EVALUATION OF IMPACTS OF INTEGRATED LIME AND FERTILIZER APPLICATION ON SELECTED SOIL CHEMICAL PROPERTIES AND SORGHUM PRODUCTIVITY IN ACID SOILS OF WESTERN KENYA

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DECLARATION

Declaration by the Candidate

This thesis is my original work and has not been presented for a degree in any other University. No part of this thesis may be reproduced without the prior written permission of the author and/or the University of Eldoret.

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DEDICATION

This thesis is lovingly dedicated to my wife, Nelly, whose unwavering support and encouragement have been my anchor; to my great children Emmanuel, Elly, Edith, and Ethan, whose laughter and curiosity inspire me to strive for a better future; and to my parents, Daniel and Catherine whose sacrifices, guidance, and values laid the foundation for all my achievements. Without their love and belief in me, this journey would not have been possible.

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With regards to many questions about my future academic endeavors from family and friends, I shall answer in the words of Sir Winston Churchill: “Now this is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.”

ABSTRACT

This research assessed sustainable strategies aimed at enhancing soil fertility and sorghum production in the acidic soils of western Kenya. Microdosing trials were carried out in Kakamega and Siaya. These were executed under two conditions: lime-treated (4 t ha^{-1}) and untreated (0 t ha^{-1}), and were factorially combined with varying application rates of nitrogen (18.8, 37.5, and 75 kg ha^{-1}) and phosphorus (6.5, 13, and 26 kg ha^{-1}). The study employed a randomized complete block design (RCBD) with treatments analyzed using ANOVA, followed by Tukey's HSD for mean separation. Results revealed liming significantly increased soil pH (from 4.50 to 6.19), reduced exchangeable Al, and improved grain N and P uptake. SOC rose across sites, with lime–fertilizer treatments showing strong positive trends. The application of lime significantly ($p < 0.001$) enhanced both sorghum biomass and grain yield by increasing soil pH, which in turn mitigated Al toxicity, improved root access to P, and promoted N assimilation. Micro-doses of N and P fertilizers were superior to recommended doses in grain and biomass yield, agronomic efficiency (AE), and harvest index (HI). Nutrient uptake efficiency ranged from 21.91–34.54%, with the maximum at $N_{18.8}P_{6.5}$. Increasing doses of fertilizer reduced NUE and AE. Combining 4 t ha^{-1} lime with $N_{75}P_{26}$ fertilizer maintained the highest gross margins and benefit–cost ratios ($BCR > 2.0$; $p < 0.001$) at sites and seasons. Seasonal differences affected profitability, with 2018-LR performing better than other years. The combined application of lime and fertilizer yielded the highest economic efficiency among the treatment options, with lime + $N_{37.5}P_{13}$ treatment proving to be the most economically viable option among the smallholder farmers. The integration of site-specific fertility management with the conventional application of lime (4 t ha^{-1}), along with microdoses of N and P fertilizers, has the potential to rehabilitate acid-degraded soils in western Kenya, thereby significantly improving sorghum productivity and increasing farmers' incomes.

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LIST OF ABBREVIATIONS

A.S.L- Above Sea Level

AE- Agronomic efficiency

AGLIME- Agricultural Lime

AGRA- Alliance for a Green Revolution in Africa

AN-Ammonium Nitrate

ANOVA-Analysis of Variance

APSRU- Agricultural Research Systems Unit

ASALs-Arid and semi-arid lands

CCE- Calcium Carbonate Equivalent

cmol- centimole

CYMMYT- International Maize and Wheat Improvement Centre

CYMV- Cowpea Yellow Mosaic Virus

DFID- Department for International Development

ECCE- effective calcium carbonate equivalent

ECEC- Effective Calcium Carbonate Equivalent

ECHO- European Commission Humanitarian Aid Office

ENP- Effective Neutralizing Power

ENV- Effective Neutralizing Value

FUE- Fertilizer Use Efficiency

FUE- Fertilizer Use Efficiency

GDP -Gross Domestic Product

GY- Grain Yield

HI- Harvest index

ICRISAT- International Crop Research Institute in Sub-Saharan Africa

KARI- Kenya Agricultural Research Institute

LBC- Lime Buffering Capacity

LR-Lime Requirement

mg- milligram

ml- milliliter

mmol- millimole

SOC- Soil Organic Carbon

ppm- Parts Per Million

RCBD- Randomized Complete Block Design

SSA- Sub-Saharan Africa

CHAPTER ONE
INTRODUCTION

1.1 Background

The Kenyan economy relies fundamentally on rain-fed smallholder farms, which are the region's mainstay. Achieving sustainable agriculture is becoming more challenging as climate change worsens soil quality. Yields of staple crops have either remained steadily low or have shown negative trends because nutrient mining among many nutrient-depleting agents has caused a tremendous decline in fertility, and as Ndungu (2024) puts it, causes major nutrient losses. In Kenya, poor climatic conditions are causing a serious constraint to the agricultural sector. Of great concern is the decline in crop production. Also, extreme weather is becoming a growing threat to agricultural productivity. As Luna & Larrea (2024) reported, these conditions have led to crop failure and loss of livestock. Maize is the key staple crop in Kenya and is the mainstay of most households. Nevertheless, the production of maize in the country has always fallen below the demand, which causes an annual shortage of about 0.4 million metric tonnes (KNBS, 2024). This situation is even worsened by the fact that the population is quickly growing at an average rate of 2.3 percent per year. To counter these pressures, interest is growing in diversifying food sources to increase national food security. A possible alternative is sorghum, which is adaptable to arid conditions and does not require a lot of input. The fact that it has been incorporated into flour blending, brewing industries, and climate-resilient food programs highlights the fact that it can be used to supplement maize and provide resilience against frequent shortages (Njagi et al., 2019).

It is not only a sound agronomic practice that should become a part of national food systems, but it is also economically strategic, particularly as climate change and the escalation of input costs take a toll. Kenya has a population growth rate of 2.7 per annum, which means that food shortages are recurring because the productivity of cereals is not high in the country. It has been estimated that the average annual grain sorghum production in Kenya is approximately 150,000–180,000 metric tons. However, the domestic national demand outstrips supply at more than 275,000 metric tons, leaving a shortfall of above 95,000 metric tons annually (Njinju et al., 2022). To close this gap, the Kenyan government imports sorghum from nations including Australia and the United States. Kenya consumed more than 104,000 metric tons of grain sorghum. In the year 2023 alone, KSh 6.5 billion was brought in, with more than 80 percent of the total amount of imported grain sorghum coming from Australia. These sorghum imports are particularly used for both food and industrial mainly used in brewing and flour-mixing. This is a clear indication that Kenya is increasingly dependent on imports to fill the supply at home. Table 1.0 summarizes Kenya's yearly production and the corresponding imports of sorghum for 10 successive years. The average sorghum yield per unit area in the country is about 0.8–1.2 tons/ha. In ideal research conditions, up to 3.5 tons/ha has been achieved (KNBS, 2024). Sorghum production in the fields of Small Holder Farmer (SHF) is quite uncertain, and even the present yields are below 1.0 ton/ha/year, especially on the acid-constrained soils.

Table 1.0: Kenya Sorghum Production and Imports (2015–2024)

Year	Production (MT)	Production (Million Bags)	Imports (MT)	Imports (Million Bags)
2015/16	189,000	2.10	98,000	1.09
2016/17	117,000	1.30	84,000	0.93
2017/18	144,000	1.60	132,000	1.47
2018/19	189,000	2.10	119,000	1.32
2019/20	288,000	3.20	129,000	1.43
2020/21	315,000	3.50	78,000	0.87

Year	Production (MT)	Production (Million Bags)	Imports (MT)	Imports (Million Bags)
2021/22	139,000	1.54	136,000	1.51
2022/23	199,000	2.21	120,000	1.33
2023/24	200,000	2.22	107,000	1.19
2024/25*	225,000	2.50	60,000	0.67

Conversion: 1 metric ton (MT) = 11.11 bags of 90 kg. Production Data Source: USDA Foreign Agricultural Service

In western Kenya, acidic soil is one of the factors that has caused reduced crop production. Exchangeable aluminum and low pH lower the nutrient levels and root growth, particularly in cereals such as sorghum. The farmers usually use nitrogen and phosphorus (NP) fertilizers, but this is not effective when the soil is not corrected to be alkaline. The use of lime is an effective measure to increase soil pH and decrease aluminum toxicity, which enhances the efficiency with which nutrients are used. In Tharaka-Nithi, several authors (Kimiti, 2018; Kirui, 2018; Wanjiru, 2018) established that lime plus fertilizer improved soil pH, calcium levels, and maize yield. In western Kenya, soils are low in nitrogen and phosphorus. Acidity makes it worse. Common liming materials like calcium oxide and calcium carbonate are used to fix this (Opala et al., 2018). Equally, Nyokabi et al. (Nyokabi et al., 2025) also indicated that the integrated management of nutrients increased the indicators of soil fertility in semiarid Kenya. There is little data on the region, specifically western Kenya, on the impact of lime and NP rates on the main soil chemical properties, such as pH, exchangeable acidity, and available phosphorus. This paper will seek to fill this gap.

Sorghum is a resistant crop to climatic conditions, although the soils are usually acidic, which reduces its yield potential. The nutrient uptake is hampered, and grain yields decrease in western Kenya, where the soil pH is often below the optimum level of 5.5. While fertilizer use is common, its efficiency is compromised without concurrent liming. Silveira et al. (2018) demonstrated that liming, especially when combined with phosphorus sources, improved dry matter partitioning and yield in sorghum. In Kenya, Kazungu (2022) observed that manure and fertilizer improved sorghum growth in degraded soils, though lime was not tested. Yield performance indices—such as harvest index, grain weight, and biomass—offer deeper insight into how well sorghum converts inputs into productive output. This study will evaluate how lime–fertilizer combinations influence these indices under real-world field conditions in acidic soils of western Kenya.

Knowing the relationship between soil health, crop performance, and profit will be important in sustainable farming. Physiological and yield characteristics of sorghum have a direct connection with the soil chemical characteristics, including the pH and the organic carbon, nutrients of the soil. Such, in their turn, affect economic returns. Nevertheless, these three dimensions have not been related to each other in one study. Nyokabi et al. (2025) discovered that integrated inputs enhanced the fertility of soil, resulting in increased yields and returns of the sorghum crop. These, in turn, have an impact on the economic returns. However, there are limited studies that have associated these three dimensions within one framework. Nyokabi et al. (2025) discovered that the better the soil was fertilized using the integrated inputs, the better the yields of sorghum and returns were. In Mali, Coulibaly et al. (2025) showed that climate-resilient sorghum systems were profitable when soil and input management were optimized. However, in Kenya, most research focuses on maize or overlooks the economic side. This study will bridge that gap by analyzing how changes in soil chemistry affect sorghum performance and profitability in acidic soils.

For smallholder farmers, every decision about inputs like lime and fertilizer is, at its core, an economic calculation. These resources aren't free, and if they don't translate into higher returns, most farmers simply won't adopt them. Economic efficiency really comes into play here—it's about how much extra yield is obtained for every shilling (or dollar) invested. This metric is key for figuring out whether investing in soil amendments is actually a smart move. Looking at western Kenya, farmers—especially those growing sorghum—are dealing with highly acidic soils, which is a serious headache for crop production. While some suggest that using lime and fertilizer together could be an affordable way to boost yields, there's little proof that this works for this particular region. Most of the studies out there, like the one by Nyokabi et al. (2025), observed that better economic returns are realized as a result of improvement of soil fertility, but those results mostly come from semi-arid regions, not the acidic zones in the current study sites. That means, for farmers in western Kenya, it's still not clear if this approach will actually deliver the benefits people hope for. Coulibaly et al. (2025) emphasized that there is a need for a thorough examination of cost-benefit analysis in sorghum production systems, a gap that remains surprisingly persistent. Consequently, this research investigates the economic efficiency of various lime and fertilizer combinations employed on acidic soils. The aim is to provide farmers with practical, evidence-based recommendations that lead to more profitable decisions for their farming activities.

1.2 Problem Statement

Sorghum (*Sorghum bicolor* L. Moench) has long been an important crop for food security and livestock feed in sub-Saharan Africa. Its ability to thrive in harsh climates and poor soils has made it a staple food crop in the local farming system. Earlier, farmers could achieve yields of 2 to 4 tha^{-1} per hectare. Recently, yields have dropped significantly. Many smallholder farmers now struggle to produce even 1tha^{-1}. This decline mainly results from the ongoing loss of soil fertility. Years of nutrient depletion, constant erosion, and poor soil management have left the soils less productive and more acidic. This problem is especially severe in western Kenya. The soils there often have low pH, high levels of exchangeable aluminum, and significant shortages of essential nutrients like nitrogen and phosphorus. These conditions cause poor growth of roots and consequently reduce nutrient uptake, which lowers crop productivity. Continuing to farm without adding nutrients only makes things worse. According to Smaling *et al.* (2015). Nutrient losses in sub-Saharan Africa average about 22 kg N and 2.5 kg P ha^{-1} each year. Regular fertilizers usually do not work well in acidic soils because the nutrients become chemically trapped and unavailable to plants. As a result, crops often do not respond well to fertilizer in these areas.

The present research seeks to explore lime to provide a solution by raising soil pH, lowering aluminum toxicity, and improving nutrient availability. When used alongside nitrogen and phosphorus fertilizers, lime can restore soil health and enhance crop performance. However, the right amounts and combinations depend on local conditions. Different soils respond to liming differently based on texture, organic matter, and rainfall. In western Kenya, most farming is small-scale, and access to inputs is limited. The situation explains why sorghum grain yields are low. There is a need for data on lime and fertilizer N and P use specific to the region.

Besides grain yields, sorghum performance also depends on factors like harvest index, grain weight, and biomass. These measurements indicate how effectively the crop converts inputs into output. These metrics are important for breeding, agronomy, and economic planning. Poor soil conditions impact these measures, leading to lower returns and less adoption of improved practices. Using fertilizer indiscriminately and depending on organic inputs has had limited success due to poor adjustment to acidic soils and high costs (Demisie, 2018; Murendo & Wollni, 2015). Microdosing, which is a more recent technology, involves placing small quantities of inorganic fertilizer directly into planting holes together with the seed. Research by Murendo and Wollni (2015) found that sorghum yields increased by 20% to 80% when the technique was used. It also improved nutrient-use efficiency by up to 50% in West Africa. Notably, adding lime or organic matter with this approach can provide even greater benefits, especially in acidic soils (Adamu et al., 2025; Dugalić et al., 2023; Zadrożny et al., 2024). Microdosing technology is therefore under examination in the current study to find out its cost-effectiveness as well as to examine its suitability in the real-life conditions of smallholder farming systems.

Soil health, crop performance, and profit are closely linked. Sorghum growth and yield are affected by changes in soil chemistry, which also impact economic results. Farmers need solutions that work for growing crops and make financial sense. However, few studies bring these factors together in one framework. Most either concentrate on maize or ignore cost-benefit analysis. It is important to understand these connections to be able to solve the problem of limited resources and soil acidity experienced by SHF in western Kenya. Lime and fertilizer cost money, and if using them does not lead to profits, farmers will not adopt them. Economic efficiency, which is a measure of the value of output compared to cost, is an essential index that helps determine if soil amendments are worth the investment. Coulibaly *et al.* (2025) found that climate-resilient sorghum systems in Mali provided good returns when inputs were managed well. Nyokabi *et al.* (2025) noted that using integrated inputs is closely linked to higher sorghum yields and profits, but their study focused on semiarid areas. There is a need for local data on the economics of lime and fertilizer in acidic soils. This study aims to address these gaps. It will evaluate how combining lime and NP fertilizers affects soil chemistry, sorghum yield components, performance measures, and economic returns. The goal is to provide regionally relevant and trustworthy insights that promote sustainable sorghum growth in the acidic soils of western Kenya.

1.3 Justification

Sorghum is an important food crop as well as a source of domestic income in sub-Saharan Africa. It grows well in tough conditions and supports millions of small farmers. However, its productivity has dropped sharply. In western Kenya, acidic soils create significant challenges. They restrict the availability of nutrients, hinder root growth, and decrease grain yields. Under extreme acidic conditions, fertilizer addition poorly responds in these soils. Nutrients get fixed within the soil matrix, and crops do not respond.

Years of continuous cropping without replacing nutrients have made the problem worse. Soil acidity, nitrogen and phosphorus deficiency, and low organic matter are now common. Smaling *et al.* (2015) estimate annual nutrient losses of 22 kg N and 2.5 kg P per hectare across SSA. These losses come from erosion, leaching, and poor soil management. Farmers are witnessing lower yields and higher costs. Traditional solutions, such as blanket fertilizer use, organic inputs, and drought-tolerant varieties, have had limited success. They often fail because they do not work well in acidic soils, the input costs are high, and their agronomic efficiency is low (Demisie, 2018; Murendo & Wollni, 2015). Application of fertilizer by the broadcasting method is expensive and not effective. Organic inputs by themselves cannot meet crop nutrient needs on degraded soils.

Lime is an effective way to manage soil. It raises soil pH, reduces aluminum toxicity, and improves nutrient uptake. When used with nitrogen and phosphorus fertilizers, lime can restore soil fertility and boost sorghum yield. However, the best application rates and mixes depend on the specific conditions of the site. In western Kenya, where smallholder farms predominate and access to agricultural inputs is constrained, there is an urgent need for region-specific agronomic data. Microdosing—placing small fertilizer doses directly into planting holes—has shown promise. The technology has proven to increase yields and improve nutrient-use efficiency. In West Africa, it raised sorghum yields by 20–80% and nutrient-use by up to 50% (Murendo & Wollni, 2015). When paired with lime or organic matter, results improve further, especially in acidic soils (Iticha et al., 2024). This approach is affordable, scalable, and well-suited to smallholder systems.

Sorghum performance is not just about yield. It includes physiological traits and efficiency indices like harvest index, grain weight, and biomass. These metrics help track how well the crop converts inputs into output. Poor soils suppress these indicators, reducing both agronomic and economic returns.

