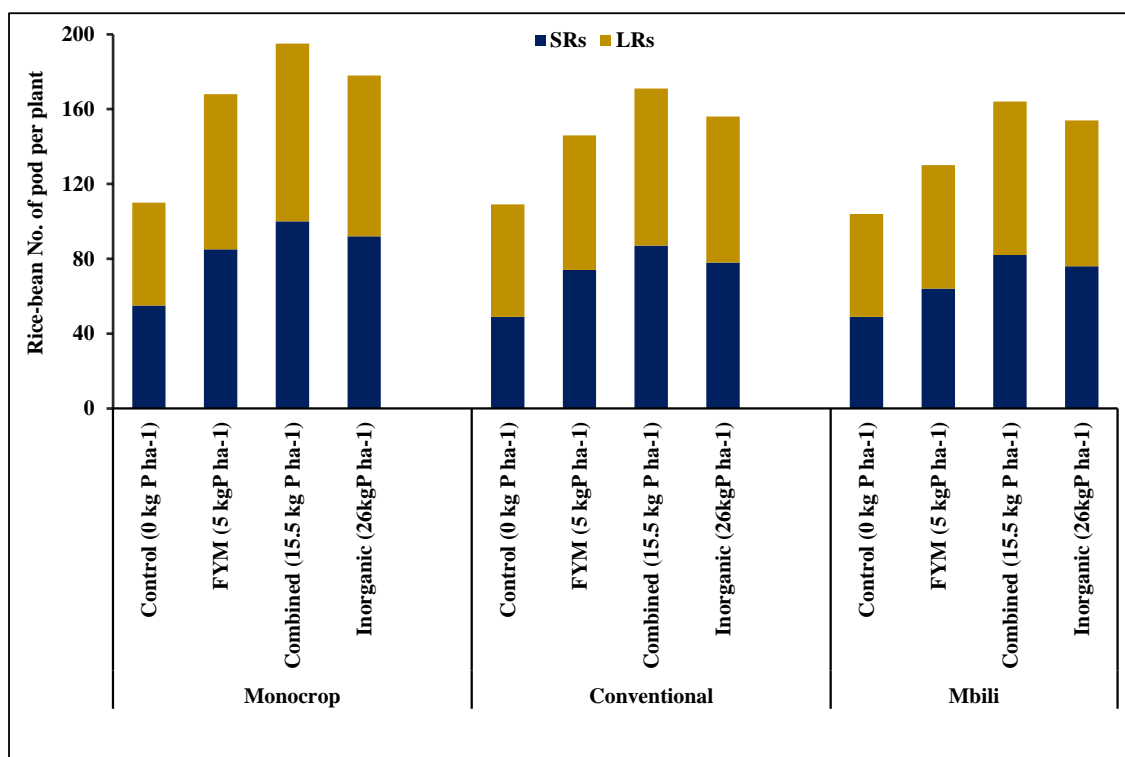


Figure 4.2b: Effect of phosphorus fertilizer and cropping systems on the number of pods per plant in rice bean during short rains of 2020 (SRs) and long rains of 2021 (LRs) across three cropping systems in Rongo.

Bars represent the number of pods per plant under different P amendment treatments

Analysis of variance (ANOVA) confirmed that cropping system ($p < 0.001$) and fertilizer treatment ($p < 0.001$) had highly significant effects on pod production, whereas season had no significant influence ($p = 0.885$). This indicates that pod formation in Rongo was more

strongly driven by nutrient availability and cropping strategy than by seasonal rainfall variation. Interaction effects between season and cropping system, as well as higher-order interactions, were not significant ($p > 0.05$). Overall, the combined P treatment ($15.5 \text{ kg P ha}^{-1}$) outperformed both FYM-only and inorganic P alone in boosting pod numbers.

In Kaimosi, the number of pods per plant in rice bean varied considerably across phosphorus fertilizer and cropping systems, with combined nutrient management consistently outperforming single-source applications (**Figure 4.2c**). The control plots without P application produced the lowest pod numbers across all cropping systems, ranging from 40 to 59 pods per plant. Application of farmyard manure (FYM) at 5 kg P ha^{-1} moderately increased pod counts to between 59 and 78 pods per plant. The combined P treatment ($15.5 \text{ kg P ha}^{-1}$ combining FYM and inorganic fertilizer) consistently resulted in the highest pod counts, producing 75–92 pods per plant across the three cropping systems. Inorganic P at 26 kg P ha^{-1} also enhanced pod production, yielding 69–87 pods per plant, but it generally performed slightly below the combined approach.

Analysis of variance (ANOVA) revealed that cropping system ($p = 0.002$) and fertilizer treatment ($p < 0.001$) significantly influenced pod formation, while seasonal effects were marginally significant ($p = 0.059$). Interaction effects between season and cropping system, as well as other higher-order interactions, were not significant ($p > 0.05$), indicating that pod response to phosphorus application was generally consistent across the short and long rains.