Farmers need solutions that work in the field and make financial sense. Lime and fertilizer cost money. If they don't pay off, adoption remains low. Economic efficiency—measured as output value per unit cost—is a key decision factor. Recent findings by Coulibaly et al. (2025) observed that climate-resilient sorghum systems in Mali provided strong returns when inputs were well managed. Nyokabi *et al.* (2025) connected integrated inputs to improved yields and profits, but their study focused on semiarid zones. This study is justified by the need to improve sorghum productivity in acidic soils using locally tested, cost-effective methods. It will assess how lime and NP fertilizer combinations affect soil chemical properties, sorghum yield components, physiological performance, and economic outcomes. The findings will guide farmers, researchers, and policymakers toward sustainable intensification in western Kenya.

1.4 Objectives of the project

General Objective: To evaluate the agronomic and economic impacts of integrated lime and fertilizer applications on sorghum productivity and soil fertility improvement in the acidic soils of Western

Specific objectives

1) To assess the effects of lime and NP fertilizer rates on selected soil chemical properties of acidic soils in western Kenya.
2) To determine the influence of lime–fertilizer combinations on sorghum yield and yield performance indices in western Kenya
3) To establish relationships among soil chemical properties, sorghum performance metrics, and economic outcomes
4) To evaluate the economic efficiency of lime–fertilizer combinations in enhancing sorghum productivity

Research Working Hypotheses (H_0)

1) Lime and NP fertilizer rates do not significantly alter key soil chemical properties of acidic soils in western Kenya.
2) Lime–fertilizer combinations have no measurable effect on sorghum yield components or physiological traits.

3) Economic indicators such as gross margin and benefit–cost ratio are not significantly affected by lime–fertilizer treatments.
4) Soil chemical properties, sorghum performance metrics, and economic outcomes show no significant interrelationships across treatment combinations.

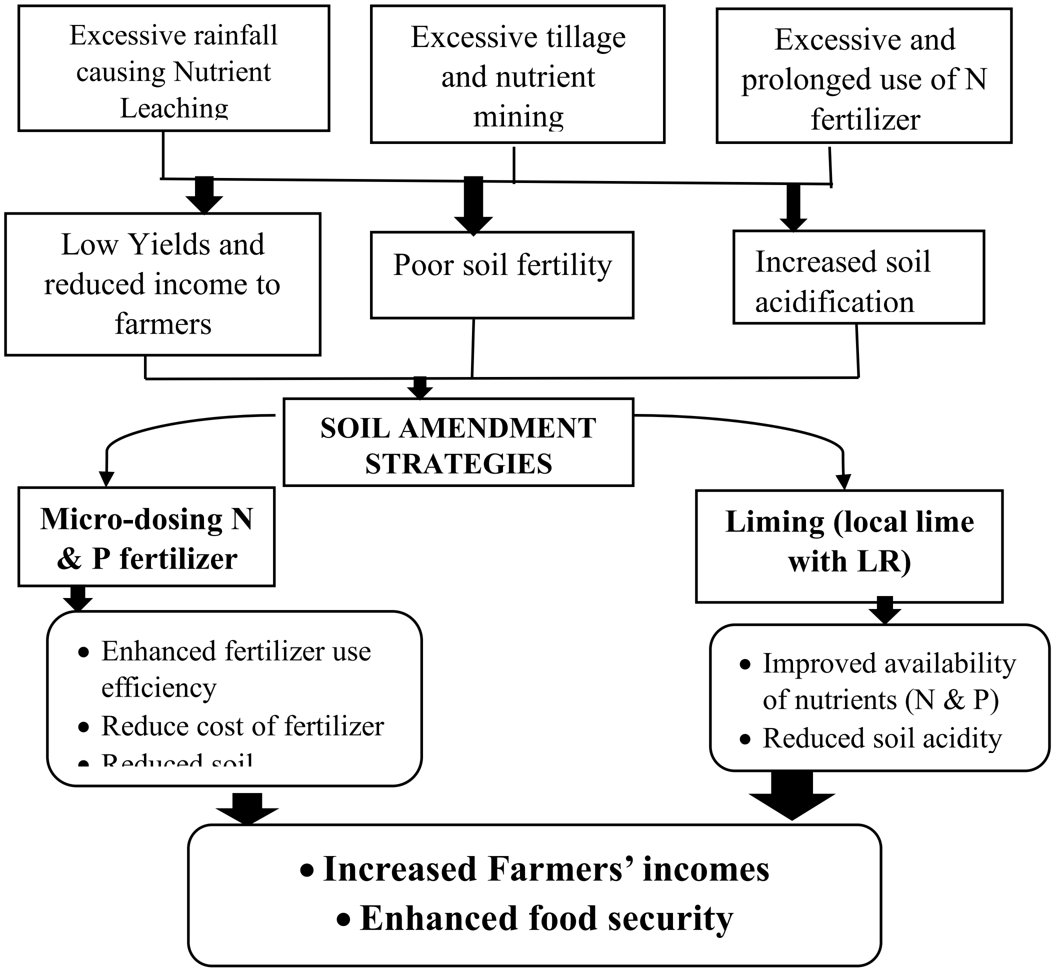
Impact hypothesis: It is anticipated that when lime and NP fertilizers are combined in the acidic soils of western Kenya, they will have the potential to greatly improve the chemical health of the soil, physiological performance, and yield components of sorghum, and economic benefits due to increased yield. Such synergistic boosters will also be paramount in advancing sustainable soil fertility management, strengthening food security, and supporting resource-effective nutrient approaches to the smallholder farming systems.

1.6 Significance of the study

The findings from this study will be beneficial to smallholder farmers practicing in Western Kenya, specifically those who have limited resources and face challenges in managing soil fertility and acidic soils. Because of using small doses of fertilizer, poor-resource farmers will benefit due to reduced costs incurred in purchasing fertilizer. The result of reduced fertilizer will also lead to reduced soil acidification. The findings will also contribute to existing knowledge integrated approach to sustained food supply, proper quantification of locally available liming material, and the effects of lime on soil properties and sorghum yields.

1.5 Conceptual framework

Figure 1.1: Conceptual framework of the study



CHAPTER TWO

LITERATURE REVIEW

2.1 Sorghum growing by smallholder farmers in western Kenya

The loss of soil fertility is a widespread limitation to agricultural productivity in Sub-Saharan Africa (SSA) and is of great importance to smallholder farming systems whose livelihoods are highly dependent on the soil. Fertility loss occurs when nutrient removal through harvest, erosion, or volatilization exceeds natural replenishment or anthropogenic inputs. In contrast to the soils in North America, Europe, or Asia, the majority of SSA soils are inherently poorly fertile because they have been highly weathered and have few nutrient reserves (Custovic et al., 2012; Khreis et al., 2017; Ndeko et al., 2024).

Sorghum (Sorghum bicolor (L.) Moench) is the second most produced cereal in Africa after maize. As Kisinyo *et al.* (2014) reported, it is widely known for drought resistance, low-input requirements, and its capacity for growing on marginal soils. In Kenya, it is an essential food security crop, especially in Arid and Semi-Arid Lands (ASALs) and medium-altitude regions where maize otherwise does not perform (Kyalo et al., 2019).

According to Wortmann *et al.* (2009), western Kenya, primarily Siaya, Bungoma, and Busia counties, accounts for more than 70% of national sorghum production. Despite this, smallholder farm yields remain low, ranging normally from 1.0 to 1.5 t/ha (Karwani et al., 2024). This is far below the global rate, with countries such as Israel and Jordan having yields in excess of 10 tons/ha^{-1} (Sierra et al., 2003).

One of the primary causes of low productivity in Western Kenya is soil acidity. Soils in this region often have pH values below 5.5, which limits nutrient availability and impairs root growth and development. Kisinyo *et al.* (2019) indicated that acidic soils in the Lower Midlands have a great negative effect on the yields of sorghum grain and stover when improved varieties are grown. Further, soil acidity enhances the growth of parasitic weeds, mainly *Striga hermonthica*. This weed infests more than 76% of sorghum and maize crops of western Kenya, causing a loss of up to USD 40.8 million every year (Kayeke et al., 2017; Mbuvi et al., 2017). All these notwithstanding, sorghum is still a key crop for small-scale farmers because of its hardness and manifold applications. It is a cereal for human consumption and a straw for animal feed, and as put by Botha & Viljoen (2008), it makes it a key crop for a mixed cropping system.

2.2 Soil fertility decline in smallholder farming systems

The loss of soil fertility is a widespread limitation to agricultural productivity in Sub-Saharan Africa (SSA). This is of great importance to smallholder farming systems whose livelihoods are very dependent on the soil. Loss of soil fertility results when the process of removal of surface soil by crop harvest, erosion, or gas release exceeds natural replenishment or anthropogenic addition. Compared to SSA soils of North America, Europe, or Asia, most SSA soils are generally low in fertility by nature, owing to their high weathering and low nutrient reserves (Custovic et al., 2012; Khreis et al., 2017; Ndeko et al., 2024). This natural infertility is further exacerbated by leaching, denitrification, and volatilization resulting from degradation processes that inhibit nutrient conservation and long-term soil productivity.

Leaching removes mobile nutrients, such as nitrate (NO_3^-) and potassium (K^+), through percolation below the root zone, particularly in sandy or acidic soils with low buffering capacity. Erosion causes physical loss of soil, with the topsoil layer being lost along with the nutrients, which, in turn, destroys root anchorage and microbial activity. Denitrification, a process usually enhanced when soil oxygen is low, reduces nitrate to

N_2 and N_2O, hence causing permanent loss of nitrogen. Volatilization of applied urea in soils with high pH results in the loss of ammonia (NH_3) into the air, decreasing nitrogen use efficiency. All these activities are aggravated by inadequate soil cover, unpredictable rainfall, and inadequate nutrient planning, resulting in extensive fertility loss (Bationo, 2009; Mucheru-Muna et al., 2010; Vanlauwe et al., 2023).

East African soils are generally acidic (pH < 5.5), leached, and low in cation exchange capacity (CEC) and organic matter, restraining their capacity to hold and provide necessary nutrients (IFA et al., 2002; Sanchez, 2019). These important chemical nutrients, including nitrogen (N), phosphorus (P), sulphur (S), magnesium (Mg), and zinc (Zn), are depleted. Past research indicates that deficiencies of N and P are common everywhere in the region (Donovan & Casey, 1998; Van Eynde et al., 2023). If organic amendments or biological nitrogen fixation are carried out in soil fertility replenishment without mineral fertilizers over several cropping seasons, soil nutrient balances progressively decline. This cumulative depletion leads to reduced crop yields and weakens resilience to climatic variability and pest pressures. Bationo (2009) put annual global income losses at US$42 billion and 6 billion hectares of productive land lost through land degradation. In SSA, the consequences are diminished food production, pervasive poverty, and increased exposure to environmental shocks. In the foregoing circumstances, addressing soil fertility decline remains the main concern if the potential of smallholder agriculture is to be attained. If this is achieved, sustainable intensification in the region will also be realized.

2.3 Effects of climate change on sorghum yields in sub-Saharan Africa

The stressful effects of climate change have adversely affected the agricultural sector, conceivably more than any other sector that provides human livelihoods (Fahad &

Wang, 2020; Fujimori et al., 2019; Kogo et al., 2020; Masud et al., 2017; Mugambiwa & Tirivangasi, 2017). In sub-Saharan Africa, where most soils have undergone extensive nutrient depletion (Pandit et al., 2018), droughts, flash floods, and the escalated temperatures associated with climate change have significantly reduced the productivity of arable lands. Consequently, this has led to serious food insecurity relative to an ever-increasing population (Anikwe et al., 2016). The disparity between actual and potential yields in the majority of African countries is wider than in Latin America and Asia. This means that resource-poor smallholder farmers in sub-Saharan Africa are exceedingly exposed to the effects of climate change (Nekesa, 2007). These farmers should hence be assisted with interventions that can increase food production as well as guard their natural resources to help them become accustomed to climate unpredictability and change (Botha & Viljoen, 2008). Being a climate-resilient crop, sorghum has potential in enhancing food security in sub-Saharan Africa due to its tolerance to drought, poor soils, and high temperatures, making it an essential food and income source for millions of vulnerable households.

2.4 Biophysical requirements for optimal sorghum cultivation

Sorghum is a genetically diverse crop, with cultivars varying widely in maturity duration and climatic adaptation. This diversity enables its cultivation across a broad range of agro-ecological zones—from semi-arid tropics to warm temperate regions. Although inherently suited to tropical climates with high temperatures and moderate to ample soil moisture, sorghum's resilience to drought and heat stress makes it particularly valuable in marginal rainfed systems. Environmental factors such as solar radiation, photoperiod, and temperature play a critical role in shaping sorghum phenology and yield, with genotypes exhibiting distinct responses to local climatic regimes (Khalilian et al., 2022; Sabadin et al., 2012).

Optimal growth occurs under mean daily temperatures of 24–30°C and seasonal rainfall between 450–750 mm, evenly distributed throughout the cropping cycle (Hambloch et al., 2021; Khalifa & Eltahir, 2023). Temperatures below 10°C or above 35°C inhibit growth, with frost and heat stress impairing germination, delaying flowering, and reducing grain set (Liaqat et al., 2025; Prasad et al., 2021). The reproductive phase—especially the 30 days preceding anthesis—is acutely sensitive to environmental stress. During this window, adequate warmth and rainfall (ideally 100–125 mm) are essential for panicle development and successful pollination. Water deficits can lead to pollen sterility, poor stigma receptivity, and floral abortion, ultimately reducing yield (Belton & Taylor, 2004; Rattunde et al., 2021).

Sorghum performs well in a variety of soil types, but optimal growth is achieved in deep, well-drained loam or silt loam soils that are rich in organic matter and capable of retaining moisture effectively (Yara Kenya, 2021; Organic Africa, n.d.). While the crop is known for its adaptability to marginal soils, especially in semi-arid regions, its productivity increases significantly when grown in fertile soils with balanced nutrient availability, particularly nitrogen, phosphorus, potassium, and micronutrients such as zinc and sulfur (Haussmann et al., 2012). Sorghum tolerates a wide pH range—from 5.0 to 8.5—but the ideal soil reaction for nutrient uptake and root development lies between pH 6.0 and 7.5, where most essential nutrients are readily available to the plant (Hambloch et al., 2021).

2.4.1 Nitrogen and sorghum physiology: Roles, deficiency symptoms, and uptake dynamics

Nitrogen (N) is a vital macronutrient in sorghum, accounting for approximately 1–5% of plant dry weight. The plant requires it for the synthesis of amino acids, nucleic acids, and chlorophyll, thereby underpinning the plant's structural integrity, photosynthetic performance, and reproductive capacity (Ostmeyer et al., 2023; L. Zhao et al., 2020).

In sorghum, nitrogen availability is directly linked to leaf development, photosynthetic efficiency, and grain yield. With sufficient supply and availability of soil nitrogen, the plant develops dark green foliage and vigorous vegetative growth due to enhanced chlorophyll biosynthesis. In the contrary, deficiency triggers chlorosis that begins in older leaves and progresses from the tip along the midrib—a hallmark of mobile nutrient redistribution (Xu et al., 2025).

Under nitrogen-limited conditions, sorghum may exhibit physiological adaptations such as increased root elongation and elevated nitrogen use efficiency (NUE), supported by genotypic variation in nitrate uptake mechanisms and metabolic traits (Bollam et al., 2021). These characteristics provide breeding opportunities for improved nitrogen responsiveness in low-input systems.

2.4.2 Nitrogen forms in soil and their relevance to sorghum nutrition

Nitrogen (N) in soils exists in both organic and inorganic forms, each playing distinct roles in sorghum growth and productivity. Total soil nitrogen content varies widely—from less than 0.02% in subsoils to over 2.5% in organic-rich peats (Barros et al., 2020). The inorganic forms of nitrogen include ammonium (NH_4^+), nitrate (NO_3^-), and nitrite

(NO_2^-), which are the most relevant for sorghum uptake and soil fertility. Other inorganic forms, such as nitric oxide (NO), nitrous oxide (N_2O), and elemental nitrogen (N_2), are either transient or biologically inert. It was reported that N_2 can only be accessed by nitrogen-fixing organisms like diazotrophs (Barros et al., 2020; Hara et al., 2019). Sorghum primarily absorbs nitrogen as NH_4^+ and NO_3^-, with uptake efficiency influenced by soil pH, moisture, and microbial activity. NO_2^- is less stable and often lost through denitrification or leaching, especially under anaerobic or high-rainfall conditions (Tóth et al., 2025). The organic nitrogen pool comprises amino acids, proteins, amino sugars, and humic-bound nitrogen compounds. These forms are not directly available to sorghum but become accessible through microbial mineralization processes (Kagwiria, 2019; Raj et al., 2025). Organic amendments such as farmyard manure and compost enhance this pool, improving nitrogen cycling and long-term soil fertility.

Recent studies in semi-arid Kenyan soils show that integrating organic and inorganic nitrogen sources improves nitrogen use efficiency (NUE) in sorghum, especially under low-input conditions (Ajeigbe et al., 2024; Ebanyat et al., 2023).

2.4.3 Nitrate vs. Ammonium uptake in sorghum: Preferences, energetics, and soil interactions

Sorghum (*Sorghum bicolor L.*) is capable of absorbing both nitrate (NO_3^-) and ammonium (NH_4^+), with uptake dynamics influenced by soil pH, genotype, and environmental conditions. While NO_3^- is typically more mobile in soil and readily available under aerobic conditions, NH_4^+ uptake is more favorable as it bypasses the reduction step required for NO_3^- assimilation (Bollam et al., 2021; Miranda et al., 2016).

Sorghum genotypes are unique in how they prefer different forms of nitrogen. Some prefer NH_4^+ under neutral pH and low-oxygen conditions, while others perform better with NO_3^- under acidic soils (Belaineh, 2023; Poonia & Bhumbla, 1973). NH_4^+ uptake tends to acidify the rhizosphere, potentially enhancing phosphorus solubility but also reducing cation availability (Clark, 1982). Conversely, NO_3^- uptake is associated with alkalinization and increased uptake of Ca^{2+}, Mg^{2+}, and K^+ (Omari & Nhiri, 2015). The energy needed to assimilate NO_3^- which requires NAD(P)H for reduction to NH_4^+, can influence nitrogen use efficiency (NUE), especially under stress conditions. Sorghum's adaptive root morphology and transporter expression allow it to modulate uptake based on nitrogen form availability and soil chemistry (Bollam et al., 2021).

2.4.4 Phosphorus in sorghum: Roles, forms, and deficiency impacts

Phosphorus (P) is a vital macronutrient in sorghum, typically comprising 0.05–0.3% of plant dry weight. It plays both metabolic and structural roles, influencing photosynthesis, carbohydrate metabolism, energy transfer, and reproductive development as reported by Elsafy *et al.* (2024) and Malhotra *et al.* (2018). Metabolically, phosphorus is central to the formation of energy-rich compounds such as adenosine triphosphate (ATP) and adenosine diphosphate (ADP), which drive photosynthetic carbon fixation and respiration (Odoom & Ofosu, 2024). Structurally, it is embedded in nucleic acids, phospholipids, coenzymes, and sugar phosphates, supporting cell division, protein synthesis, and membrane integrity (Rizvi et al., 2021). In sorghum, phosphorus deficiency leads to reduced photosynthetic rates, delayed flowering, poor grain filling, and stunted root development (Cao et al., 2025; Chadalavada et al., 2021; Liaqat et al., 2025; Sopandie & Wirnas, 2023). Deficiency symptoms often manifest as purple or bronze discoloration on lower leaves due to anthocyanin accumulation, progressing along leaf margins—a pattern consistent with P mobility within the plant (Mathibela, 2021). Phosphorus availability in soils is constrained by fixation into insoluble forms, especially in acidic tropical soils where aluminum and iron oxides dominate. Sorghum grown in such soils often requires starter P fertilization or integration with phosphate-solubilizing microbes to enhance uptake and yield (Adnan et al., 2025; Rizvi et al., 2021).

2.5 Drivers of soil acidity and implications for sorghum cultivation

Most soils in the areas that grow sorghum are characterized by acidity due to natural (pedogenic) and anthropogenic factors that significantly affect the productivity of crops (Hue, 2022). The leaching of base cation, especially calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^{+}), and sodium (Na^{+}), is sped up during heavy rain as highly weathered ferralsol and acrisol soil types common in tropical landscapes are exposed (Hue, 2022). When the pH drops below 5.5, solubilized exchangeable aluminum (Al^{3+}) is released into the soil solution. This causes a phytotoxic effect on sorghum. Of immediate concern are the prevention of the root elongation, the inhibition of nutrient uptake, and general plant vigor (Bakari et al., 2020). Soil acidity is aggravated by farming activities, especially the extended use of acidic-forming fertilizers. As acid-containing fertilizers such as ammonium sulfate, urea, and diammonium phosphate (DAP) are used, they produce hydrogen ions upon nitrification (Esilaba et al., 2018). Additionally, organic acids are released when organic matter decomposes, and eventually, they contribute to soil acidification. (Getaneh & Kidanemariam, 2021). The weathering processes that lead to soil formation, particularly those arising from acidic parent materials such as granite and rhyolite, contribute significantly to soil properties. These conditions, coupled with wet climatic conditions, render such terrains very vulnerable to persistent acidity (Jyoti, 2023).

Since sorghum has the optimal pH range between 6.5 and 7.5, it is crucial to manage acidity well. Such comprehensive measures as liming, organic amendments, and the use of aluminum-tolerant genotypes are necessary to maintain productivity and resilience in acid-prone conditions (Kipsang, 2023).

2.6 Fertilizer-induced soil acidification in sorghum systems

Under acidic conditions, one of the major effects is the release of aluminum compounds, which are bound to avail in the clay minerals. At pH below 5.5, the oxides of Al become soluble and phytotoxic, forming Al^{3+}, $Al(OH)^{+}$, and $Al(OH)^{2+}$, causing damage to root tissues and fixation of soil phosphorus, making it less available to the crop (Tan et al., 1993). As much as sorghum has mechanisms that make it tolerant to acid conditions, which include organic acid exudation or Al exclusion, these mechanisms are not uniform in all genotypes (Chikuta, 2010). Without correction, aluminum leads to high losses in yield. At near-neutral pH, Al precipitates into gibbsite and aluminate forms, which are not toxic, and there is unrestricted root functioning and enhanced mineral absorption (Brautigan, 2010; Sharma et al., 2025). To counter the acidification and some of its knock-on impacts, soil fertility management packages like liming, the use of small amounts of fertilizers, and the use of organic inputs are important in enabling sorghum to continue being productive even in acidic soils (Esilaba et al., 2022; Opala, 2023).

The management of acidic soils is vital to maintaining sorghum yield and the health of soils, especially in the western regions of Kenya, where soils are deficient in phosphorus and an influx of aluminum is a problem in acidic soils. Sorghum is among the crops that are sensitive to acidic soils, as they suffer significant growth retardation when grown in soils that have a low pH 6.0-7.5, due to poor root extension, nutrient restrictions, and toxic effects of exchangeable aluminum ions (Khalifa & Eltahir, 2023). Liming has become one of the backbones of strategies in neutralizing excess hydrogen ions, reducing in saturation of aluminum, and opening up nutrient availability (Esilaba et al., 2022; Mangale et al., 2016). The most popular limes are agricultural, dolomitic lime, and pelletized ones, and the level of application varies between 2-4 tha^{-1}, depending on the pre-limed soil pH value (Opala, 2023).

Previous findings have demonstrated that the use of lime to amend acidic soils has been shown to improve sorghum grain yield by up to 130% when applied 2-3 months before the planting period. However, the results are much more significant when applied together with organic and mineral fertilizers (Esilaba et al., 2022; Mangale et al., 2016). Farmyard manure, crop residues, and compost, besides preventing the pH decline, will enhance the cation exchange capacity and microbial resistance as well (Gurmessa et al., 2021). A combination of lime and farmyard manure and balanced application of fertilizers, particularly in NPK, has shown synergy when Kenyan environments, fertilizer incorporation of 4 tons per hectare of farmyard manure and 75 kg of nitrogen and 26 kg of phosphorus has led to higher yields of more than 250 percent over control treatments (Esilaba, Opala, et al., 2023; Opala, 2023). Economic calculations indicate further that split applications and similar methods, where half-rate manure is combined with half-rate fertilizer, can be very economical and profitable, with benefits exceeding KSh 56,769 per hectare (Esilaba et al., 2022). When combined, these findings prove that the sorghum reacts favorably to the reduction of soil acidity.

2.7 Soil Acidity and Aluminum Toxicity in Sorghum Production Systems

Aluminum (Al) is among the commonest components of the earth crust, which is mostly found in the minerals and the oxides of aluminosilicate clays in the soil matrix. These forms are considerably insoluble under neutral to slightly alkaline conditions and have no adverse effects on crop growth. Nevertheless, at lower pH values of the acidic soils, especially those with a pH lower than 5.5, Al becomes more soluble and releases phytotoxic species like Al^{3+} and Al hydroxylated complexes (Al^{3+} and $Al(OH)^{2+}$) into the soil solution (Munyaneza et al., 2024). Below a pH of 5.0, Al hydrolyzes to produce reactive species, which disrupt the division of root cells and membrane integrity. These are also important in the fixation of phosphorus (P), which makes less P available to sorghum and other crops. On the other hand, gibbsite ($Al(OH)_3$) or aluminate ($Al(OH)_4$), which are not toxic and are also immobile to a great degree, make Al insoluble at almost the neutral pH (Munyaneza et al., 2024). Sorghum tolerates the presence of moderate soil acidity in terms of root elongation and nutrient uptake as well. This is a toxicity that is enhanced in soils that are not well saturated with bases and those that lack calcium (Ca^{2+}) and magnesium (Mg^{2+}) that would otherwise buffer the Al solubility and counter its deleterious effects (Tan & Keltjens, 1995). When the soil pH is below 5.5, the hydrogen ions (H^+) are concentrated in the rhizosphere, disrupting the integrity of the membrane of the root, which disrupts the absorption of essential cations, including calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and ammonium (NH_4^+) (Kochian et al., 2004). These disturbances affect the transport of nutrients and absorption of water, which eventually decreases the vigor and yield of sorghum (Munyaneza et al., 2024). One of the worst effects of soil acidification involves toxicity from Al^{3+}. This problem gets worse when the pH drops below 5.0. Al toxicity interferes with the permeability of the cell membranes of sorghum plants. It also disrupts the uptake of key nutrients. At the same time, it increases shortages in P, Ca, Mg, and Mo (Grundon et al., 1987). One of the most detrimental effects of acidification is aluminum (Al^{3+}) toxicity, which is induced at pH < 5.0. The toxic ion Al^{3+} quickly causes sorghum root elongation inhibition, which is evident within hours of exposure, and it specifically affects the root apical part that is sensitive to Al^{3+}, including the meristem, elongation region, and root hairs (Li et al., 2019; Poschenrieder et al., 2008).

2.8 The impact of rainfall on soil fertility

In areas of high rainfall, soils undergo geological evolution resulting in acidity, as bases are relatively easily leached, hence soils are left acidic. It is usually caused by excessive rainfall, which washes nutrients deep down into the subsoil beyond the reach of new roots. When nutrients such as Ca^{2+}, Mg^{2+}, K^{+}, and Na^{+} are leached from the soil, these base cations are removed, and as a result, the ratio of H^{+} to the other elements increases. This decreases the pH of the soil; thus, the soil becomes more acidic. Therefore, a severe lack of basic nutrients in soil leads to soil acidification.

Acid rain is also identified as an important contributory factor to the acidification of soil in certain parts of the world. (Rengel, 2003). 'Clean' rain is usually slightly acid, with a pH of between 5 and 5.6 due to dissolved carbon dioxide (CO_2) and the dissociation of the resultant carbonic acid (H_2CO_3). Soil exposed to such pure rain, but no other acidifying inputs, and receiving no lime, would attain the same equilibrium pH as that of the rain (Goulding, 2016).

2.9 Soil fertility decline from acidification

Researchers have found that about 43% of the world's tropical land is classified as acidic. This includes roughly 68% of tropical America, 38% of tropical Asia, and 27% of tropical Africa. In 48 developing countries, acidic soils span a total of 1.66 billion hectares. Overall, the total area affected by soil acidity reaches around 4 billion hectares (Gemada, 2021). Scott et al. (1999) approximated the total area of topsoils affected by acidity throughout the world to be 3.777 x 10^9 to 3.950 x 10^9 ha and estimated the total area affected by subsoil acidity to be 2.918 x10^9 ha. This implies that almost 30% of the total ice-free land area of the world is prone to hyperacidity and acid-induced constraints. As a result, about 70% of arable land is subjugated by acid soil. It is widely known by researchers that the largest areas of acid soils are in South America, North America, Asia, and Africa. The area of acid soils far exceeds the area under cultivation in most regions, signifying that sizeable areas of acid soils are still under natural forest or grassland vegetation.

2.10 Lime as a strategy for soil acidity amelioration

Soil acidity poses a significant constraint to sorghum productivity, particularly in high-rainfall regions of Kenya and sub-Saharan Africa. Lime application remains the most effective strategy for neutralizing toxic concentrations of hydrogen (H^+), iron (Fe^{3+}), and aluminum (Al^{3+}) ions, which impair root development and nutrient uptake in sorghum (Fageria & Baligar, 2008). By raising soil pH, lime enhances the availability of calcium (Ca^{2+}), magnesium (Mg^{2+}), phosphorus (P), and molybdenum (Mo), while improving sorghum's uptake of nitrogen and phosphorus (Van Straaten, 2007). Locally available phosphate rock (PR) deposits offer a dual benefit: they supply phosphorus and exert a liming effect suitable for correcting soil acidity (Nekesa, 2007). PR-enriched composts have shown comparable yield benefits to chemical fertilizers in sorghum, while also enhancing microbial activity and phosphorus solubilization (Sarr et al., 2020). Lime application further stimulates microbial diversity and enzymatic activity in the rhizosphere, accelerating organic matter decomposition and nutrient mineralization (Adams & Martin, 2015; Wijaya et al., 2025). These microbial processes contribute to the release of fixed phosphorus into plant-available forms, supporting sorghum growth during critical phenological stages.

2.11 Inorganic fertilizers and soil acidification

A projected 65.6 million hectares of the world's acid soils are distributed across the SSA (Sharma et al., 2025), where food insecurity is common. Acid soils are prevalent in Eastern Africa, particularly in the highlands and mid-altitude areas of Kenya, Uganda, Tanzania, and Ethiopia, distinguished by high rainfall (Cameron et al., 2017). Of the acidic soil, Ferralsols constitute around 745 million ha (Mwesige et al., 2024). Kanyanjua *et al.* (2002) and Sileshi et al. (2017) reported that 13% of the total arable land in Kenya is masked by acidic soil, mostly acrisols, ferralsols, and nitisols, with a larger proportion in western Kenya, where over 70% of the sorghum cultivation in the country is undertaken. Nearly 18% of the yield is lowered by soil acidity (Grant, 1981), which confers its enormous influence on sorghum production. Some soils have adequately strong acidity for soluble Aluminum to be toxic for most crop species.

Soil acidification is frequently inevitable in agriculture that relies on either N_2 fixation or cheaper (ammonium-containing) N fertilizers. Tadesse (2024), Fan (2024), Tao (2024), and Zamanian (2024), and Warke (2024) reported that the most important causes of soil acidification on agricultural land are the application of ammonium-based fertilizers and urea, and elemental S fertilizer. For farmers to achieve satisfactory yields and returns to their scarce resources under these soil conditions, they need to use improved soil fertility management that they continually find unaffordable. For this reason, even though soil fertility in most areas of East Africa is low, farmers have not managed to resolve the degenerating trend of soil fertility.

2.12 Constraints of fertilizer use to improve soil fertility

Background information regarding several economic constraints that limit soil fertility has been documented (Debie, 2024; Islam et al., 2024; Kpoviwanou et al., 2024; Selvam et al., 2024; Sufardi, 2024). Further, technical constraints have been emphasized by Kabato et al. (2025) and Wu et al. (2024) as the major limitations that hinder the improvement of soil fertility management. Reports by Sinha *et al.* (2022), IFA *et al*. (2002), Wise (2020), Powlson *et al.* (2016), Vanlauwe et al. (2015), Donovan & Casey (1998), and other researchers have summarized many constraints related to efficient and economical fertilizer use. These include the high cost and limited purchasing power of mineral fertilizers by smallholder farmers, as described by Mwinuka *et al.* (2017) and Negese (2017).

Poor research and extension were singled out by other authors as a longstanding impediment to the integration of technology, productivity, and empowerment of farmers in sub-Saharan Africa (Bamire et al., 2002; Boulestreau et al., 2022; Muluneh et al., 2022). Bamire et al. (2002) pointed out that there was little institutional linkage between research and extension systems, which restricts the access of innovations to the smallholder farmers. Muluneh et al. (2022) highlighted that participatory research, localized extension, and access to training were lacking in Ethiopia and were thus limiting the application of integrated crop management practices. In the study by Nahayo et al. (2017), farmers were not willing to participate in the intensification programs at the national level due to low-quality extension activities and underprovision of inputs. As Shako et al. (2021) indicate, the low rate of digital use on digital extension platforms in Kenya and Uganda is due to the insufficient levels of digital literacy and infrastructure among women and youth. Sileshi et al. (2017) asserted that the existence of decentralized research-extension-farmer-input linkages still compromises the efforts of sustainable intensification, and this necessitates a more strengthened institutional coordination with farmer-led innovation systems. Obsolete fertilizer-use recommendations have been reported by Soropa et al. (2019). Additionally, poor communication to farmers regarding approved fertilizer use appropriate to their emerging situation was observed by Penuelas et al. (2023) and Roy (Penuelas et al., 2023; Roy, 2021). Traditional approaches in farming still prevail, as Kenya's smallholder farmers still use small amounts of fertilizer inputs. This, in turn, leads to decreased profits in maize production coupled with the increase in the prices of fertilizers. The Russia-Ukraine conflict, along with supply chain disruptions, pushed fertilizer prices to jump from Ksh 2,600 to Ksh 6,000 within the 2021-2022 period (Business Daily, 2022). A KSh 3.55 billion government subsidy introduced to reduce fertilizer expenses by the government of Kenya did not improve accessibility because of distribution problems and interference by middlemen (KENAFF, 2023). Farmers started choosing affordable organic farming methods instead of conventional ones, even though organic farming does not achieve the same level of high yields (Business Daily, 2022). Current challenges are reducing both farming output and potential earnings on the farms. These limitations obtain in the sub-Saharan countries of Africa, except for South Africa.

2.13 Effect of low soil pH on Sorghum production

Most sorghum production in East Africa occurs on soils with a pH < 5.5. Mbuvi *et al.* (2017) reported that acid soils cover more than 7.5% of arable land in Kenya and that in some parts, Al saturation is high (4-55%) and drastically affects the availability of phosphorus. Like most field crops, the agronomic performance of sorghum is adversely affected by soil acidity. Mashao and Prinsloo (1994) and Muui (2014) reported the possibility of sorghum being more tolerant to alkaline soils than other grain crops, hence it can be cultivated successfully on soils with a pH (KCl) between 5.5 and 8.5. (Butchee et al., 2012; Enserink, 1995) reported that grain sorghum has traditionally been grown on soils with a pH of >6.5. Aluminum toxicity often occurs in acidic soils and is one of the major abiotic stresses that limit sorghum productivity worldwide. Soil acidity is therefore an important factor in sorghum production, and it reduces yield by about 18% (Dapaah et al., 2003; Nyang'wara & Obanyi, 2003). Most of these soils have high Al saturation (4-55%) and/or low available P (2-5 mg kg^{-1} soil) (MacCarthy et al., 2009), which contribute to low yields. In different experiments carried out by Enserink (1995), Butchee *et al*. (2012), and El Naim (2012), soil acidity reduced grain sorghum yield by 10% at soil pH 5.42 or less. Further research by Duncan *et al*. (1980) observed different grain sorghum genotypes to determine their acid tolerance. The yields of a sorghum grain hybrid grown on a sandy loam soil dropped from 2069 kg ha^{-1} at soil pH 4.8 to 163 kg ha^{-1} at soil pH 4.4. Further, they found that Potassium chloride-exchangeable aluminum levels above 18mg kg^{-1} resulted in yield reductions of 10% or greater. This suggests that with a soil pH of 5.42 or below, liming should be done to ensure that significant yield reductions associated with soil acidity are avoided.