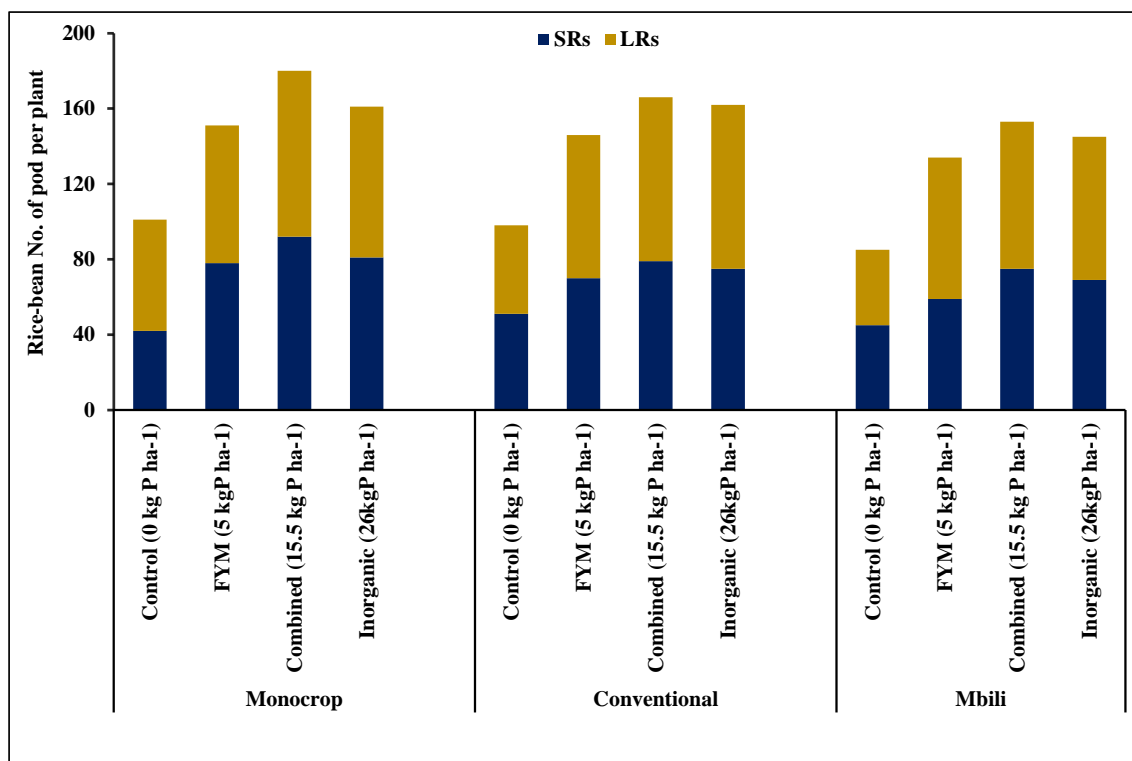


Figure 4.2c: Effect of phosphorus fertilizer amendments and cropping systems on the number of pods per plant in rice bean during short rains of 2020 (SRs) and long rains of 2021 (LRs) across three cropping systems in Kaimosi.

Bars represent the number of pods per plant under different P amendment

4.3 Effect of Phosphorus Fertilizer and Cropping Systems on Rice Bean Yields and Yield components

4.3.1 Effect of Phosphorus Fertilizer and Cropping Systems on Rice Bean Yield

Phosphorus fertilizer amendments and cropping systems exhibited a marked influence on rice bean grain yields across the three sites (Siaya, Rongo, and Kaimosi) and two seasons (Table 4.3). Grain yields varied widely, ranging from 0.24 t ha⁻¹ in the conventional control plots during the long rains in Siaya to 1.72 t ha⁻¹ in monocropped plots receiving the combined P amendment (15.5 kg P ha⁻¹) at Rongo. Across all sites and seasons, Siaya

and Rongo consistently recorded higher yields than Kaimosi under equivalent treatment conditions. Monocropping generally produced the highest mean yields across sites, with combined treatment (combined FYM+inorganic P) and inorganic-only amendments consistently outperforming control and FYM-only treatments. For example, at Rongo, integrated and inorganic treatments yielded 1.34 t ha^{-1} and 1.30 t ha^{-1} , respectively, compared to 0.78 t ha^{-1} in the control. In Siaya, yields followed a similar trend, with integrated and inorganic P applications producing mean yields above 1.0 t ha^{-1} . FYM alone provided moderate yield improvement, whereas control plots without P exhibited the lowest yields across all cropping systems and sites. Conventional and MBILI systems produced lower yields than monocropping, although integrated P application in these systems still achieved significant yield gains relative to the control. In Kaimosi, for instance, MBILI with combined P achieved 0.64 t ha^{-1} compared to 0.37 t ha^{-1} in the control.

Analysis of variance confirmed that cropping system, season, and P treatments significantly affected rice bean yields across all sites ($p \leq 0.001$). Interactions between cropping system and season ($CS \times S$), cropping system and amendments ($CS \times AM$), and in some cases the three-way interaction ($CS \times S \times AM$), were also significant, indicating that the yield response to P amendments was context-dependent. Seasonal effects were evident, with short rains generally supporting higher yields than long rains.

Table 4.3: Rice Bean Yields (t ha⁻¹) Under Different Cropping Systems and Phosphorus fertilizer across Sites and Seasons (short rains of 2020 and long rains of 2021)

Cropping system	Amendment	Siaya			Rongo			Kaimosi		
		Short rains	Long rains	Mean	Short rains	Long rains	Mean	Short rains	Long rains	Mean
Monocrop	Control (0 kg P ha ⁻¹)	0.88	0.63	0.76 ^{de}	0.92	0.64	0.78 ^d	0.89	0.62	0.75 ^c
	FYM (5 kg P ha ⁻¹)	0.97	0.76	0.87 ^e	1.23	0.83	1.03 ^e	1.10	0.75	0.92 ^d
	Combined (15.5 kg P ha ⁻¹)	1.37	0.93	1.15 ^f	1.72	0.95	1.34 ^f	1.47	0.80	1.14 ^e
	Inorganic (26 kg P ha ⁻¹)	1.30	0.84	1.07 ^f	1.56	1.03	1.30 ^f	1.31	0.88	1.09 ^e
	mean †	1.13	0.79	0.96	1.36	0.87	1.12	1.19	0.76	0.98
Conventional	Control (0 kg P ha ⁻¹)	0.48	0.24	0.36 ^a	0.46	0.23	0.34 ^a	0.38	0.32	0.35 ^a
	FYM (5 kg P ha ⁻¹)	0.66	0.39	0.53 ^{abc}	0.84	0.44	0.64 ^{bcd}	0.79	0.57	0.68 ^{bc}
	Combined (15.5 kg P ha ⁻¹)	0.65	0.56	0.60 ^{cd}	0.89	0.55	0.72 ^{cd}	0.72	0.61	0.67 ^{bc}
	Inorganic (26 kg P ha ⁻¹)	0.62	0.41	0.52 ^{abc}	0.89	0.49	0.69 ^{cd}	0.70	0.60	0.65 ^{bc}
	mean †	0.60	0.40	0.52 ^{abc}	0.77	0.43	0.60	0.65	0.52	0.59
MBILI	Control (0 kg P ha ⁻¹)	0.48	0.31	0.4 ^{ab}	0.48	0.35	0.41 ^{ab}	0.45	0.29	0.37 ^a
	FYM (5 kg P ha ⁻¹)	0.58	0.46	0.52 ^{abc}	0.59	0.41	0.50 ^{abc}	0.58	0.48	0.53 ^b
	Combined (15.5 kg P ha ⁻¹)	0.71	0.46	0.59 ^{bcd}	0.63	0.52	0.57 ^{bcd}	0.72	0.55	0.64 ^{bc}
	Inorganic (26 kg P ha ⁻¹)	0.56	0.45	0.51 ^{abc}	0.62	0.49	0.56 ^{abcd}	0.70	0.52	0.61 ^{bc}
	mean †	0.58	0.42	0.50	0.58	0.44	0.51	0.61	0.46	0.54
P values	Cropping_system	<.001			<.001			<.001		
	Seasons	<.001			<.001			<.001		
	Ammendment	<.001			<.001			<.001		
	CSx AM	0.009			<.001			<.001		
	CSxAM	0.022			0.001			0.009		
	SxAM	ns			0.088			0.034		
	CSxSxAM	ns			ns			0.013		
	s.e.	0.10			0.11			0.08		
	CV%	15.1			15.5			13		