Soil pH is important to plants because of its effect on nutrient availability and the toxicity of related elements or ions. For example, the nutrient phosphorus is most available for plant uptake at pH 6.0 to 6.8. Low crop yields are aggravated by soil acidity, which is associated with aluminum toxicity. The element aluminum, which is not a nutrient but is a component of most soil minerals, becomes increasingly soluble and toxic at soil pH < 5. On highly acidic soils (pH <5.5), the rhizotoxic aluminum species, Al^{3+}, is solubilized, inhibiting root growth and function in the majority of crops (Hajiboland et al., 2023; Munyaneza et al., 2024). It is now widely known that for grain sorghum, as reactive Al concentration increased, the symptoms of Al toxicity also increased (Baligar et al., 1989; Kipsang, 2023; Too et al., 2014) Tan and Keltjens (1995) established that inhibited root development and reduced uptake of N, K, and Mg are attributed to Al toxicity, and that liming a soil with a pH of 4.3 and raising it to pH 4.7 alleviated the Al toxicity. Ohki (1987) studied the relationship between root Al concentration and growth and found the Al critical toxicity level for grain sorghum was 54 mmol kg^{-1} in root tissue dry matter. Later, Magalhaes et al. (2004) concluded that all sorghum genotypes grown at Al saturation above 70% performed poorly. In western Kenya, an Al saturation of 27% stressed sorghum and significantly reduced root and shoot dry weight (Sierra et al., 2003; Wortmann et al., 2009). They also found that the growth and grain yield of sorghum in unlimed soil were very poor, and liming increased grain yield by an average of 35%. Furthermore, grain sorghum plants grown in acid soils may express water stress due to root damage, which can limit their ability to extract water from the soil (Abreha et al., 2022; Abu-Ria et al., 2024; Yahaya & Shimelis, 2022).

2.14 The effect of lime on the production of sorghum in acidic soil

Lime treatment directly addresses these limitations by raising the soil's pH, rendering hazardous Al^{3+} ions nonreactive, and facilitating better nutrient absorption. In addition, it boosts soil nutrient retention and structure by enhancing cation exchange capacity (CEC). The combined effect of all of these is a better root environment and increased crop response to both organic and inorganic treatments.

The recent Soil Acidity and Liming Handbook in Kenya included a thorough report by Esilaba et al. (2023) that detailed the efficacy of lime in managing soil acidity in various agroecological regions of the country. The book demonstrates that applying lime at a rate of 1.5–2.0 t ha^{-1} resulted in a considerable improvement in production levels (e.g., a 131% increase in wheat yields in Uasin Gishu County) and an increase in soil pH from below 5.0 to above 5.5 in several trials. The authors stress liming as a control strategy to avoid negative acidification impacts in order to maximize the potential for fertilizer use and agricultural output in smallholder farming systems. Liming the topsoil layer to neutralize exchangeable Al is the common method of managing acid soils (Ohki, 1987). Numerous writers have emphasized the importance of liming for the treatment of acid soils in Kenya (Bolan et al., 2023; Kanyanjua et al., 2002; Kisinyo, Opala, et al., 2014; Y. Wang et al., 2021). According to Kisinyo et al. (2009) and Esilaba et al. (2023), the use of fertilizers with liming effects or crop germplasm that is resistant to Al toxicity can also enhance crop production in acidic soils with Al toxicity. If the soil pH is lower than the critical level at which grain sorghum was produced. Butchee et al. (2012) suggested liming as a means of raising it.

By precipitating out as inert $Al(OH)_3$, lime (typically calcium oxide or calcium carbonate) raises the soil pH, eliminating harmful Al^{3+}. This reduces exchangeable aluminum in the soil solution, a significant limitation in acidic soils such as Ferralsols and Acrisols, thereby alleviating aluminum toxicity. In Kenyan acid soils, Kisinyo et al. (2014) found that 20% to 45% of the Al saturation was at toxic levels for the majority of crops. The lime treatment efficiently reduced this saturation, promoting root development and nutrient absorption. While lime does lower the solubility of Fe^{3+} and Mn^{4+} at high pH, it does so to a lesser extent than for Al^{3+}. In very acidic soils, there is a risk of Mn toxicity, which liming helps to mitigate by oxidizing Mn^{2+} to less soluble

Mn oxides. Fe is often less limiting, except for severely weathered or waterlogged soils. Excessive liming reduces the availability of Fe and Mn to the point that it causes shortages, especially in sandy soils or those with low organic matter content. It was discovered that phosphate ions were strongly absorbed by aluminum (III), iron (III), and manganese (IV) oxides, which resulted in the precipitation of insoluble complexes and a decrease in the availability of P. Lime indirectly increases the availability of both indigenous and applied phosphorus by lowering the activity of these cations, which in turn lowers the sorption capacity for phosphorus. Earlier studies by Opala (2023) in Western Kenya confirmed that the bicarbonate-extractable P increased and the exchangeable Al decreased significantly with the addition of lime. Lime at a rate of 4 t ha1 was found to maintain a pH above 5.5 for three years, which led to a 40% increase in the amount of P fertilizer that could be recovered. Kenya Soil Acidity and Liming Handbook by Esilaba *et al* (2023) also provides evidence that lime prevents P absorption and increases P availability, particularly in the presence of organic matter or phosphatic fertilizers. Although additional soil modifications like organic and inorganic compounds can be utilized to lower soil acidity, lime is known to have a longer-lasting residual effect on acid soils in comparison (Too et al., 2014).

2.15 Properties, mechanisms, and effectiveness of liming materials in soil acidity management

Liming materials are alkaline soil amendments that are mainly constituted by calcium and magnesium salts in the carbonate, oxide, hydroxide, or silicate form. Their ability to neutralize acidity is expressed as the Calcium Carbonate Equivalent (CCE), and calcium carbonate of 100% purity has a CCE of 100%. Calcitic lime ($CaCO_3$), dolomitic lime ($CaMg(CO_3)_2$), quicklime (CaO), and hydrated lime ($Ca(OH)_2$) will differ according to their reactivity, solubility, and fineness, which will be used to define the agronomic efficacy. Additionally, industrial byproducts, including basic slag ($CaSiO_3$), have been cited as helpful on low-phosphorus soils due to their liming and residual mineral content (Hubbs, 1999). The mechanisms by which liming ameliorates soil acidity are fundamentally chemical. Liming raises soil pH by neutralizing hydrogen ions (H^+) and precipitating toxic aluminum ions (Al^{3+}). When calcium carbonate dissolves in soil water, it releases calcium (Ca^{2+}), bicarbonate (HCO_3^-), and hydroxide ions (OH^-). The OH^- ions combine with available H^+ to produce water, thus decreasing active acidity. Simultaneously, Al^{3+} ions react with OH^- to form insoluble aluminum hydroxide [$Al(OH)_3$], thereby precipitating phytotoxic Al from solution. The following chemical reactions are utilized to represent:

$$CaCO_3 + H_2O \rightarrow Ca^{2+} + HCO_3^- + OH^- \; OH^- + H^+ \rightarrow H_2O \; Al^{3+} + 3OH^- \rightarrow Al(OH)_3 \downarrow$$

By the reactions above, the processes of cation exchange and base saturation are hence increased, resulting in the release of soil nutrient immobilization and enhancing root growth conditions. Liming has a significant effect on the availability of P on acid soils. P is immobilized by Al^{3+} and Fe^{2+} compounds through fixation at low pH, when it is precipitated as insoluble Al–P and Fe–P complexes. Liming by increasing pH and precipitating Al and Fe hydroxides releases bound P, which increases its solubility and availability to plants. Optimal soil pH ranges between 5.5 and 6.5 support phosphorus mobility, whereas over-liming above pH 7 may result in Ca–P precipitation that re-immobilizes phosphorus (Islam et al., 2024; Ylivainio et al., 2024). The contribution of microbial functions to the N dynamics of the soil in terms of nitrogen mineralization and nitrification under acidic conditions is a highly important process to regulate the N dynamics of the soil, especially on the limed soils, which are acidic in nature. Liming is employed to induce an increase in Nitrosomonas and Nitrobacter populations by the increase in ammonium (NH_4^+) to nitrate (NO_3^-) conversions. Liming enhances symbiotic nitrogen fixation by promoting the growth and survival of the rhizobia and nodules at lower levels of pH (Islam et al., 2024; Ylivainio et al., 2024). These impacts translate to higher nitrogen uptake, higher nutrient use efficiency (NUE), and extended crop yield. The estimate of lime requirement (LR) defines the amount of lime to remove exchangeable acidity and raise soil pH to agronomically acceptable values. Buffer pH methods estimate, e.g., the Mehlich equation:

$$LR\ (t\ ha^{-1}) = 16.988 - 2.722 \times pH\_buffer$$

The specific need varies with original soil pH, texture, cation exchange capacity (CEC), base saturation, and aluminum toxicity susceptibility of crops. The central role of liming in soil reclamation and higher agronomic efficiency is confirmed by the current field experiments. Ylivainio et al. (2024) demonstrated that liming of acid soils in Ethiopia resulted in insignificantly increased pH, a smaller amount of poisonous aluminum, increased phosphorus and nitrogen uptake, and increased the grain output of sorghum. Similar complementary evidence in Bangladesh reported such gains in wheat, such as enhanced nutrient response and root strength (Islam et al., 2024). Such evidence supports liming as a necessary intervention in the sustainable management of acidic soils, especially under smallholder systems.

2.16 Fertilizer microdosing

The fertilizer microdosing method, also known as mineral fertilizer hill placement, was developed by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and partners in 1999. It aims to help resource-poor farmers in semi-arid regions of southern Africa by allowing them to use small amounts of fertilizer effectively. Research has shown that even a small application of 9 kg of nitrogen fertilizer per hectare can increase crop yields significantly, with farmers in some areas experiencing productivity increases of 50 to 100%. On-farm trials have further demonstrated that using around 10 kg of nitrogen can boost yields by 30 to 100%.

The microdosing approach was implemented in 2003/2004 with support from organizations like the European Commission and the Department for International Development. Over 160,000 farmers have participated in this initiative, which is now popular among smallholder farmers in countries such as Zimbabwe, Mali, and Mozambique. The technique encourages farmers to invest in fertilizers, thus enhancing agricultural productivity and contributing to more sustainable farming practices. It is considered a climate-smart solution for improving agricultural systems in sub-Saharan Africa.

Research in Eastern and Central Kenya indicates that many farmers apply low amounts of up to 5 kg/ha. Sorghum, which can thrive in less-than-ideal soil conditions, benefits from small fertilizer additions that improve yields. The microdosing technique involves applying precise doses of fertilizer to specific areas, enhancing its effectiveness and reducing waste. This targeted approach improves fertilizer usage, particularly in sub-Saharan regions with erratic rainfall patterns and agricultural challenges.

2.16. 1 The fertilizer microdosing method's inception

Rebafka (1993) claims that the fertilizer microdosing technique, sometimes known as mineral fertilizer hill placement, was initially developed by the International Crops Research Institute for the Semi-Arid Tropics, Sahelian Center (ICRISATSC) in 1999. Ultimately, ICRISAT collaborated with the International Maize and Wheat

Improvement Center (CIMMYT) and the Agricultural Production Systems Research Unit (APSRU) to develop a simulation model (APSIM Agricultural Production Systems Simulator Model) (Keating et al., 2003) that was used to explore the sorts of resource allocation issues that resource-poor farmers in the semiarid regions of southern Africa encounter. The theory suggests that farmers can start investing in small amounts of fertilizer (Rohrbach et al., 2005). The responses to even 25 kg N ha-1 of N fertilizer yielded results that were surprising and contradicted the conclusions of the published soil fertility studies conducted in the region (Mafongoya et al., 2007; Mushayi et al., 1999). For instance, simulations showed that during the rainy season in southern Zimbabwe from 1951 to 1999, farmers may increase their average productivity by 50 to 100% by applying just 9 kg N ha^{-1}. In several regions of Africa, soils are so degraded that a small amount of fertilizer, applied under specific circumstances, may increase crop yield, and in others, a small amount of fertilizer can almost double it (Carberry et al., 2004). At that time, on-farm trials were initiated with farmers using microdosing either alone or in combination with easily available animal manures (Ncube et al., 2007). According to the on-farm trial data, farmers may increase their yields by 30 to 100% by applying around 10 kg N ha^{-1} (Rusike et al., 2006). The microdosing of ammonium nitrate fertilizer was implemented in 2003/2004 with financial support from the European Commission Humanitarian Aid Office (ECHO) and the Department for International Development (DFID). Over 160,000 farmers have participated in the microdosing initiative (Rohrbach et al., 2005; Twomlow et al., 2006). The fertilizer microdosing technique is now more popular among smallholder farmers in Zimbabwe, Mali, Burkina Faso, Niger, Mozambique, and the southern African region (ICRISAT, 2009; Twomlow et al., 2010). Microdosing technology has created a foundation for increased productivity in the future because it teaches farmers to invest more in inputs as they strive to improve returns. Consequently, it acts as a bridge for increased fertilizer use in farmers' fields, potentially leading to more sustainable development(Tabo et al., 2008). Microdosing is acknowledged as a climate-smart technique and a way to improve agricultural systems in sub-Saharan Africa (Murendo & Wollni, 2015).

2.16. 2 The Introduction of Fertilizer Microdosing in Sub-Saharan Africa

The primary objectives of ICRISAT in the 1980s and 1990s were to develop and promote early maturing varieties of sorghum and pearl millet, to increase productivity and reduce the likelihood of drought in Africa's semiarid agroecologies. The positive adoption rate was aided by the new cultivars' early maturity and large grain size. But nonetheless, small improvements in crop yields and productivity were achieved because of the low natural fertility of most soils in the area and farmers' reluctance to take the chance of investing in fertilizers. To predict how different soil fertility technologies would function in areas with high rainfall variability, ICRISAT started utilizing crop simulation modeling in the late 1990s.

2. 16. 3 Microdosing of sorghum in sub-Saharan Africa

For example, research in Eastern and Central Kenya has found that inorganic fertilizer application rates are sometimes as low as 5 kg ha-1 of N, P, and K (Hulugalle & Lal, 1986; Okalebo et al., 2007; Tabo et al., 2008). Because of its high cost, the majority of crops, including sorghum, are frequently grown by small farmers without the use of fertilizers. Because sorghum can withstand poor soil fertility and low pH, as well as live in low soil moisture levels, it may benefit from modest fertilizer additions that boost its yield. The production of small grains is now being increased via microdosing. The approach involves using the appropriate amount of fertilizer in certain areas of widely dispersed crops like sorghum. This greatly enhances the efficacy of fertilizer application.

An internationally recognized low-input but effective approach to nutrient management, fertilizer microdosing delivers tiny yet targeted doses of fertilizer to seed and root zones for resource-limited farmers. In dryland sorghum production, this method minimizes fertilizer waste while maximizing nutrient uptake and yield production. This strategy is most beneficial for semiarid agricultural areas due to sporadic rainfall patterns, as well as cost and distribution difficulties. Twomlow et al. (2010), Yenesew et al. (2024), Kuyah et al. (2021), and Kalida-Singh et al. (2023) have all conducted research that supports the use of fertilizer microdosing. Research from Sub-Saharan Africa has demonstrated that microdosing methods address the area's widespread problem of soil degradation and improve the capacity for sorghum production. Studies conducted in Mali, Niger, and Burkina Faso have revealed that microdosing techniques, which use around 10% less fertilizer than is advised by conventional policies, result in yield gains of 30% to 120% when compared to traditional farming methods (Aune et al., 2017; Kolapo et al., 2024). Microdosing enhances the efficiency with which farmers utilize fertilizers, especially in the arid conditions that characterize the entire sub-Saharan region. Experimental trials carried out in Kenya have shown the benefits of microdosing technology for farmers in arid and semiarid regions (ASALs) in terms of increasing both sorghum returns on investment and production rates.

Measured as returns on fertilizer investments, microdose application improves agricultural efficiency and produces higher productivity gains than conventional blanket approaches, as reported by Beshir (2024) and Kisinyo (2015). In order to encourage both sustainable farming practices and food security, the farming strategy adheres to national policies under Kenya's agricultural policy.

2.17 Fertilizer uptake efficiency (NUE)

Hawkesford *et al.* (2014) defined nutrient utilization efficiency (NUE) as a plant's capacity to effectively utilize mineral nutrients available to it. NUE refers to the link between biomass yield and nutrient or fertilizer usage. The efficiency of fertilizer use by plants depends on the mode of application, as reported by Vanlauwe *et al*. (2010), with hill placement being the most efficient method. Aulakh and Benbi (2008) also reported that management practices that enhance FUE include the proper method (technique) and the right time of fertilizer application, among others. Since fertilizer use efficiency is inversely proportional to fertilizer rates, it follows that the more fertilizer used, the lower the FUE. Karim and Ramasamy (2015) reported that cultural practices (such as micro-dosing and legume intercropping) meant for promoting integrated nutrient management will help to influence savings in the amount of fertilizer applied to the crops and therefore improve fertilizer use efficiency. Other than maximizing profits through a reduced amount of fertilizer use per unit area, this can be achieved through increased yields per unit of fertilizer applied. There is therefore a need for nutrient-use-enhancing cropping techniques sustainable for resource-poor smallholder farmers in western Kenya.