Values represent grain yields in t ha⁻¹. Different superscript letters within the same column indicate significant differences ($p < 0.05$). Statistical significance of main effects and interactions (cropping system, season, and amendment) are provided along with standard error (SE) and coefficient of variation (CV%), CS-Cropping systems, S- Seasons, AM-Amendments,

4.3.2 Effect of Phosphorus Fertilizer and Cropping Systems on Phosphorus agronomic efficiency (PAE) of Rice Bean

PAE expressed as the ratio of yield increase per unit of P applied (kg kg^{-1}), exhibited significant variation across cropping systems, fertilizer amendments, sites and seasons (**Table 4.4**). PAE values ranged widely, from as low as 3.21 kg kg^{-1} under MBILI with inorganic P during the short rains in Siaya to as high as 63.42 kg kg^{-1} under monocropping with the combined P treatment during the short rains in Rongo. Across sites, Rongo generally exhibited the highest PAE under monocropping and conventional systems, particularly when FYM or combined P treatments were applied. For instance, monocropping with FYM achieved 48.76 kg kg^{-1} on average, while the combined treatment reached 40.18 kg kg^{-1} , reflecting efficient P utilization in this site's moderately fertile soils. In contrast, Kaimosi displayed intermediate PAE values, while Siaya recorded lower efficiencies under inorganic P, with mean values of 11.93 kg kg^{-1} in monocrops and 7.68 kg kg^{-1} in conventional systems.

Among fertilizer treatments, FYM alone consistently produced higher PAE than inorganic P, particularly in conventional and MBILI systems. For example, in Kaimosi conventional plots, FYM achieved 60.48 kg kg^{-1} compared to 12.47 kg kg^{-1} for inorganic P. Integrated (combined) P treatments yielded variable efficiencies exceptionally high under monocropping in Rongo (40.18 kg kg^{-1}) but lower in MBILI at all sites suggesting that the benefits of combined application depend on cropping system and site-specific conditions. Cropping systems significantly influenced PAE ($p < 0.001$), with monocropping generally outperforming MBILI in terms of P use efficiency. MBILI plots tended to exhibit lower PAE, with mean values of 15.30 , 14.65 , and 17.47 kg kg^{-1} in Siaya, Rongo, and Kaimosi,

respectively. Seasonal differences in PAE were also notable. Short rains generally supported higher PAE than long rains across most sites and treatments, aligning with the yield trends observed in **Section 4.3**.

Overall, these findings indicate that FYM and combined P amendments enhance phosphorus use efficiency compared to sole inorganic fertilizers, particularly in monocropping systems and during short rains. MBILI and conventional systems provide more diversified production and long-term soil fertility benefits but at the cost of lower short-term PAE.

4.3.3 Effect of Phosphorus Fertilizer and Cropping Systems on the Harvest Index (HI) of Rice Bean

The harvest index (HI) of rice bean, which reflects the efficiency of partitioning total biomass into economic yield, varied significantly across cropping systems, phosphorus (P) fertilizer amendments, sites, and seasons (**Table 4.5**). Mean HI values ranged from as low as 3.03% under monocropping without P in Siaya to as high as 11.10% under the conventional system with combined P in Siaya. Overall, the conventional system exhibited the highest HI values across sites, followed by MBILI and then monocropping, indicating that intercropped or conventionally managed systems allocated a greater proportion of biomass to grain compared to sole rice bean stands.

Table 4.4: Rice bean Phosphorus Agronomic Efficiency (PAE, kg kg⁻¹) Under Different Cropping Systems and Phosphorus fertilizers across sites and seasons (short rains of 2020 and long rains of 2021)

Cropping system	Amendment	Siaya			Rongo			Kaimosi		
		short rains	long rains	Mean	short rains	long rains	Mean	short rains	long rains	Mean
Monocrop	FYM (5 kg P ha ⁻¹)	13.17	16.89	15.03 ^d	45.53	52.00	48.76 ^e	31.60	32.60	32.10 ^f
	Combined (15.5 kg P ha ⁻¹)	38.08	19.03	28.56 ^g	63.42	16.93	40.18 ^d	45.61	11.74	28.67 ^{ef}
	Inorganic (26 kg P ha ⁻¹)	5.72	18.15	11.93 ^c	27.89	14.95	21.42 ^b	11.69	13.53	12.61 ^{ab}
	Mean	23.13	13.88	18.51	45.61	27.96	36.79	29.63	19.29	24.46
Conventional	FYM (5 kg P ha ⁻¹)	29.60	6.40	18.00 ^e	32.35	36.10	34.23 ^{cd}	59.25	61.70	60.48 ^g
	Combined (15.5 kg P ha ⁻¹)	14.81	28.74	21.77 ^f	34.97	21.03	28.00 ^{bc}	22.11	18.90	20.51 ^{cd}
	Inorganic (26 kg P ha ⁻¹)	7.48	7.87	7.68 ^b	16.50	9.94	13.22 ^a	14.02	10.92	12.47 ^{ab}
	Mean	17.30	14.34	15.82	27.94	22.36	25.15	31.79	30.51	31.15
MBILI	FYM (5 kg P ha ⁻¹)	27.10	36.61	31.86 ^h	31.23	12.40	21.81 ^b	17.43	31.60	24.51 ^{de}
	Combined (15.5 kg P ha ⁻¹)	11.85	7.70	9.78 ^{bc}	13.96	14.45	14.21 ^a	14.74	19.24	16.99 ^{bc}
	Inorganic (26 kg P ha ⁻¹)	3.21	5.30	4.25 ^a	7.94	7.92	7.93 ^a	11.50	10.31	10.9 ^a
	Mean	14.05	16.54	15.30	17.71	11.59	14.65	14.55	20.38	17.465
P values	Cropping system	<.001			<.001			<.001		
	Seasons	<.001			<.001			0.03		
	Amendments	<.001			<.001			<.001		
	CSx S	<.001			<.001			<.001		
	CSxAM	<.001			<.001			<.001		
	SxAM	ns			<.001			<.001		
	CSxSxAM	<.001			<.001			<.001		
	s.e.	2.327			3.591			3.137		
	CV%	14.5			14.1			12.9		

Values represent PAE per treatment combination. Different superscript letters within the same column indicate significant differences ($p < 0.05$). Statistical significance of main effects and interactions (cropping system, season, and amendment) are provided along with standard error (SE) and coefficient of variation (CV%), CS-Cropping systems, S- Seasons, AM-Amendments,

In Siaya, the conventional system under combined P application achieved the highest mean HI (11.10%), reflecting improved biomass partitioning due to enhanced nutrient availability. Conversely, monocrop systems maintained consistently lower HI values, with means between 3.03% and 3.90% across amendments. Similar trends were observed in Rongo, where the highest HI (10.44%) was obtained under the conventional system with inorganic P, while monocrop systems under FYM and control treatments produced HI values below 4.0%. Kaimosi recorded intermediate HI values overall, with the conventional FYM treatment achieving the highest HI (9.65%), while the monocrop control remained lowest at 3.06%.