2.18 Agronomic Efficiency in sorghum production

Agronomic efficiency (AE) is a key metric for evaluating the effectiveness of nutrient inputs in sorghum systems, particularly under resource-constrained conditions. AE as provided by Dobermann (2007), quantifies the increase in harvestable grain yield per unit of applied nutrient and is calculated as:

$$AE = (Y - Y_0) / F$$

Where:

- **Y** = yield of the crop with nutrient applied
- $\mathbf{Y_0}$ = yield of the crop without nutrients applied
- **F** = amount of nutrient applied

In sorghum, AE reflects both the recovery efficiency of the applied nutrient and the physiological efficiency with which the crop converts absorbed nutrients into grain. Studies in semi-arid Kenya have shown that AE for nitrogen peaks at moderate application rates (e.g., 6.5 kg N/ha), beyond which diminishing returns are observed due to reduced recovery and increased losses (Nguluu et al., 2023). Genotypic variation also plays a critical role: N-efficient sorghum cultivars such as TTKKIAMA6 and KTIRASTAMMA4 exhibit high AE values (up to 139 kg grain/kg N), even under low-input conditions, making them suitable for nutrient-limited environments.

AE can be enhanced through soil amendment practices that improve nutrient retention and uptake, such as lime application in acidic soils or co-application of organic matter and phosphate rock. Additionally, agronomic interventions like rainwater harvesting and optimized planting density have been shown to improve AE by increasing nutrient recovery and synchronizing nutrient availability with crop demand (Kubiku et al., 2023).

Harvest Index (HI)—the ratio of grain yield to total above-ground biomass—is a critical indicator of physiological efficiency and assimilate partitioning in sorghum (Chakwizira et al., 2023). While agronomic interventions often target total biomass, HI reflects the crop's ability to channel photosynthates toward economically valuable grain. In sorghum, HI values typically range from 0.35 to 0.55, with higher values associated with improved genotypes and optimized management practices (Prihar &

Stewart, 1991). Notably, HI is sensitive to environmental conditions such as planting density, irrigation regime, and temperature during grain filling, yet remains relatively stable across moderate stress levels—making it a robust metric for cultivar comparison (Hammer & Broad, 2001). Recent studies in Kerala, India, demonstrated that zero tillage combined with optimal spacing and nutrient management yielded HI values up to 0.43, underscoring the role of conservation agronomy in enhancing grain partitioning (Badiyal et al., 2024). For acid soil environments in sub-Saharan Africa, where biomass accumulation may be constrained, HI offers a strategic lens to evaluate the effectiveness of soil amendments and genotype selection in maximizing grain output per unit biomass.

2.19 Determinants of NUE

Nutrient use efficiency in sorghum is shaped by both fertilizer inputs and environmental conditions. While inorganic nutrients like nitrogen and phosphorus are essential for grain development, their uptake and utilization depend heavily on factors such as solar radiation, temperature, rainfall, and soil acidity (Giller et al., 2006; Mengel & Kirkby, 1982). Efficient phosphorus use, for instance, often requires adequate nitrogen during early growth stages (Han et al., 2022). Soil, amendments like lime and organic matter, help mitigate acidity and improve nutrient recovery, especially in low-pH soils common to western Kenya (Nekesa, 2007; Van Straaten, 2007). Organic inputs also enhance soil structure and moisture retention, which are critical for nutrient diffusion and uptake under erratic rainfall (Kubiku et al., 2023). Together, these factors underscore the need for integrated nutrient and soil management tailored to sorghum's physiological demands and agroecological context.

Economic analysis of sorghum production under smallholder systems in sub-Saharan Africa often employs partial budgeting approaches that emphasize variable costs and direct returns. In this context, the use of Total Variable Cost (TVC), Gross Income (GI), and Benefit-Cost Ratio (BCR) provides a practical framework for evaluating the profitability of soil amendment treatments on sorghum yield. TVC includes all input costs that vary with treatment—such as fertilizer, seed, lime, phosphate rock, farmyard manure, and labor—while GI is derived from the market value of harvested sorghum grain, typically priced at the farm gate to reflect actual farmer earnings (Gittinger, 1982; Listman, 1999). The BCR, calculated as GI divided by TVC, serves as a direct indicator of economic efficiency, with values greater than 1 denoting profitable intervention. This method aligns with findings from Kumar et al. (2020), who reported a BCR of 1.72 in sorghum seed production systems in India, and Gebisa et al. (2023), who found BCRs of 2.60 and 2.03 for improved sorghum varieties Assosa-1 and Adukara, respectively, in Ethiopia. By focusing on variable costs and excluding fixed assets, this approach supports decision-making under resource constraints and reflects the realities of smallholder farmers. Accurate pricing of inputs and outputs—based on recent transactions and verified through local sources—is essential to ensure that the analysis mirrors field conditions and farmer experiences.

CHAPTER THREE

MATERIALS AND METHODS

The study was carried out in four counties of western Kenya, which were previously reviewed and identified as areas affected, but soil fertility constraints were considered in the present study. Secondary background review was undertaken as outlined in section 3.2.1 for Siaya (Siaya) and Kakamega (Koyonzo) for lime and microdosing experiment (Figure 1). The experiments were carried out in three seasons of 2016-LR, 2017-LR, and 2018-LR long rains with similar treatments repeatedly. In each of the experiments, an RCBD design was adopted. Some characteristics of the experimental sites are presented in Table 3.1. and 3.2. Generally, all sites experienced warm climates and a moderate rainfall pattern. A reconnaissance sampling of soils identified in the exploratory soil map of Kenya (Sombroek et al., 1982) for the purposes of identifying acidic and non-acidic soils was conducted in 2016-LR as a prerequisite for site selection. The soil was sampled from representative sites at 0-20 cm depth for analysis of soil parameters summarized in Table 3.2.

The characteristics of the study sites are summarized in Table 3.1.

Table 3.1: Comparative overview of study sites

Parameter	**Siaya (Siaya)**	**Kakamega (Koyonzo)**
Latitude	0° 15' N	~0° 16' N
Longitude	34° 20' E	~34° 45' E
Altitude (m a.s.l)	1140–1400	~1585
Annual Rainfall (mm)	800–1200	1280.1–2214.1
Rainfall Pattern	Bimodal (2 wet seasons)	Bimodal, evenly distributed; erratic in 2nd season
Temperature Range (°C)	15–17 (low); 27–30 (high)	18–29
Temperature Variation	Distinct high and low ranges	Hottest: Jan–Mar; Coolest: Jul–Aug
Humidity (%)	62%–76% (monthly averages)	Average: 67
Soil Type	Orthic Ferralsols	Orthic Acrisols
Study Focus	Micro-dosing and liming	Micro-dosing and liming

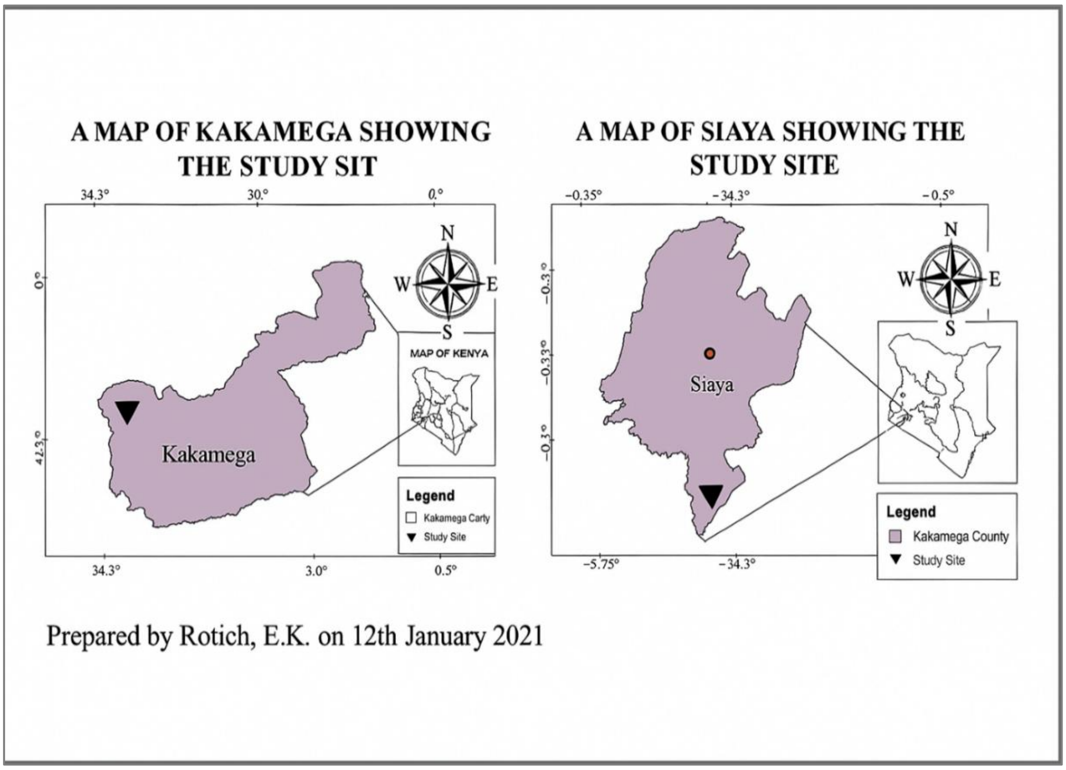


Figure 3.1: Map showing experimental sites in Western Kenya.

Source: API Data management- 2016, 2017, and 2018

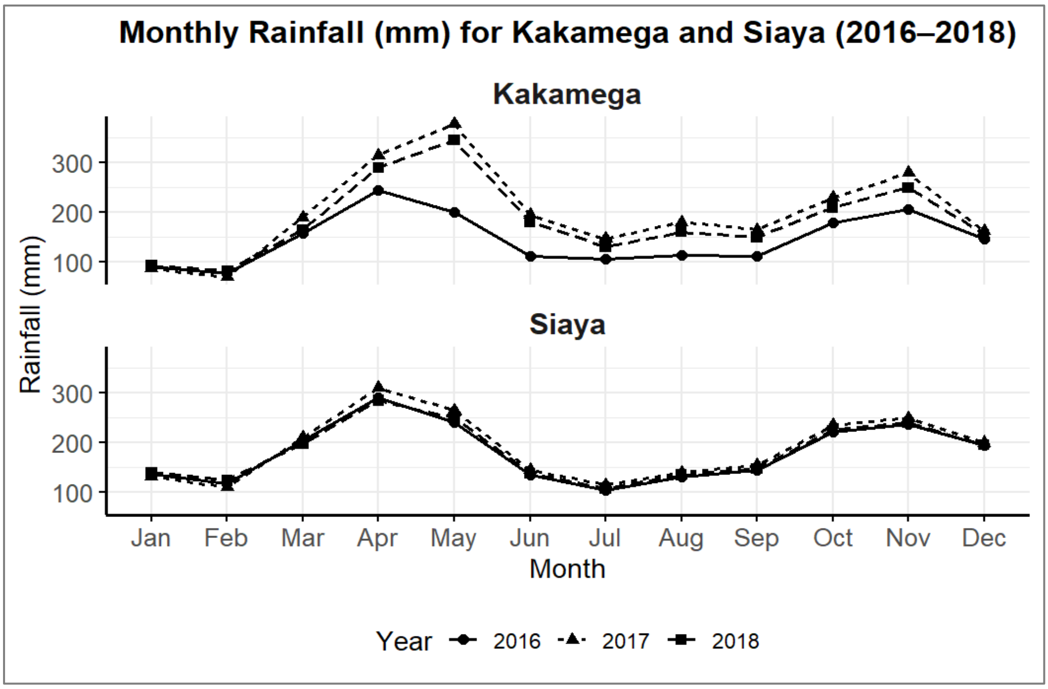


Figure 3.2: Rainfall distribution across the sites during the cropping periods

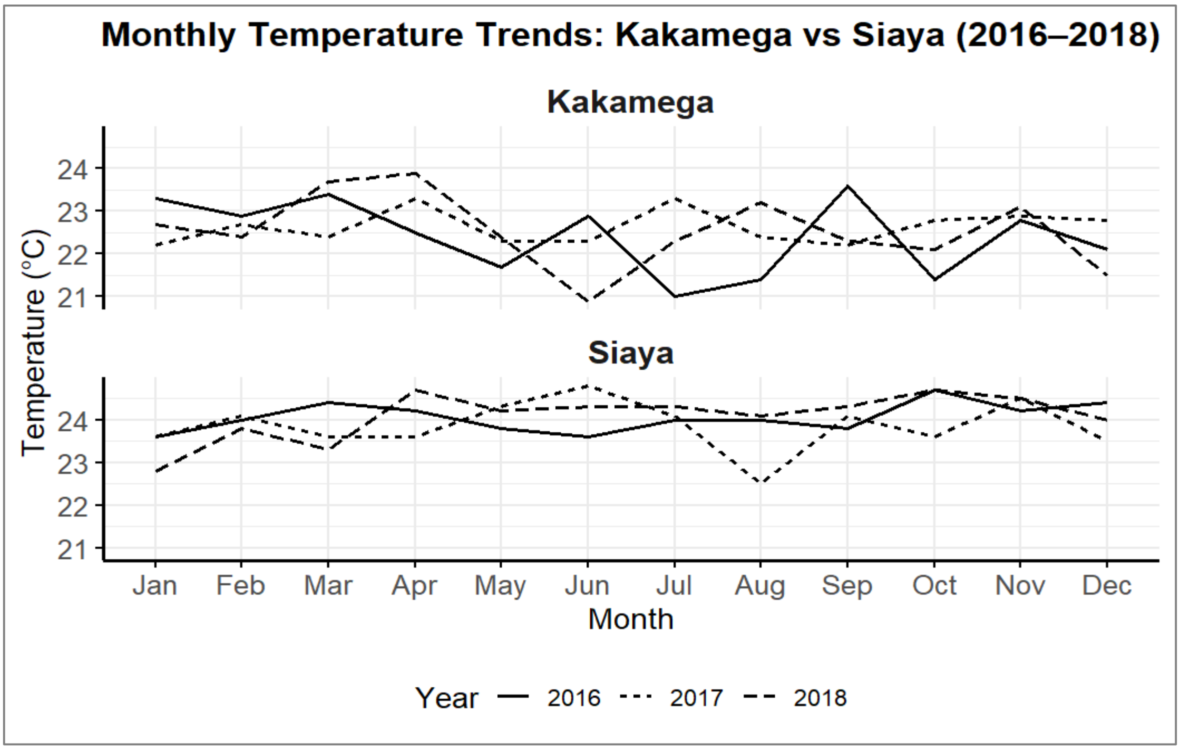


Figure 3.3: Monthly temperature across experimental sites during the cropping period

Table 3.2: Initial soil characteristics of the study sites

Site	pH (H2O)	SOC (%)	N (%)	Al^{3+} (mg kg^{-1})	P (ppm)	K^{+} Cmol kg^{-1})	Sand (%)	Clay (%)	Silt (%)	Texture class
Siaya 2	4.8 ± 0.18	1.4 ± 0.26	0.09 ± 0.02	1.57 ±0.08	5.4 ± 1.2	0.05 ± 0.02*	26 ± 4	62 ± 5	12 ± 3	Clay*
Siaya 1	4.6 ± 0.20	1.8 ± 0.31	0.12 ± 0.01	1.81 ±0.10	3.9 ± 0.9	0.05 ± 0.01*	24 ± 3	60 ± 5	16 ± 4	Clay
Kakamega	4.9 ± 0.22	1.9 ± 0.34	0.22 ± 0.05	1.87 ±0.12	3.7 ± 0.8	0.05 ± 0.01*	50 ± 7	28 ± 4	22 ± 5	sandy clay loam

3.2 Objective 1: To evaluate the effect of lime and fertilizer N and P microdosing on selected soil chemical properties

3.2.1 Secondary data review

A secondary review of existing literature was conducted to establish the justification for the proposed fieldwork, focusing on the current state of soil fertility in the study area (Figure 3.1). This process entailed analyzing findings from previous soil fertility assessments carried out in Western Kenya counties that were relevant to the objective of the current study. The gap in the sustainability of fertilizer use for optimized yield and soil fertility maintenance informed the microdosing approach. The decision to use lime for soil amendment was guided by previous findings as summarized in Table 3.2. Unlike with fertilizers, where recommendations have been made for specific crops countrywide, it is advisable to carry out a soil test and determine lime requirement, and broadcast 2-4 t ha^{-1} to give optimum pH for most crops as detailed by Esilaba *et al.* (2023). Due to this background, lime requirement was estimated using the Single Addition of $Ca(OH)_2$ method as summarized in Appendix I. There are no similar records on lime combined with microdosing experiments for sorghum productivity in western Kenya, which led researchers to choose the present study. Fertilizer microdosing was decided based on the estimated recommendations from farm management information in the Farm Management- Handbook of Kenya (Jaetzold, 2010).

3.2.2 Initial site characterization

To establish soil chemical and physical properties and lime requirement for Kakamega and Siaya sites, soil sampling was carried out in each site.

Pre-trial sampling: Following a zig-zag procedure, five composites per site were collected within the demarcated experimental plot before the layout, then mixed and separated into 3 samples of 0.5kg each. Every site, therefore, had three subsamples to represent three replications. From the three sites, there were a total of 9 samples.

Post-harvest soil samples were done randomly from the demarcated experimental plots following a zig-zag procedure. Soils were then extracted by using a soil auguring at soil depths of 0-30cm. Three composites of nine subsamples were done per replicate in each site to eliminate variability. This gave a total of eight samples per replicate and a total of twenty-four samples per site. Each sample weighed 0.5 kg, making approximately 12 kg from each study site, which were Kakamega, Siaya Site 1, and Siaya Site 2, all being farmers' farms. In total, fifteen samples were submitted to the laboratory for selected chemical (pH, P, N, SOC, exchangeable acidity) and physical (texture and bulk density) parameters as discussed in section 3.13.

3.2.3 Soil and plant tissue analysis

Soil sampling was conducted at the initiation of the first season's field trials, followed by a second sampling at the point of sorghum harvesting. This was repeated at every experimental site and for each of the three cropping seasons. At the start of the trial, it was determined that changes in the soil nutrient concentratio n at harvesting were caused by treatment effects.

At both study sites, laboratory analysis of selected soil fertility parameters was carried out using standard procedures described next.