Fertilizer amendments significantly influenced HI across all sites ($p < 0.001$). FYM alone produced moderate HI increases, consistent with its slower nutrient release. Seasonal differences were also evident: short rains often produced higher HI values than long rains. Cropping system \times amendment interactions (CS \times AM) were significant in Siaya and Kaimosi, indicating that the response of HI to P amendments was system-specific. For instance, combined P applications in conventional plots produced nearly threefold higher HI than monocrop plots under the same amendment.

Table 4.5: Harvest Index (%) of Rice Bean Under Different Cropping Systems and Phosphorus Amendments across Sites and Seasons (short rains of 2020 and long rains of 2021)

Cropping system	Amendment	Siaya			Rongo			Kaimosi		
		Short rains	Long rains	Mean	Short rains	Long rains	Mean	Short rains	Long rains	Mean
Monocrop	Control (0 kg P ha ⁻¹)	2.90	3.16	3.03 ^a	3.65	3.37	3.51 ^a	3.24	2.88	3.06 ^a
	FYM (5 kg P ha ⁻¹)	2.81	3.70	3.25 ^a	3.90	3.81	3.86 ^a	3.66	2.95	3.30 ^a
	Combined (15.5 kg P ha ⁻¹)	3.77	4.02	3.90 ^a	5.13	3.93	4.53 ^{abc}	4.46	2.79	3.63 ^a
	Inorganic (26 kg P ha ⁻¹)	3.48	3.56	3.52 ^a	4.55	4.32	4.434 ^{ab}	4.07	3.08	3.58 ^a
	Mean	3.24	3.61	3.43	4.31	3.86	4.08	3.86	2.93	3.40
Conventional	Control (0 kg P ha ⁻¹)	10.11	4.95	7.53 ^b	7.06	4.33	5.70 ^{abcd}	6.05	6.60	6.32 ^b
	FYM (5 kg P ha ⁻¹)	7.51	6.19	6.85 ^b	12.25	5.78	9.02 ^{efg}	10.23	9.07	9.65 ^e
	Combined (15.5 kg P ha ⁻¹)	10.44	11.77	11.10 ^c	13.51	7.16	10.34 ^{fg}	8.47	7.82	8.15 ^{bcd}
	Inorganic (26 kg P ha ⁻¹)	10.45	6.88	8.67 ^b	13.90	6.98	10.44 ^g	9.52	8.99	9.25 ^{de}
	Mean	9.96	7.12	8.54	11.68	6.06	8.87	8.57	8.12	8.35
MBILI	Control (0 kg P ha ⁻¹)	9.35	7.77	8.56 ^b	9.11	5.79	7.45 ^{cdef}	7.74	6.49	7.11 ^{bc}
	FYM (5 kg P ha ⁻¹)	9.88	8.08	8.98 ^{bc}	7.80	5.98	6.89 ^{bcd}	7.80	7.74	7.77 ^{bcd}
	Combined (15.5 kg P ha ⁻¹)	9.58	7.36	8.47 ^b	8.27	7.56	7.91 ^{defg}	9.28	8.85	9.07 ^{de}
	Inorganic (26 kg P ha ⁻¹)	7.80	7.60	7.70 ^b	8.08	6.97	7.53 ^{defg}	8.74	8.59	8.67 ^{cde}
	Mean	9.15	7.71	8.43	8.31	6.57	7.44	8.39	7.92	8.16
P value	Cropping system	<.001			<.001			<.001		
	Seasons	<.001			<.001			0.007		
	Amendments	<.001			<.001			<.001		
	CSx S	<.001			<.001			ns		
	CSxAM	<.001			0.005			<.001		
	SxAM	ns			ns			ns		
	CSxSxAM	ns			ns			ns		
	s.e.	1.159			1.475			0.931		
	CV%	17.10			21.70			14.00		

Values represent harvest indices per treatment combination. Different superscript letters within the same column indicate significant differences ($p < 0.05$). Statistical significance of main effects and interactions (cropping system, season, and amendment) are provided along with standard error (SE) and coefficient of variation (CV%), *CS-Cropping systems*, *S- Seasons*, *AM-Amendments*,

CHAPTER FIVE

DISCUSSION

5.1 Soil Available Phosphorus under Different Amendments and Cropping Systems

The findings of this study clearly demonstrate that phosphorus fertilizer amendments significantly improved soil available P concentrations across all experimental sites, with the highest values consistently observed under inorganic P application and the lowest in the control treatments. These results indicate that P availability in soils is highly responsive to the quantity and type of P input and reflects the importance of external nutrient supplementation in smallholder legume production systems where inherent soil fertility is often low. The effect of soil available P to inorganic fertilizer could be explained that mineral P sources provided readily soluble P for plant uptake and soil improvement. These results corroborates with those reported by Kisinyo et al., (2019) who found out that application of 26 kg P ha⁻¹ from TSP greatly increased the soil available P as compared to treatments which contained combined P sources from both organic and inorganic fertilizers in sorghum fields. This could be due to the increase in P solution as provided by the applied inorganic fertilizers. The little increment in soil available P from FYM was because the FYM had very low P content and there also existed probable fixed P desorption. Some P in the FYM had to first be mineralized for their availability to be recognized. In combined P (15.5kg P ha⁻¹) treatments, the organic matter probably decreased the P sorption hence making both the applied P and native P from to be available in the soil. The soil phosphorus got was far away less than the required 10 mg kg⁻¹ which is deemed adequate for crops in western Kenya. The collection of phosphorus data was done after crop harvest when most of the phosphorus had been fixed in the soil. These

lower quantities of phosphorus could state that the residual effect on subsequent crops would be low requiring application of phosphorus fertilizers to be done seasonally in the fields.

Increases in soil available phosphorus as a result of increase in the quantities of phosphorus applied in acid soils in western Kenya has also been reported (Asbon et al., 2015). Interestingly, the combined application of farmyard manure (FYM) and inorganic P at $15.5 \text{ kg P ha}^{-1}$ produced moderately high available P levels across sites and cropping systems. This combined approach is consistent with integrated soil fertility management (ISFM) strategies, where organic inputs improve soil structure and microbial activity, enhancing P availability and reducing fixation. The enhanced performance of the combined treatment in this study indicates that partial substitution of inorganic P with FYM could sustain soil P levels while improving organic matter content, potentially offering a more sustainable approach to soil fertility management than reliance on mineral fertilizers alone (Mahmood et al., 2017).

Cropping systems influenced soil P concentrations, though their effects were not statistically significant ($p > 0.05$). Nonetheless, a trend was observed in which monocropping and MBILI systems retained higher soil P levels than the conventional intercropping system. Monocropping may reduce interspecific competition for applied P, allowing more P to remain in the soil after crop uptake, while the MBILI system may enhance nutrient capture. A similar observation was reported by Ndungu-Magiroi et al., (2017), who found that structured intercropping systems improved nutrient use efficiency and reduced nutrient losses in Western Kenya compared to unstructured intercropping. In

contrast, conventional intercropping may accelerate P depletion due to competition among crops with overlapping root zones, particularly in soils with low inherent P reserves.

Seasonal variations also played a significant role in determining soil P availability, with slightly higher concentrations recorded during the long rains. This seasonal effect could be attributed to enhanced mineralization of organic P and reduced P fixation under higher soil moisture conditions. Moreover, the flushing effect of rains may increase P mobility in the soil solution, temporarily boosting availability during peak rainfall periods. These seasonal trends are consistent with findings from He & Dijkstra (2015), who noted that soil moisture availability increased P availability in smallholder fields, though heavy rainfall events may also lead to runoff losses if not properly managed.

Site-specific differences in soil P dynamics were evident. Siaya generally maintained higher mean available P compared to Rongo and Kaimosi under similar treatments. These differences may be attributed to variations in baseline soil fertility, texture and mineralogy among the sites. Highly weathered Ferralsols and Acrisols, which dominate parts of Rongo and Kaimosi, are prone to P fixation due to the presence of iron and aluminum oxides, whereas Acrisols of Siaya exhibit lower fixation potential (Oloo, 2016). Consequently, the same rate of P application resulted in higher available P levels in Siaya than in the other two sites.

The interaction between cropping system and P amendment ($CS \times AM$) was significant in Siaya ($p < 0.001$), suggesting that the effect of fertilizer on soil P was influenced by the cropping arrangement. This interaction aligns with findings by Mongare et al. (2020), who demonstrated that the efficiency of applied P in western Kenya varied with the cropping pattern, with structured intercropping and monocropping showing superior P retention

compared to conventional intercropping. Such interactions have practical implications for designing site-specific ISFM strategies that combine optimized P input with the most appropriate cropping system.

From a practical standpoint, the results of this study have important implications for sustainable rice bean production in Western Kenya and similar agro-ecologies. First, reliance solely on organic sources such as FYM may not provide sufficient available P to meet crop demand in the short term, although it contributes to long-term fertility improvement. Second, sole inorganic P application remains the most effective for immediate soil P enrichment but may be economically unsustainable for smallholder farmers without complementary organic inputs to maintain soil health. Third, adopting cropping systems that minimize competition for applied P, such as monocropping or structured intercropping like MBILI, can improve nutrient retention and enhance the efficiency of applied fertilizers.

The study confirms that soil available P under rice bean production is highly responsive to P fertilizer amendments, with the highest improvements observed under inorganic application, moderate under combined (FYM + inorganic) management, and minimal under control conditions. Seasonal effects and site-specific soil characteristics further modulate P dynamics, highlighting the need for localized and integrated nutrient management approaches. Comparisons with similar studies in Kenya and across sub-Saharan Africa reinforce that sustained productivity in legume-based systems requires consistent P supplementation, preferably through integrated approaches that combine mineral and organic sources to enhance short-term availability and long-term soil fertility.

5.2 Effect of Phosphorus fertilizer and cropping systems on rice bean phenology (Days to 75% flowering and physiological maturity)

The timing of 75% flowering and days to physiological maturity in rice bean across the three study sites Siaya, Rongo and Kaimosi demonstrated clear responsiveness to phosphorus fertilizer amendments and cropping systems, with observable differences in phenological behavior under varying nutrient regimes and spatial conditions. Across all sites, control plots without P consistently exhibited delayed flowering and physiological maturity. This delay is consistent with the established role of phosphorus in enhancing early plant development, root vigor, and energy metabolism. Phosphorus is integral to ATP formation and nucleic acid synthesis, which drive floral initiation; thus, deficiency commonly manifests as delayed flowering and prolonged vegetative phases (Mardamooto et al., 2021) .

The application of FYM at 5 kg P ha⁻¹ moderately improved flowering time, reducing the duration by approximately 7–10% relative to the control and reduced delay physiological maturity. This suggests that FYM effect on early phenology is less pronounced compared to mineral sources. Combined P treatments (15.5 kg P ha⁻¹ from FYM + inorganic) consistently produced the earliest flowering across all sites and seasons, with reductions of up to 17-20 days compared to the control in mono cropping systems. The synergy between organic and inorganic P likely enhanced both immediate and residual P availability, improving root growth and hastening transition to reproductive stages. These findings corroborate those of Bala et al. (2022), who reported reduced days to flowering and physiological maturity while evaluating green bean response to various nutrient sources with the poultry manure application in Nigeria. The combined organic-inorganic nutrient

management accelerates phenological progression in legumes by synchronizing nutrient supply with crop demand.

Inorganic P application at 26 kg P ha^{-1} also reduced flowering time and physiological maturity, though in some instances, combined P produced slightly earlier flowering and physiological maturity. The pattern could depict that FYM improves the structure of the soil, the microbial activity and enhancement of micronutrient availability. These activities improve faster reproductive development. In Zimbabwe, it has been demonstrated that in cow pea and common bean cultivation, the application of phosphatic fertilizers improves flowering and maturity making the crops to escape from terminal drought periods (Kanonge et al., 2015). In some countries like Ethiopia, Lishan et al., (2023) observed that integrated fertility management reduced crop flowering period and physiological maturity in haricot bean production.

In Siaya a reduction in flowering under P fertilization was due to its poor soil fertility and good rainfall patterns which eased the nutrient uptake. The longer durations of flowering in Rongo were due to its cooler conditions which extended crop vegetative growth. Kaimosi had the longest days to flowering due to its poor soil fertility and cooler temperatures which slowed the pace of metabolic and reproductive processes. Moisture stress reduce the crop phenological development of grain legumes (Farooq et al., 2017). The lack of significant three-way interactions (cropping system \times season \times P amendment) across sites suggests that P availability exerted a consistently dominant effect on phenology, overriding seasonal variability in most cases.