3.2.4 Soil pH (H_2O) Determination at a 1:2.5 Soil-to-Water Ratio

To measure soil pH, 20 grams of air-dried soil (sieved to 2 mm) were combined with 50 ml of distilled water, maintaining a 1:2.5 soil-to-water ratio. The mixture was stirred thoroughly for two minutes and then left to settle for 30 minutes. After this resting period, the suspension was stirred again for two minutes, and the pH was recorded using a calibrated pH meter.

3.2.5 Olsen Extractable Phosphorus (mg kg^{-1})

Available soil phosphorus in soil was determined using the Phosphomolybdate method, earlier described by Olsen (1954) and later outlined by Okalebo et al. (2002). In this procedure, phosphate ions react with ammonium molybdate to form a phosphomolybdate complex, which is subsequently reduced by ascorbic acid to yield a blue-colored complex. The intensity of this blue coloration corresponds to phosphorus concentration, measured spectrophotometrically at 880 nm. Phosphorus levels in parts per million (ppm) are determined by comparing absorbance readings against a standard calibration curve, from which sample concentrations are derived.

3.2.6 Total Nitrogen (N) Determination

Analysis of total nitrogen content in soil or plant tissue samples was done using the micro-Kjeldahl digestion method followed by colorimetric detection, as adapted from Okalebo *et al.* (2002). Approximately 0.3 g of finely ground, oven-dried sample was placed into clean digestion tubes. Into this sample, a digestion mixture was added, including reagent blanks for quality control, after which the samples were digested at 110 °C for one hour. After cooling, hydrogen peroxide was added incrementally to promote complete oxidation. The temperature was then increased to 330 °C and maintained until the solution became clear, indicating that the digestion was complete. Once the digest was cooled, distilled water was added, and the solution brought to a fixed volume (50 ml), mixed thoroughly, and allowed to settle. A clear aliquot from the supernatant was then used for nitrogen analysis.

3.2.7 Total organic carbon (%) content of soils

Walky and Black's (1934) method of oxidation as described by Okalebo et al., (2002) was used to determine soil total organic carbon. This procedure involves the complete oxidation of organic carbon using an acid (H_2SO_4) dichromate solution. Excess or unreacted dichromate (Nelson & Sommers, 1996) was determined by titration using ferrous ammonium sulfate. The endpoint is noted by the colour change from greenish to brown, and the titer is used to calculate organic carbon after making the blank correction.

3.2.8 Exchangeable Acidity Determination

To assess exchangeable acidity, an unbuffered 1M potassium chloride (KCl) extraction method was used. A 10 g portion of air-dried soil was mixed with 25 ml of 1M KCl solution and shaken for 10 minutes using a reciprocal shaker. The mixture was allowed to settle for 30 minutes, after which filtration was done. The soil was further leached with five successive 25 ml portions of 1M KCl. The filtrate was titrated with a 0.1M sodium hydroxide (NaOH) to quantify the exchangeable hydrogen (H^+) and aluminum (Al^{3+}) ions present in the extract.

3.2.9 Phosphorus in plant samples

After sulfuric acid digestion and the addition of a catalyst, plant tissues were used to determine the value of total P in the tissue. The process centers on oxidation of organic material, which results in inorganic, soluble phosphate. Using the phosphomolybdate colorimetric method, the absorbance (blue color level) is observed at an 880 nm wavelength setting on a spectrophotometer. The mean blank reading is taken away from the sample reading to make a blank correction. An absorbance versus standard P concentration graph is created, and from it, the solution P concentration in samples is identified. The results from the nutrient analysis were used to find out how much nutrients the plants had absorbed.

3.2.10 Soil Bulk Density and Total Porosity

A cylindrical core sampler with an internal radius of 2.5 cm and a height of 5.0 cm was used to assess soil bulk density, following the approach of Ngome *et al.* (2011). The empty core was first weighed using an electronic balance to obtain its mass (Mo). Soil samples were then collected from the 0–30 cm depth in each plot. The fresh (moist) soil mass was calculated by subtracting the core's tare weight from the total weight of the core plus moist soil. To determine the dry mass (Ms), the samples were oven-dried at 105 °C to constant weight. The water content was estimated by the difference between moist and dry mass, and bulk density was calculated using the oven-dry mass and the volume of the core. Total porosity was later derived from the bulk density and particle density values.

3.2.11 Particle Size Analysis

Using the hydrometer method, the distribution of soil particles was determined as set out by Oklalebo *et al.* (2002). First, the air-dried soil was separated into its main particle groups: sand (2.00 to 0.05 mm), silt (0.05 to 0.002 mm), and clay (smaller than 0.002 mm) particles. It happens because certain particles move upward through water faster, following the rules of Stokes' Law. It is assumed that the particles have a spherical shape of a sphere with a specific gravity of 2.65. Flow rates of particles depend on their size, the temperature of the liquid, and viscosity, so sample measurements are adjusted for temperature. Based on the composition of each soil fraction, each sample was assigned a class with respect to soil texture.

3.2.12 Experimental design and field layout

This study was set out in Siaya (Siaya County) and Koyonzo (Kakamega County), where soil pH is below 5.5 and requires liming. The experiment was laid out in a randomized complete block design (RCBD) with three replications with plot sizes of 3 X 3.5m. The lime-microdosing study evaluated eight treatments that involved a combination with and without lime treatments (0 and 4 t ha^{-1}) with four nitrogen and phosphorus application levels: 0 kg N ha_{-1}+0 kg P ha_{-1} (N_0P_0-Absolute control), 18.8 kg ha^{-1} N + 6.5 kg ha^{-1} P ($N_{18.8}P_{6.5}$), 37.5 kg ha^{-1} N + 13 kg ha^{-1} P ($N_{37.5}P_{13}$), and 75 kg ha^{-1} N+26 kg P ha^{-1} (Table 3.3). The treatment descriptions are summarized in Table 3.3, and the field layout is summarized in Figure 3.4.

Table 3.3: Treatment description for lime-micro-dosing experiment

Lime (t ha^{-1})	Nitrogen and Phosphorus combination (kg ha^{-1})	Designation
0	0 Nitrogen+0 Phosphorus	$L_0N_0P_0$
0	18.8 Nitrogen+6.5 Phosphorus	$L_0N_{18.8}P_{6.5}$
0	37.5 Nitrogen+13 Phosphorus	$L_0N_{37.5}P_{13}$
0	75 Nitrogen+26 Phosphorus	$L_0N_{75}P_{26}$
4	0 Nitrogen+0 Phosphorus	$L_1N_0P_0$
4	18.8 Nitrogen+6.5 Phosphorus	$L_1 N_{18.8}P_{6.5}$
4	37.5 Nitrogen+13 Phosphorus	$L_1N_{37.5}P_{13}$
4	75 Nitrogen+26 Phosphorus	$L_1N_{75}P_{26}$

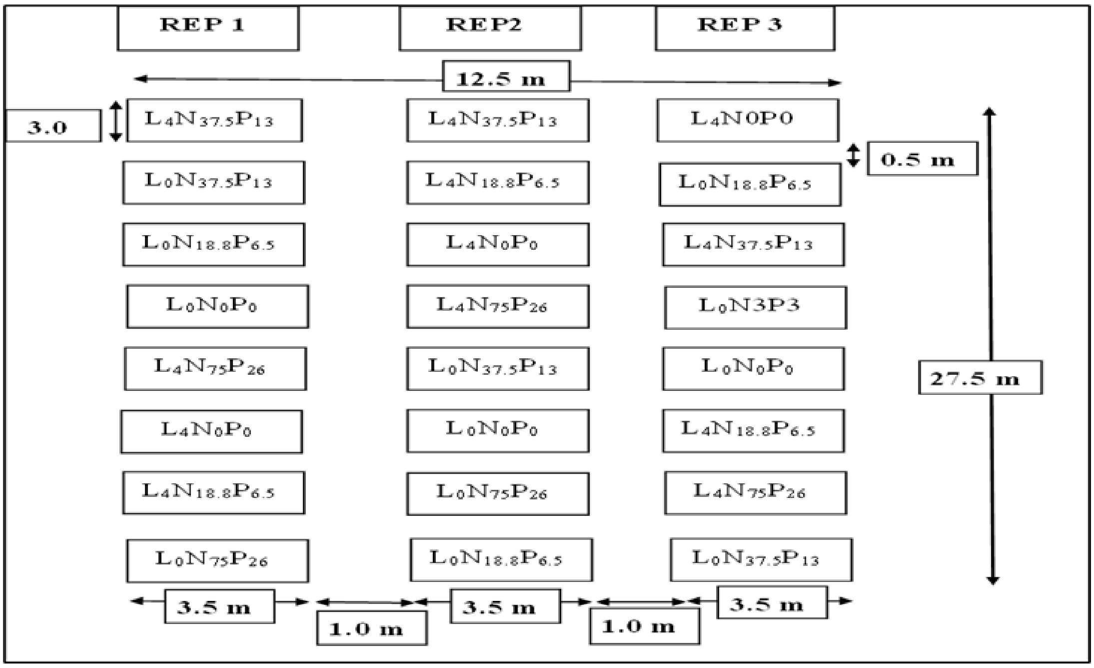


Figure 3.4: Field layout of fertilizer microdosing and liming experiment in Siaya and Kakamega

3.2.13 Experimental model used in microdosing experiment

Analysis of variation was carried out to determine the influence of lime and fertilizer doses (independent variables) on growth, yield, and soil parameters (dependent variables). Where significant differences were observed, post hoc analysis was conducted with Tukey's Honestly Significant Difference (HSD) test to identify significant differences between treatment means after data collection for effective interpretation of lime and nutrient microdosing effects. The following model was then used:

$$\mathbf{Y_{(ijk)} = \mu + \tau_i + \varphi_j + (\tau\varphi)_{ij} + \beta_k + \varepsilon_{(ijk)}}$$

Where:

$Y_{(ijk)}$ = Observed response under the *i-th* lime level, *j-th* fertilizer rate, and *k-th* block

μ = Overall mean

$\boldsymbol{\tau_i}$ = Fixed effect of the *i-th* lime level (i = 1, 2)

$\boldsymbol{\varphi_j}$ = Fixed effect of the *j-th* fertilizer level (j = 1, 2, 3, 4)

$\boldsymbol{(\tau\varphi)_{ij}}$ = Interaction effect between lime and fertilizer levels

$\boldsymbol{\beta_k}$ = Random effect of the *k-th* block (k = 1, 2, 3)

$\boldsymbol{\varepsilon_{(ijk)}}$ = Random error term, assumed to be normally distributed with mean zero and constant variance

This model was set to account for the main effects of fertilizer (τi), lime (βj), and their interaction ($(\tau\beta)ij$), including the random effects of blocks (γk) and error (ϵijk). By randomly allocating treatments within blocks, it is possible to determine whether variations in outcomes are due to the treatment effects or to external influences.

3.2.14. Field and laboratory data analysis

All data were analyzed using R-4.3.2 for Windows. Analysis of variance (ANOVA) was done for yield, soil nutrients, and crop nutrient uptake for all seasons. Where significant, treatment means were separated by Tukey's HSD Test for multiple comparisons at $p \leq 0.05$. Subsequently, step-wise regression analysis was done to obtain average responses and was further used to produce corresponding visual response curves. For micro-dose experiments, standardized parameters were obtained by fitting the model on a standardized version of the dataset. Approximation of the Wald t-distribution was used to calculate 95% Confidence Intervals (CIs) and p-values. Pairwise comparisons were done using independent-samples t-tests, corrected with Holm's sequential Bonferroni procedure. Further, Pearson's product-moment correlation between treatment responses was performed, and the effect sizes were labelled following Funder and Ozer (2019) recommendations.

3.3 Objective 2: To determine the influence of lime–fertilizer combinations on sorghum yield components and physiological performance

3.3.1 Seedbed preparation and planting

Planting was done at Siaya and Koyonzo, in the long rains of 2016-LR, 2017-LR, and 2018-LR. No fertilizer was applied to the control experiment. Field layout was set up one month before the onset of planting, upon which lime was applied to lime-treated plots. This was done by broadcasting 4.2 kg of lime per plot size of 10.5m^2. Lime was then incorporated into the soil using a hand hoe. Early lime application was necessary to allow it to react and reduce acidity in the soil before planting. Fertilizer doses were applied at planting as per the treatment description in Table 3.3. The remaining N was applied six weeks after planting (WAP) as top-dressing. Fertilizer was mixed with soil in the planting hole during sowing, and the top dressing was applied around the base of the growing plants. Weeding was done manually, twice in both experiments. To protect the crop from stalk borer (*Buseola fusca L.*) damage, Beta-cyhalothrin (Bulldock GR 0.05) pesticide was used at a rate of 6 kg ha^{-1} by applying it in the whorl of each sorghum plant after thinning. Sorghum heads were harvested when plants were physiologically mature.

During harvesting, the four central rows of each plot were selected to avoid edge effects. Sorghum within the common effective area of 4.2 m^2 was used. All above-ground sorghum biomass (including stem, leaves, and panicle) at the base of each plant was cut. Immediately, the weight of the total fresh biomass in the field was taken using a digital balance. The total fresh weight per plot was taken. From the harvested material, 5 representative plants were selected, placed in a well-ventilated and clean carrier bag, and labeled properly. The samples were dried in a greenhouse for over 72 hours. Fresh and dry weights of the subsamples were recorded for the calculation of dry biomass yield.

3.3.2 Total Grain yields and crop components (t/ha) determination (Calculation)

Grain and the relevant crop components were measured using harvests from a 4.2 m^2 plot. The values were used to estimate per-hectare output (t/ha), since a hectare is 10,000 m^2. Calculation of grain yield was performed using the formulae:

1. Yield plot-1 = (Total fresh weight × Sample dry weight)/Sample fresh weight (1)

2. Grain yield (t/ha) = [Grain yield/plot (g) × 10,000 m^2]/Effective area (m^2) harvested.

Effective area = harvested portion of the plot, less the guard rows and plants at the end of each row.

3. Nutrient uptake (kg/ha) =Nutrient content × Dry mass production (kg/ha)/ 100

Leaf sampling done at silking was used to determine the amount of nitrogen (N) and phosphorus (P) uptake in sorghum. In each plot, twelve plants of sorghum were randomly chosen, and any dusty or soil-contaminated leaves were avoided. Any soil or dirt stuck on the leaves was avoided. The ears were first air-dried in a greenhouse and then ground to a fine powder for nutrient testing. For the analysis of grain N and P, ground sorghum seed samples were digested using a mixture comprising sulfuric acid, hydrogen peroxide, selenium powder, and lithium powder. Nutrient concentrations in the resulting digests were analyzed following the standard procedures described by Okalebo *et al.* (2002). The nutrient concentration data from the leaf samples were used to compute the total nutrient uptake by the sorghum crop.

3.3.3 Analysis of sorghum grain N and P contents

Nitrogen (N) and phosphorus (P) concentrations in sorghum grain were determined from digested ground grain samples, as previously described. Total nitrogen content was converted to crude protein by applying a standard conversion factor of 6.25 (i.e., protein = TN × 6.25), following the Micro-Kjeldahl method outlined by AOAC International (2000).

3.3.4 Percentage grain yield increase over control

This is the ratio of the net increase in grain yield due to fertilization relative to the total grain yield from the unfertilized plot. This parameter is computed as: Percentage Yield Increase Over Control = (Treatment Yield−Control Yield/ Control Yield) ×100

3.3.5 Nutrient Use Efficiency

The nutrient use efficiency (NUE) could be represented as units of fertilizer application per yield or in terms of fertilizer application recovery. Nutrient use efficiency (NUE) is an important concept in crop production system analysis.

3.3.6 Harvest index

Harvest index is the ratio of the crop economic yield (grain yield) to the total crop yield at harvest (grain and Biomass yields). Harvest index (HI) of both sorghum and cowpea crops was calculated by the method of Bange *et al.* (1998). It is obtained by the formula, HI = Economic (grain) yield/Total (grain and biomass) crop yield

3.3.7 Agronomic efficiency

Agronomic efficiency (AE) is the ratio of the net increase in grain yield due to fertilization relative to the total amount of fertilizer applied. The AE of applied fertilizer to sorghum was calculated as described by Dobermann (2007). The formula used was:

AE = amount of grain yield from an N or P fertilized plot - amount of grain yield from an unfertilized plot/amount of N or P fertilizer applied.

3.3.8 Nitrogen and phosphorus uptake

The N, P, and K uptake in sorghum grain and stover was calculated as N or P or K uptake (kg ha-1) =% N or P yield (their content as determined in either grain or stover) */Yield * 100

The Nyadundo 1 sorghum line was grown in all the microdosing experiments in all the sites. This sorghum variety is red-seeded in color and is the most preferred by women exclusively in terms of grain color, ease of harvesting and threshing, and also due to its aesthetic beauty on their farms. Nyadundo 1 is an early maturing variety attaining 50% flowering at 57 days and is also tolerant to drought and Striga and can withstand some of the diseases (Gudu et al., 2012). It is the most sought-after among the top new varieties, although it is not the highest yielding (2233 kg ha^{-1}) among the counties. However, it is a short, red-seeded variety preferred by women exclusively.

3.4 Objective 3: To establish relationships among soil chemical properties, sorghum performance metrics, and economic outcomes.