Rongo and Siaya had shorter physiological maturity durations than Kaimosi. This was because of moderately fertile soils in the region which improved nutrient uptake and plants

metabolic processes. Kaimosi had the longest days to physiological maturity as the soils had very low cation exchange capacity slowing nutrient mineralization and overall crop development. The short rains of 2020 produced delayed maturity compared to the long rains of 2021. This observation is in line with the observation made Kinyua et al., (2024), who identified that seasonal weather conditions and crops rotation used can influence phenological development of legumes..

The monocrop systems with combined P management ($15.5 \text{ kg P ha}^{-1}$) had the earliest flowering and physiological maturity periods while the conventional intercropping with the control treatments had the longest durations. These differences likely arise from intra- and interspecific competition for nutrients and light. MBILI may facilitate better resource partitioning and light interception compared to conventional intercropping, thereby enhancing early development under sufficient P (Gebru, 2015).

Overall, the flowering and physiological maturity responses to P fertilization and cropping system demonstrate that combined nutrient management is an effective strategy to hasten rice bean phenology, which may be advantageous in regions with short or unpredictable rainy seasons. By achieving earlier flowering and potentially earlier maturity, farmers can reduce exposure to terminal drought and enhance the chances of achieving stable yields. This phenological plasticity, induced by P availability and optimized cropping systems, underscores the agronomic value of integrating organic and inorganic nutrient sources in legume production systems of Western Kenya and similar agroecologies.

5.3 Effect of Phosphorus Fertilizer and Cropping Systems on Pod number, grain yields, phosphorus agronomic efficiency and harvest index Rice Bean

The number of pods per plant is a critical yield component in rice bean production and this study revealed clear and consistent responses to phosphorus fertilizer amendments and cropping systems across all three sites. Across the board, control plots without P fertilizer produced the lowest pod counts, while combined (15.5 kg P ha⁻¹) consistently resulted in higher pod numbers. In Siaya, the combined P treatment (15.5 kg P ha⁻¹ from FYM + inorganic) produced the highest pod counts. FYM alone moderately enhanced pod production, demonstrating the slow nutrient release characteristic of organic sources, which improves soil fertility over time but may not fully meet the peak P demand during reproductive stages (Shakoor et al., 2015).

In addition, the variations in rice bean grain yield across the three study sites and cropping systems demonstrate the strong influence of phosphorus availability, cropping arrangement and site-specific environmental conditions on legume productivity. The consistently higher yields observed in monocropping systems compared to conventional and MBILI systems can be attributed to the absence of interspecific competition for light, water and nutrients, which allows rice bean to maximize resource use under favorable nutrient conditions. In contrast, intercropped systems likely experienced competition from associated crops during early growth stages, which can suppress biomass accumulation and delay reproductive development, even though intercropping may offer long-term soil fertility benefits. The higher grain yields were as a result of improved yield components (Lishan et al., 2023). The strong yield response to combined P application (15.5 kg P ha⁻¹ from FYM + inorganic fertilizer) reflects the synergistic benefits of combining fast-releasing

inorganic P with organic amendments that improve soil structure, moisture retention and microbial activity. Inorganic P (26 kg P ha^{-1}) also enhanced yields substantially, though slightly lower than the integrated approach, particularly in Kaimosi, where cooler and more acidic soils may have promoted higher P fixation, reducing immediate availability to crops (Sebnie et al., 2020). FYM alone led to moderate yield improvement, likely due to its slow mineralization rate, which may not fully meet the P demand during the critical early growth stages.

These results indicate that the effectiveness of the applied phosphorus in converting to the harvest of the grain in the management systems as well as the ecology in the smallholder systems are highly dependent on the environment. Among the fertilizer treatments, farmyard manure was the only one that gave high PAE than the sole inorganic P particularly in conventional system and MBILI. This finding underscores the effectiveness of organic modification in promoting efficiency of nutrient utilization since they emanate nutrients gradually and sustainably that contributes to the build-up of organic substances and the ability to augment the activity of the soil microbes and to maintain the soil water. P fixation can also be inhibited by using FYM that enhances the synthesis of organic acids in the rhizosphere that releases phosphorus fractions that are scarcely soluble (Andriamananjara et al., 2019).

The plots with monocrop in Rongo had extremely high values of PAE when compared to the ones with MBILI systems. This phenomenon implies that the synergistic value of organic and inorganic nutrient utilization is achieved when monocropping is applied whereby there are few competitors of the available resources hence, rice bean can use the nutrients used to the full extent. In its turn, this limited productivity of the MBILI plots can

be attributed to interspecific competition over the light, water and nutrients that decreases the ratio of applied phosphorus directly converted into the productivity of rice beans.

The site-specific conditions also played an important role in determining agronomic efficiency of phosphorus. The overall trend of Rongo was that the greatest PAE was experienced in monocropping system and conventional system especially in FYM and integrated treatment. The situation of fairly fertile soils and even distribution of rainfall at the location must have contributed to the good absorption and dispersion of nutrient to the reproductive growth. The moderate yields in Siaya, with a rather low PAE, had a single inorganic P which might be due to the fact that the phosphorus fixation was more in its Acrisols that are richly endowed with iron and aluminum oxides.

Kaimosi presented intermediate values of PAE as compared to the other two, where FYM treatment is performing well but poor performance is being displayed by integrated or inorganic P. The high rainfall and cooler climate at Kaimosi may decrease mineralization of rain fed nutrients and also enhance leaching loss that leads to low nutrient phosphorus adequately transforming into grain yield. The agronomic effectiveness of phosphorus was also influenced by seasonal effect and in most situations and sites, the short rainy season was more favorable than the long rainy season. This trend corresponds to the trends of yield in the **Section 4.3.1** and can be attributed to the fact that these shorter rains result in decreased waterlogging, improved aeration and improved mineralization of nutrients that offer optimal conditions of phosphorus uptake and assimilation. The general intense rains throughout the long rains were most likely to result in the loss of nutrient either through leaching or interim anaerobic condition, which limited the ability of crop to convert the phosphorus applied to increment. The harvest index of rice bean that is the ratio of total

above-ground biomass to economic yield showed a great variance across the amendments of Phosphorus (P) fertilizer, crop systems, site and seasons.

Across all treatments, HI values ranged from 3.03% in monocrop control plots in Siaya to 11.10% under the conventional system with combined P in the same site, indicating that management practices and nutrient availability strongly influence biomass partitioning efficiency (Mensah et al, 2016). In general, conventional systems exhibited the highest HI values, followed by MBILI and monocropping, suggesting that intercropped or conventionally managed systems enhanced assimilate partitioning to grain, possibly due to reduced vegetative growth dominance compared to sole rice bean stands.