Sorghum performance was analyzed in relation to soil chemical properties by looking at how different traits of treated soils affect plant performance, yield, and yield efficiency. Lime application and the effects of lower fertilizer rates on sorghum were studied through a field experiment in Western Kenya. Soil chemical parameters assessed at harvest included Soil pH, Exchangeable aluminum (Al^{3+}), Available phosphorus (P), Total nitrogen (N), Soil organic carbon (SOC), and C: N ratio. Sorghum performance indicators included: Plant height, Number of tillers, Biomass yield, Grain yield, Harvest index (HI), Agronomic efficiency (AE), and Nutrient uptake efficiency (NUE). Sampling and analysis of the soils were done as described in section 3.2.2. Crop data were collected using both field observations and after the harvest was completed. The strength and direction of linear links between individual soil features and the performance of sorghum were analyzed using r values. All data were tested for normality using the Shapiro–Wilk test and for homoscedasticity, a requirement for parametric correlation analysis, before any analysis. The Pearson correlation coefficient was computed using the formula:

$$\boldsymbol{r} = \frac{\sum(Xi - \bar{X})(Yi - \bar{Y})}{\sum(Xi - \bar{X})^2 \cdot \sum(Yi - \bar{Y})^2}$$

Where:

$\mathbf{X_i}$ and $\mathbf{Y_i}$ represent individual observations of soil and plant parameters, respectively

$\bar{\mathbf{X}}$ and $\bar{\mathbf{Y}}$ are the respective sample means

r denotes the correlation coefficient

The interpretation of correlation strength followed the guidelines proposed by Funder and Ozer (2019), which suggest more conservative thresholds suitable for field-based experimental research:$|r| < 0.10$ → Trivial; $0.10 \leq |r| < 0.20$ → Small; $0.20 \leq |r| < 0.30$ → Medium, and $|r| \geq 0.30$ → Large. This framework was adopted to ensure a realistic interpretation of effect sizes in the context of environmental and agronomic variability. Relationships classified as "large" were considered meaningful and potentially actionable for agronomic recommendations. All tests in the study used a significance value of 0.05 ($p \leq 0.05$), and highly significant findings were recorded at $p \leq 0.01$. Based on this framework, only soil factors with the biggest effects were taken into account for giving farming advice. The analysis determined which soil procedures, such as using lime and smaller amounts of fertilizer, were most needed for each site. Moreover, the study results justified why integrated soil management makes sense for smallholder sorghum farming.

3.5 Objective 4: To evaluate the economic efficiency of lime–fertilizer combinations in enhancing sorghum productivity

Input and output prices were collected locally and used to analyze the profitability of the intercrop systems. The amount of material, input costs, and harvested yields were systematically documented for gross margin purposes.

To determine the cost of lime and fertilizers for use in Kakamega and Siaya experiments, input costs were established from agrochemical dealers.

The cost variables used here were common with prevailing prices in the local markets in Kenya during 2016. Sorghum was available for KShs 50 per kilogram. These are common farm-gate prices obtained in regional markets during the cropping period. A normal bag of 50 kg NPK fertilizer sold at KShs 3,000, in line with the wholesale prices by agro-dealers in Uasin Gishu and surrounding counties. Labour was paid KShs 236 per person-day. This was a normal casual labour rate for work in the fields, like planting, weeding, and harvesting.

Koru farm lime is an amendment material used locally as a by-product of the thermal process of calcium carbonate ($CaCO_3$), which is mainly composed of calcium oxide (CaO). Its application in modifying soil pH makes it agronomically sound because it is highly reactive, and thus it neutralizes the soil acidity in a short time. This was applied a month before the onset of planting. 6kg per plot was applied, translating to 4t/ha. On application, CaO mixes with the moisture of the soil to create calcium hydroxide

($Ca(OH)_2$), which practically increases pH. Koru lime is economically reachable by the smallholder farmers, selling at around KShs 500 per bag of 50kg, and the production of the same locally gives it regional availability at minimal transport expenses.

Economic analysis was done mainly by gross margin analysis. In the analysis, costs were assessed by dividing gross income by total variable costs (Gross Income – Total Variable Costs), using the approach discussed by Johnson (1990). All of the agricultural activities were analyzed, one by one, so that all input-related costs were captured properly. The benefit-cost ratio (BCR) was used to find out how much was returned for every shilling used in the business (BCR = GM ÷ TVC). More efficient systems were indicated when the BCR increased to or above 2. The study used break-even analysis to find out what product price is needed to meet input expenses. Economic return was calculated mainly by using grain yield as the key indicator in gross margin analysis.

CHAPTER FOUR

RESULTS

Objective 1: To assess the effects of lime and NP fertilizer rates on selected soil chemical properties of acidic soils in western Kenya.

4.1 Effect of liming and fertilizer doses on soil pH as indicated by H^+ concentrations

Across all three sites, applying lime at a rate of 4 t ha^{-1} led to a clear decline in soil hydrogen ion concentration, suggesting a strong pH increase (refer to Table 4.1). In Kakamega, lime alone brought about a 59.65% reduction in [H^+], while combining lime with fertilizer treatments—specifically $N_{37.5}P_{13}$ and $N_{75}P_{26}$—resulted in even greater decreases of 66.28% and 76.36%, respectively. There was a similar effect at Siaya Site 1, where all treatments decreased [H^+] by varying amounts. At Siaya Site 2, using only lime reduced [H^+] by 38.22%, with only slightly less reduction observed when lime was combined with $N_{37.5}P_{13}$ (38.18%) and $N_{75}P_{26}$ fertilizer doses (38.50%). Where fertilizer was spread without lime, we measured a much smaller reduction in H^+ levels. Kakamega achieved a drop of 7.63% for $N_{37.5}P_{13}$ and 11.38% for $N_{75}P_{26}$, while the changes at the Siaya sites remained very low. The findings indicate that either lime or a combination of lime, nitrogen, and phosphorus fertilizers strongly reduced the soil's acidity. Big improvements were seen when lime alone or in combination with fertilizers was used, showing how significant this is for acidic soil. However. Fertilizer alone did not raise or reduce soil pH significantly.

Tukey's HSD post hoc (Appendix I) showed that lime addition increased mean soil pH to as high as 6.19, in Siaya 2 site in 2017-LR and 2018-LR, where the initial soil pH was 5.50 and

Table 4.1: Main and interaction effects of lime and fertilizer doses on percent change in soil pH and P (±SE) compared to control (L0+N0P0) in the experimental sites during the cropping periods

		----------------- KK ----------------			---------------- SY1 ------------			------------- SY2 ------------		
Soil pH		Estimate (±SE)	% Change	Signif.	Estimate (±SE)	% Change	Signif.	Estimate (±SE)	% Change	Signif.
	Constant (No Lime, N_0P_0) (Control)	4.99			5.13			5.17		
	4t Lime ha^{-1}	5.39 ± 0.11	↓ 59.65 ± 7.1	***	5.54 ± 0.12	↓ 61.19 ± 7.8	***	5.38 ± 0.09	↓ 38.22 ± 4.5	***
	$N_{18.8}P_{6.5}$	3.38 ± 0.10	↑ 4.88 ± 6.4		3.51 ± 0.11	↑ 7.45 ± 7.6		3.40 ± 0.09	↑ 6.60 ± 4.2	***
	$N_{37.5}P_{13}$	3.17 ± 0.11	↓ 7.63 ± 7.6	*	3.27 ± 0.12	↓ 3.33 ± 7.6		3.14 ± 0.09	↓ 3.67 ± 4.2	
	$N_{75}P_{26}$	3.08 ± 0.11	↓ 11.38 ± 7.6	**	3.18 ± 0.12	↓ 5.65 ± 7.6		3.07 ± 0.09	↓ 4.90 ± 4.2	
	4t Lime + N_0P_0	5.05 ± 0.14	↓ 48.74 ± 13.0	**	5.38 ± 0.15	↓ 56.42 ± 13.4	**	4.89 ± 0.11	↓ 27.69 ± 7.5	***
	4t Lime + $N_{37.5}P_{13}$	5.64 ± 0.14	↓ 66.28 ± 13.0	***	5.52 ± 0.15	↓ 64.14 ± 13.4	***	5.38 ± 0.11	↓ 38.18 ± 7.5	***
	4t Lime + $N_{75}P_{26}$	5.87 ± 0.14	↓ 76.36 ± 13.0	***	5.59 ± 0.15	↓ 65.65 ± 13.4	***	5.40 ± 0.11	↓ 38.50 ± 7.5	***
Soil P	Constant (No Lime, N_0P_0) (Control)	3.26 ± 0.350	—	***	2.98 ± 0.360	—	***	2.59 ± 0.458	—	***
	4t Lime ha^{-1}	1.97 ± 0.313	↑60.4%	***	1.03 ± 0.322	↑34.6%	ns	3.16 ± 0.409	↑122.0%	***
	$N_{18.8}P_{6.5}$	0.35	—	ns	0.43 (ns)	—	ns	0.75	—	ns
	$N_{37.5}P_{13}$	0.87 ± 0.443	↑26.7%	*	0.71 (ns)	↑23.8%	ns	0.59	↑22.8%	ns
	$N_{75}P_{26}$	1.66 ± 0.443	↑50.9%	***	1.15 ± 0.456	↑38.6%	**	1.99 ± 0.579	↑76.8%	***
	4t Lime + N_0P_0	0.59	—	ns	0.51	—	ns	~0.00	—	ns

4t Lime + $N_{37.5}P_{13}$	1.1	↑33.7%	ns	0.63	↑21.1%	ns	0.18	↑6.9%	ns
4t Lime + $N_{75}P_{26}$	2.27 ± 0.857	↑69.6%	**	0.74	↑24.3%	ns	1.2	↑46.3%	ns
Model R^2	0.57	—	—	0.3	—	—	0.57	—	—
SE (Residual)	1.29	—	—	1.37	—	—	1.76	—	—
F-statistic	12.30***	—	***	3.84	—	***	11.86	—	***

Note: Arrows indicate direction of change in soil [H^+] relative to the N_0P_0 control; Significance codes: ***p < 0.001, **p < 0.01, *p < 0.05, blank = not significant. The yellow highlight emphasizes changes that were significant.

4.50 respectively. The highest response of pH change occurred in Siaya 2 in the 2018-LR cropping period, which caused a pH change from an initial 4.50 to 6.19, representing a 27.3% pH change. In Kakamega Site, where the initial soil pH was 5.74, a small change of 6% due to lime addition was observed in the 2018-LR cropping period. In summary, the application of 4t Lime ha^{-1} was the only treatment that consistently and significantly increased soil pH across the three study sites, while the fertilizer treatments and their interactions with lime did not have a significant impact on soil pH, except for the positive effect of the $N_{75}P_{26}$ treatment at the Siaya 2 site in the main effects model (Table 4.1).

4.1.2 Effect of lime, inorganic N and P fertilizer doses, and their interaction on soil available phosphorus

Lime at a rate of 4t Lime ha^{-1} remained effective in increasing the available soil P, but the response differed at the three sites as shown in Table 4.1. It was apparent that the average, maximum, and minimum response of available soil P to lime and fertilizer treatments were site dependent. At Kakamega, lime application at 4t ha^{-1} overall increased soil P by 60.4%. At Siaya 1, lime application at 4t Limeha^{-1} for soil P increased by 34.5% ($p < 0.001$). However, when lime was not in combination with the lower fertilizer NP doses ($N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$), significant values of observed soil P values relative to control (N_0P_0) were not observed, especially at Siaya 2, where in the main effects model, the difference observed was 22.8 % and in the interaction model, there was no observable difference. N_0P_0 (absence of fertilizer) treatment impaired soil P status significantly at Kakamega by 23.8% ($p <.05$) and slightly at Siaya 1. However, N_0P_0 showed a small but significant rise of 8.5% ($p < .001$) in Siaya 2. The $N_{37.5}P_{13}$

treatment increased soil P by 26.8% at Kakamega ($p < 0.05$), but at Siaya 1 it increased by 23.7% while there was no change at Siaya 2. The obtained positive impacts were most stable in the $N_{75}P_{26}$ treatment; soil P was raised by 50.8% in Kakamega site ($p < .001$) and by 38.5% in Siaya 1 ($p < .01$), whereas no noticeable change was noted at Siaya 2. Concerning combined treatments and analyzed aspects of the samples taken from the soil, with the use in Kakamega, it was found that the addition of lime in combination with $N_{75}P_{26}$ raised the content of P by 69.6% ($p <.01$). For lime with no fertilizer at Siaya 2, soil P was increased by 17.5% ($p < 0.001$) and there was no change in any of the other parameters at Siaya 1 for combined treatments. Using the present findings, the goodness-of-fit for the present models was relatively high at Kakamega and Siaya 2, with R^2 values between 0.523—0.743, while at Siaya 1, only a moderate fit, ranging between 0.269-0.296, was observed.

A summary shown in Appendix I indicates that soil available P ranged from 2.73-4.28 mg kg^{-1} (2016-LR), 2.91-5.16 mg kg^{-1} (2017-LR), and 3.68-5.48 mg kg^{-1} (2018-LR) in Kakamega, Siaya 1, and Siaya 2, respectively. Soil available P change of up to 70% was observed from the control treatment in Kakamega Site in 2018-LR when $N_{37.5}P_{13}$ fertilizer dose was used. The variation between soil P from the control treatment of lime and fertilizer, with that of combined lime and fertilizer, was highest in Kakamega, with a soil P change of 85% (1.38-9.52 mg kg^{-1}). There was consistency in the trend of fertilizer N and P doses and the amount recorded in the sorghum root zone P. However, several instances showed that there was no significant difference between the available P levels of fertilizer N and P doses. For instance, in Siaya 1 in 2016-LR, soil P level showed no significant difference between $N_{75}P_{26}$ and $N_{18.8}P_{6.5}$ application. In Siaya 2 (2016-LR), Kakamega (2016-LR), and Siaya 1 (2017-LR), no significant difference was recorded in the application of $N_{75}P_{26}$ and $N_{37.5}P_{13}$ doses. During the 2018-LR period, available soil P showed no significant difference with the application of N_0P_0 and $N_{18.8}P_{13}$. In the 2018-LR period, the available soil P was not significantly different between N_0P_0 and $N_{18.8}P_{13}$ treatments. Without applying lime, there was a proportionate significant increase in the amount of soil P with N and P rate. In Kakamega, for instance, soil available P was observed to regress linearly from N_0P_0 to $N_{75}P_{26}$ with R^2 values of 0.60 over the cropping periods (Fig. 4.2(a)). A similar trend was observed through all study sites in all seasons. This observation ascertained the influence of fertilizer doses on the residual effect of available soil P.

4.1.3 Effect of lime, inorganic N and P doses, and their interaction on exchangeable soil Aluminum

Fig. 4.1 shows the changes in soil exchangeable Al as affected by the treatments. The effects of lime and fertilizer applications on soil exchangeable aluminum (Al) concentrations were evaluated using two regression models—one including only main effects and the other incorporating interaction terms. In both models, lime application consistently resulted in a statistically significant reduction in Al levels. The responses of exchangeable aluminum (Al) to lime and fertilizer treatments show different trends, which are measurable in the three sites. At Kakamega, the highest concentration was found in control plots with no fertilizer or lime inputs, where Al was about 2.0 cmol/kg. Control treatment (0 t ha^{-1}) decreased Al by about 1015 percent, and it was also still high (excess of 1.5 cmol/kg). Lime-amended soils lowered Al, and the latter was lowered significantly by 40–60% in treated soils compared to the control. The level of Al toxicity was the best restrained (to approximately 0.8 cmol/kg) under the N75P26 + lime treatment. Overall, there was also a statistically significant ($p < 0.05$) difference between lime and non-lime treatments at high fertilizer rates. In Siaya 1, the control and non-limed plots both had similarly high Al concentrations (~2.0 cmol/kg). All the lime treatments reduced Al by 50–60% with final values of approximately 0.7–0.9 cmol/kg. Notably, all the lime treatments were statistically different from control and fertilizer-only treatments, implying consistent acidity alleviation regardless of nutrient application. Conversely, Siaya 2 had baseline Al levels of about 1.4–1.6 cmol/kg for all treatments, where there were no significant differences. This signifies lower initial acidity and less sensitivity to lime or fertilizer amendments. Typically, liming application reduced exchangeable Al in acidic soils by up to 60% in Kakamega and Siaya 1, with fertilizer application alone having minimal effect.

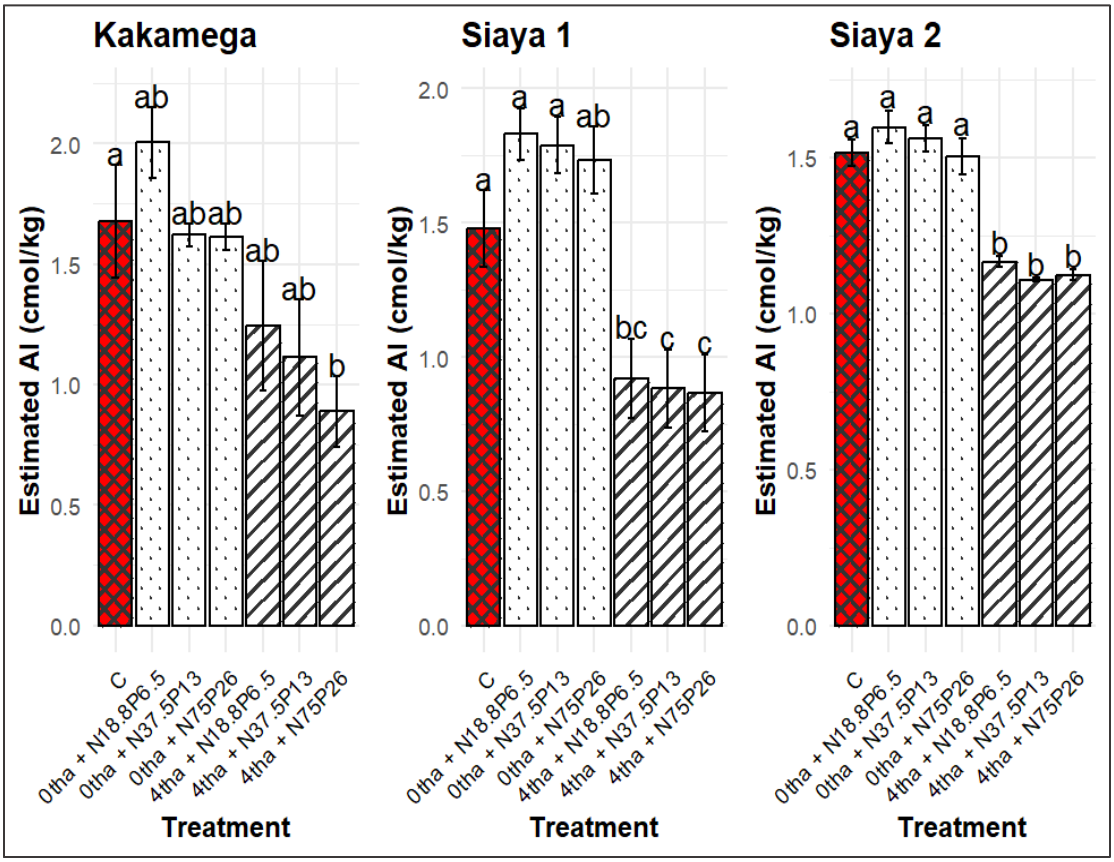


Figure 4.1: Means of root zone soil Al changes (cmol kg^{-1}) as influenced by the interaction of lime and fertilizer in 2016, 2017, and 2018 cropping seasons. The first bar in every panel represents the control. Note: Treatments labeled with red capital 'C' represent control plots with no lime or fertilizer applied.