In Siaya, the conventional cropping system responded most positively to phosphorus enrichment, achieving a mean HI of 11.10% under the combined FYM+inorganic treatment. This demonstrates the beneficial effect of integrated nutrient management in improving reproductive allocation by supplying both readily available and slow-release phosphorus. Monocropped plots, on the other hand, maintained consistently lower HI values (3.03–3.90%), implying that while sole cropping maximizes total biomass, a larger proportion remains in vegetative structures under low fertility conditions. Rongo followed a similar trend, with the conventional system achieving the highest HI (10.44%) under sole inorganic P application, whereas monocrop plots with FYM and control treatments produced values below 4.0%. The response in Rongo suggests that soil and climatic conditions at this site favored biomass partitioning when sufficient P was available. High HI under conventional intercropping may also reflect a compensatory growth effect, where competition with companion crops suppresses excessive vegetative development, thus enhancing reproductive allocation. In Kaimosi, HI values were intermediate across the

treatments, reflecting the site's cooler and wetter conditions. The highest HI (9.65%) occurred under the conventional FYM treatment, while the lowest (3.06%) was observed in monocrop control plots. The superior performance of FYM in this site could be attributed to its gradual nutrient release and soil conditioning benefits, which improve root growth and moisture retention in wetter environments.

Compared with other researchers, Otieno et al., (2018) demonstrated that phosphorus fertilization significantly increased pod numbers and overall in soy bean yields under Kenyan conditions, with integrated P sources outperforming single sources. Similarly, Avorny & Manu, (2020) reported that P fertilization increased reproductive output in soybean, mainly by reducing flower abortion. In cowpea, Kamara et al., (2018) found that crop yield attributes increased with P fertilization, highlighting the nutrient's role in reproductive efficiency. Furthermore, the increase in phosphorus applications increase the pod and yields of common beans in Ethiopia (Tesfaye et al, 2015)

The results indicated that Kaimosi, characterized by slightly lower baseline fertility and cooler conditions, recorded lower absolute pod counts than Siaya and Rongo. The reduced pod numbers under similar treatments reflected slower nutrient mineralization in the cooler, high-rainfall environment of Kaimosi, where P availability is limited by potential leaching and fixation. Despite this, the ranking of treatments remained consistent, with combined P > inorganic P > FYM > control, underscoring the robustness of P management in enhancing reproductive performance across contrasting agroecologies.

This was confirmed by studies of Kinyua et al., (2024) which found that season difference affected the phenological properties of crops. The difference in soil fertility, temperature and rainfall patterns saw Siaya and Rongo register more yields than Kaimosi. All the sites

had more yields in the short rains than the long rains. This was because there was increased efficiency in the utilization of radiation in the short rains that enabled pod development and filling of seeds. The long rains provided water that spread vegetative growth so as to cause the late flowering. This augmented cases of pests and flower abortions hence decreased yields. Legumes are very sensitive to a lack of phosphorus in soils (Vanlauwe et al., 2010; Mwadalu et al., 2022). The combined P treatment was very successful as it has provided nutrient that was readily available and moreover enhanced the soil organic matter and microbial activity due to FYM. The plants in the monocropping systems received enough sunlight, water and nutrients with less competition hence yielded better. In the intercropping systems, there existed a competition between nutrients. This aligns with the findings of Jensen et al (2017), who reported that intercropped legumes often suffer yield penalties due to interspecific competition, unless fertility inputs are carefully optimized. The distribution of rainfall and the intensity of radiation affect legume yields (Sennhenn et al., 2017). There was a significant interaction between cropping system, season, and P treatment. Ejigu & Tulu, (2021) stated that that soybean and common bean yields in Eastern Africa were strongly influenced by combined nutrient management. Vanlauwe et al., (2010.) also highlighted on the significance of integrating organic and inorganic nutrient sources to improve legume productivity in low-input systems.

These results highlight the necessity of changing to a combined approach to soil fertility control and site-specific cultivation to maximize the reproductive efficiency and the yield potential in rice bean. Overall, the research demonstrates the significance of phosphorus fertilization, particularly the use of a combination of FYM and inorganic fertilizers to enhance the productivity of rice bean in the case of a smallholder-based system.

Monocropping documents the highest yields when nutrients are supplied adequately, MBILI and conventional systems are diversified, although they require adequate supply of nutrients to overcome the competitive connotations. Such results are consistent with the principles of sustainable intensification and it is emphasized that the nutrient management of integrated yield of low-input legume schemes has the potential to address yield gaps. The mechanisms that transpire behind such responses are on the complementary effects of organic and inorganic inputs. FYM enhances the coalescence of soil, its holding capacity to water and is made reachable to microorganisms, which elevates nutrient availability. Integrated nutrient management takes advantage of all these benefits and at the same time provides instant phosphorus in the form of mineral fertilizers which result in short run and long run payoffs of yield. Single inorganic fertilizers on the other hand, despite their ability to contribute to the increase of absolute yields, are less efficient due to fixation and leaching of highly weathered tropical soils. The poor performance of MBILI and to some extent, conventional systems in terms of PAE is always the reflection of the impact of interspecific competition on intercropping system. Even though such systems can lead to improved soil fertility and long-term sustainability of the systems, it apportions a portion of the nutrients applied to the companion crops, which essentially reduces the agronomic efficiency of the rice bean being quantified.

Overall, it can be seen that harvest index of rice bean is highly influenced by the supply of phosphorus, seasonality, and cropping pattern. HI, particularly in the traditional systems is highly enhanced through the integrated nutrient management practice particularly when FYM and inorganic P are applied together. These findings reveal that the nutrient balance

management must be correlated to the choice of the cropping system to attain the yield besides the partitioning efficiency within the smallholder rice bean cultivation.

From a practical perspective, the findings of this study suggest that farmers aiming to maximize short-term returns per unit of phosphorus applied should prioritize integrated nutrient management under monocropping, particularly during the short rains when conditions favor efficient nutrient uptake. In contrast, farmers practicing MBILI or conventional intercropping should combine organic and inorganic sources to maintain soil fertility and ensure moderate efficiency, recognizing that the immediate PAE will likely be lower due to competition effects. These results underscore the importance of site- and system-specific nutrient recommendations to optimize both productivity and nutrient use efficiency in smallholder rice bean systems.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study reveals that phosphorus (P) fertilizer amendments and cropping systems significantly affect soil available phosphorus in rice bean production systems in Western Kenya. The results showed that inorganic P fertilizer at 26 kg ha^{-1} consistently yielded the highest soil available P levels across all sites, while combined P application of farmyard manure (FYM) with inorganic fertilizer produced moderately high soil P levels. Monocropping and MBILI systems exhibited slightly higher P retention than conventional intercropping, though the cropping system effect was less visualized compared to the influence of P amendments. The study demonstrates that phosphorus (P) fertilizer amendments and cropping systems significantly influence the phenology and reproductive performance of rice bean across varying agro-ecological sites. Monocropping generally exhibited the earliest flowering and highest pod numbers under high-P conditions, whereas conventional and MBILI systems produced delayed flowering. These findings confirm that phosphorus is a critical driver of early reproductive initiation and reproductive output in rice bean and that cropping system choice interacts with nutrient availability to influence phenology.

The study clearly demonstrates that phosphorus (P) fertilizer amendments and cropping systems significantly influence rice bean yields and yield components across the three sites. Integrated management of nutrients mixing FYM and inorganic P ($15.5 \text{ kg P ha}^{-1}$) consistently gave highest yields, pod numbers and improved PAE. Monocropping

generally resulted in higher yields and P use efficiency compared to MBILI and conventional systems.

6.2 Recommendations

1. It is recommended that smallholder farmers adopt a combined soil fertility management approach ($15.5 \text{ kg P ha}^{-1}$) to improve both short-term crop performance and long-term soil health for rice bean production.
2. Extension services and local agricultural authorities should promote the MBILI and monocropping systems in areas with better water retention, provide training on timing and methods of P application and ensure that affordable P fertilizers are accessible to farmers.
3. Future research should focus on long-term experiments to evaluate the cumulative effects of repeated P fertilizer applications and integrated cropping systems on soil fertility, nutrient cycling, and rice bean yield sustainability. Studies should also investigate the economic viability and environmental impacts of these practices to facilitate scaling in diverse smallholder contexts.

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APPENDICES

Appendix I: Fertilizer calculations for field experimental plots

Nutrient	Nutrient source	Amount applied ha ⁻¹
Phosphorus (P)	Triple superphosphate (TSP) (46% P ₂ O ₅)	26 kg P
		13 kg P
Nitrogen (N)	CAN fertilizer (26% N)	22 kg N
		11 kg N
Nitrogen (N)	CAN for maize only	75 kg N

Appendix II: Experimental layout during the field trials



(Source: Author, 2020)

Appendix III: Data collection during the field trials



(Source: Author, 2020)

Appendix IV: Laboratory activities during the study.



(Source: Author, 2021)

Appendix V: Farmers' participation during the field days.



(Source: Author, 2021)

Appendix VI: ANOVA Table for the Number of pods in Siaya ATC

Siaya					
Analysis of variance					
Variate: Number of pods Pods_per_plant					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Cropping_system	2	1596.03	798.01	25.83	<.001
Season	1	210.13	210.13	6.8	0.012
Fertilizer amendments	3	16145.49	5381.83	174.23	<.001
Cropping_system.Season	2	149.08	74.54	2.41	0.1
Cropping_system.ammendments	6	273.31	45.55	1.47	0.207
Season. amendments	3	457.71	152.57	4.94	0.005
Cropping_system.Season. amendments	6	317.58	52.93	1.71	0.138
Residual	48	1482.67	30.89		
Total	71	20631.99			
d.f.		s.e.	cv%		
48		5.5578	12.7		

Appendix VII: ANOVA Table for the Number of pods in Rongo University

Rongo					
Analysis of variance					
Variate: Number of Pods_per_plant					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Cropping_system	2	1981.78	990.89	18.66	<.001
Season	1	1.12	1.12	0.02	0.885
Fertilizer ammendments	3	11935.49	3978.5	74.93	<.001
Cropping_system.Season	2	101.33	50.67	0.95	0.392
Cropping_system. ammendments	6	511.56	85.26	1.61	0.166
Season.treatmnts	3	172.38	57.46	1.08	0.366
Cropping_system.Season.ammendments	6	66	11	0.21	0.973
Residual	48	2548.67	53.1		
Total	71	17318.32			
d.f.		s.e.	cv%		
48		7.2868	12.8		

Appendix VIII: ANOVA Table for the Number of pods in Kaimosi Friends University

Kaimosi					
Analysis of variance					
Variate: Number of Pods_per_plant					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Crooping_system	2	1166.08	583.04	7	0.002
Season	1	300.13	300.13	4	0.059
Fertilizer ammendments	3	13557.82	4519.27	56	<.001
Cropping_system.Season	2	40.08	20.04	0	0.78
Cropping_system.ammendments	6	106.14	17.69	0	0.968
Season. ammendments	3	46.93	15.64	0	0.9
Cropping_system.Season.ammendments	6	983.03	163.84	2	0.079
Residual	48	3858.67	80.39		
Total	71	20058.87			
d.f.		s.e.	cv%		
48		8.966	12.8		

Appendix IX: ANOVA Table for the number of days to flowering in Siaya ATC

Siaya					
Analysis of variance in Siaya					
Variate: Days_to 75%_Flowering					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Cropping_system	2	1666.78	833.39	14	<.001
Season	1	110.01	110.01	2	0.187
Fertilizer ammendments	3	3142.6	1047.53	17	<.001
Cropping_system.Season	2	279.11	139.56	2	0.114
Cropping_system.ammendments	6	358.78	59.8	1	0.454
Season.ammendments	3	440.6	146.87	2	0.08
Cropping_system.Season.ammendments	6	385.78	64.3	1	0.408
Residual	48	2949.33	61.44		
Total	71	9332.99			
d.f.		s.e.	cv %		
48		7.8387	13.2		

Appendix X: ANOVA Table for the number of days to flowering in Rongo University

Rongo					
Analysis of variance					
Variate: Days to 75% Flowering					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Cropping_system	2	770.25	385.12	18.08	<.001
Season	1	747.56	747.56	35.09	<.001
Amendments	3	2252.28	750.76	35.24	<.001
Cropping_system.Season	2	22.69	11.35	0.53	0.591
Cropping_system.fertilizer amendments	6	146.97	24.5	1.15	0.349
Season.amendments	3	8.78	2.93	0.14	0.937
Cropping_system.Season.amendments	6	50.31	8.38	0.39	0.88
Residual	48	1022.67	21.31		
Total	71	5021.5			
d.f.		s.e.	cv%		
48		4.6158	13.9		

Appendix XI: ANOVA Table for number of days to flowering in Kaimosi Friends University College

Kaimosi					
Analysis of variance					
Variate: Days_to 75% Flowering					
Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Cropping system	2	1038.5	519.3	4.69	0.014
Season	1	20.1	20.1	0.18	0.672
Fertilizer ammendments	3	5451.4	1817.1	16.41	<.001
Cropping system.Season	2	75	37.5	0.34	0.714
Cropping system.ammendments	6	193.5	32.2	0.29	0.938
Season.treatmnts	3	163.2	54.4	0.49	0.69
Cropping system.Season.ammendments	6	297.4	49.6	0.45	0.843
Residual	48	5316.7	110.8		
Total	71	12555.8			
d.f.		s.e.	cv%		
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