Pairwise comparison for chemical analysis, summarized in Fig. 4.1, showed that in all experimental sites there were no significant differences in the amount of Al concentrations. Tukey's HSD test (Appendix I) revealed Kakamega Site registered the highest grand mean Al saturation of 2.04 cmol kg^{-1} in the 2018-LR cropping season. Lime addition reduced Al saturation within a range of 22-86%. In Siaya 2, liming lowered Al concentration from 2.2 to 0.31 mg kg^{-1} in 2017-LR, which represented an 86% change. The lowest mean Al concentration was observed in Kakamega Site in 2017-LR, when a mean of 1.03 mg kg^{-1} was recorded. However, this was an 82% reduction from the initial 1.76 to 0.31 cmol kg^{-1}. In some instances, such as in Siaya 2 in the 2016-LR season, soil exchangeable Al was observed to rise with lower levels of fertilizer N and P (Appendix 2). No significant changes in soil exchangeable Al at varying fertilizer doses were observed in 2017-LR in all study sites. Up to 75.8% increase of soil Al saturation (1.32-2.32 cmol kg^{-1}) was caused by adding $N_{75}P_{26}$ levels of fertilizer in Kakamega during the 2018-LR cropping season. Control treatment of N_0P_0 fertilizer rates caused the lowest change in soil Al concentration in all sites and in all experimental sites.

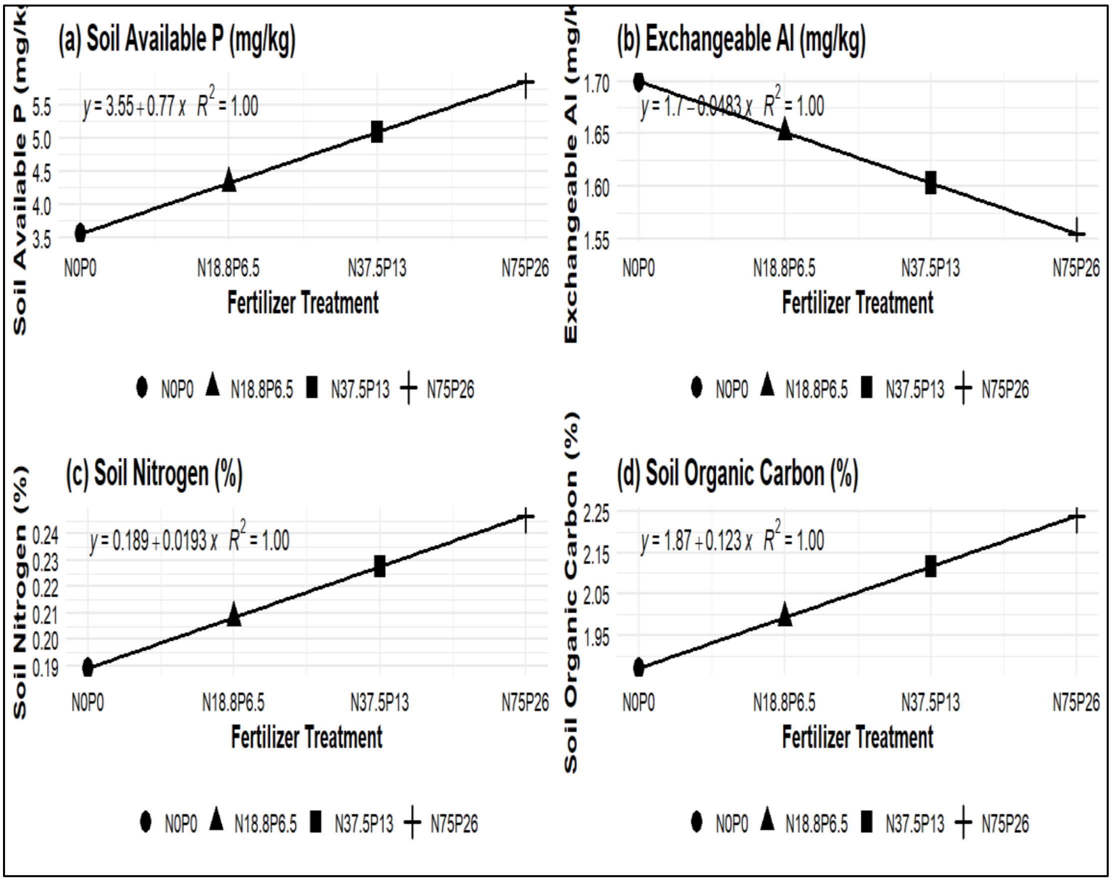


Figure 4.2: Linear regression analyses showing the relationship between fertilizer level and soil chemical properties across three sites.

Note: R^2 values from linear regressions across fertilizer levels were as follows: (a) Soil available P ($R^2 = 0.60$), (b) Exchangeable Al ($R^2 = 0.52$), (c) Soil N ($R^2 = 0.32$), and (d) Soil organic C ($R^2 = 0.21$).

4.1.4 Effect of lime, inorganic N and P fertilizer doses, and their interaction on soil Nitrogen

The influence of lime and fertilizer treatments on total nitrogen (N) was assessed using site-pooled regression models. Both the main effects and interaction models indicate that lime and fertilizer application can affect N levels in the soil, although the magnitude of change and statistical significance vary by input and model specification. The results are summarized in Figure 4.3. Sitewise, fertilizer and lime treatment had differential impacts on soil N, with trends varying under main treatment effects and due to interaction. N interaction in treatment plots in Kakamega gave the lowest N at ~0.08%, with the highest rate of fertilizer ($N_{75}P_{26}$) increasing soil N to ~0.14%. In Kakamega, Soil N in treatment plots was lowest (~0.08%), and the highest rate of fertilizer ($N_{75}P_{26}$) boosted the N in the soil to ~0.14 per cent. Lime alone had a slight increase in soil N (~0.09%), while lime + fertilizer interaction had more pronounced effects. N75P26 + lime showed the largest increase, to ~0.16%, which indicates more N retention. Comparisons between control, fertilizer, and lime-fertilizer mixes were significant. Soil N in Siaya 1 was initially low (~0.11%) and when treated with the recommended rates of N and P (N75P26), it increased to ~0.17%. Lime and lime-fertilizer combinations also raised soil N, with N75P26 + lime rising above ~0.19%. Significant differences were noted between control and all other treatments, but especially where lime and higher fertilizer rates were combined. In Siaya 2, soil N values showed minimal variation, ranging from ~0.13% to 0.15% across all treatments. Neither lime nor fertilizer had a statistically significant effect, indicating limited treatment responsiveness—possibly due to stable baseline fertility or stronger organic matter buffering. In general, the largest responses of soil nitrogen to lime-fertilizer combinations at higher N rates were found in those conditions with previous lower soil fertility in Kakamega and Siaya 1. Siaya 2, on the other hand, did not show much change, indicating that there are site-specific nutrient dynamics and amendment efficiency. The results showed highly significant treatment effects on Kakamega and Siaya 1, where there was an interactive effect of fertilizer and lime, which enhanced soil N status.

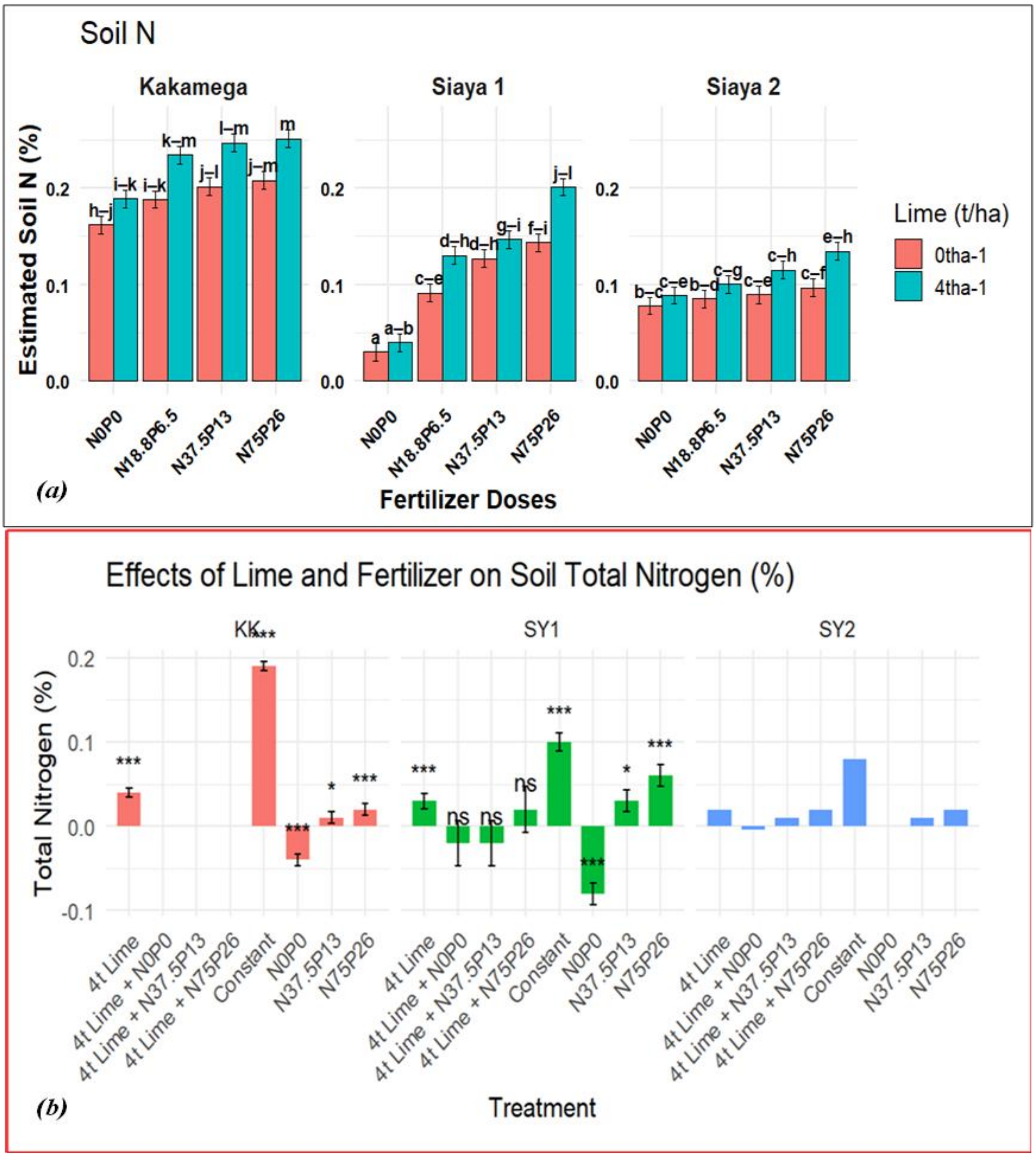


Figure 4.3: Estimated mean values *(a)* and corresponding treatment changes *(b)* in response to the interaction of lime and varying inorganic N and P fertilizer doses in the study sites over the seasons

The 2017-LR cropping period in Kakamega had the highest mean soil N of 0.22%. This study observed the highest N change of 40% in Siaya 2, during soil liming for crop period 2018-LR through a changing pattern from 0.08–0.11%N (Appendix I).

On all three sites, the treatment that had no fertilizer (the N_0P_0 treatment) consistently produced significantly lower soil N content than other treatments, which used higher doses such as those recommended for treatments $N_{37.5}P_{13}$ and $N_{75}P_{26}$. At both Kakamega and Siaya 1 sites, but not at Siaya 2, this regimen did not induce a significant difference in soil nitrogen content between the $N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$ treatments. On Siaya 1, the distribution of nitrogen between these fertilization levels was such that $N_{18.8}P_{6.5}$ actually resulted in a significant increase in nitrogen content when compared with N_0P_0. No such disparity was evident in Siaya 2. Across sites, but with significant differences, fertilizing with $N_{75}P_{26}$ eventually showed very dissimilar effects. At Siaya 1, the result was a substantial increase in soil N due to the $N_{75}P_{26}$ fertilizer treatment level compared to $N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$. Unexpectedly, at Siaya 2, $N_{75}P_{26}$ resulted in a decrease in soil nitrogen. Soil N in the study sites responded to doses of fertilizer N and P. As shown in Figure 4.3 (c), a strong linear regression (R^2=0.60) was observed as N and P doses are increased from N_0P_0 to $N_{75}P_{26}$.

4.1.5 Effect of lime, inorganic N and P doses, and their interaction on soil SOC

Results showing the influence of treatments on soil organic carbon (SOC) are summarized in Table 4.2. The addition of fertilizer and lime had substantial results in increasing SOC, where its reference was fixed as 0.974 units, and an increment of 0.245 units was seen, which constitutes a 16.2 percentage points rise ($p < 0.001$). SOC increases were progressively larger with fertilizer applications, from $N_{18.8}P_{6.5}$ by 0.156

units (10.3%, $p < 0.05$), to $N_{37.5}P_{13}$ by 0.257 units (17.0%, $p < 0.001$), and to $N_{75}P_{26}$ by 0.365 units (24.1%, $p < 0.001$). Lime × fertilizer interaction terms were marginal (3.5–4.8%) and statistically non-significant, and implied additive effects over and above synergistic ones. They highlight the independent contributions of lime and fertilization towards organic carbon acquisition, especially in more advanced N–P regimes.

Tukey's HSD pairwise comparison showed that the mean SOC ranged between 1.43-2.30% across the experimental sites. All experimental sites and in all seasons exhibited highly significant (p<0.001) changes due to the addition of varying fertilizer doses. Mean SOC was significantly increased from the addition of $N_{0}P_{0}$ to $N_{18.8}P_{6.5}$ fertilizer doses in Kakamega and Siaya 2 in 2016-LR and 2017-LR cropping periods. However, the rise of fertilizer dose from $N_{18.8}P_{6.5}$ to $N_{37.5}P_{13}$ did not significantly change the level of soil SOC. The highest change of soil OC was observed in Kakamega, where 43% change from control to $N_{75}P_{26}$ was recorded (Appendix 2). As observed in Figure 4.3 (d), there was a strong positive trend from nil treatment

Table 4.2: Main and interaction effects of lime and fertilizer doses on organic carbon and C: N ratio in the experimental sites during the cropping periods

Variable	Term	Estimate (Main)	% Change	p	Estimate (Interaction)	% Change	p
SOC	Intercept	1.513	—	***	1.536	—	***
	4t Lime	0.245	16.2%	***	0.198	12.9%	*
	$N_{18.8}P_{6.5}$	0.156	10.3%	*	0.125	8.1%	ns
	$N_{37.5}P_{13}$	0.257	17.0%	***	0.23	15.0%	*
	$N_{75}P_{26}$	0.365	24.1%	***	0.329	21.4%	***
	4t Lime × $N_{18.8}P_{6.5}$	—	—	—	0.062	4.0%	ns
	4t Lime × $N_{37.5}P_{13}$	—	—	—	0.054	3.5%	ns
	4t Lime × $N_{75}P_{26}$	—	—	—	0.073	4.80%	ns
CNR	Intercept	14.803	—	***	14.486	—	***
	4t Lime	–0.844	–5.7%	ns	–0.210	–1.4%	ns
	$N_{18.8}P_{6.5}$	–0.131	–0.9%	ns	0.223	1.5%	ns
	$N_{37.5}P_{13}$	–1.071	–7.2%	ns	–0.831	–5.7%	ns
	$N_{75}P_{26}$	–1.723	–11.6%	*	–1.049	–7.2%	ns
	4t Lime × $N_{18.8}P_{6.5}$	—	—	—	–0.708	–4.9%	ns
	4t Lime × $N_{37.5}P_{13}$	—	—	—	–0.480	–3.3%	ns
	4t Lime × $N_{75}P_{26}$	—	—	—	–1.349	–9.3%	ns

Highlight (green) indicates estimates that were significantly different from the control; Significant codes: ***p≤0.001, **p≤ 0.01, *p≤ 0.05

to $N_{75}P_{26}$ with an R^2 value of 0.88. This generally showed the responsiveness of these soils to progressive increases of fertilizer N and P.

4.1.6 Effect of lime, inorganic N and P doses, and their interaction on soil C: N Ratio

The combination of fertilizer and lime applications had a high impact on the C: N ratio of soil in the three sites: Kakamega, Siaya 1, and Siaya 2 (Table 4.2).

A C: N ratio of about 13.1 was the highest it reached under the baseline treatment (N_0P_0 without lime) at the Kakamega site. Adding lime to the same N_0P_0 treatment lowered the C: N ratio by 13.7%, reflecting a drastic shift in favor of enhanced nitrogen availability. With increased application of NP fertilizer with liming, the C: N ratio decreased further: $N_{18.8}P_{6.5}$, $N_{37.5}P_{13}$, and $N_{75}P_{26}$ treatments registered 19.0%, 22.1%, and 23.7% reductions compared to the unlimed control, respectively.

For Siaya 1, the unlimed N_0P_0 treatment contained a C: N ratio of approximately 15.4. Lime application lowered the C: N ratio by 7.1% in the no-fertilizer treatment. Higher reductions were found at greater fertilizer applications under limed treatments: $N_{18.8}P_{6.5}$, $N_{37.5}P_{13}$, and $N_{75}P_{26}$ gave declines of 11.0%, 13.6%, and 15.6%, respectively, compared with the unlimed control.

In Siaya 2, the highest C: N ratio (17.3) was once more recorded in the N_0P_0 treatment without lime application, which lowered the C: N ratio by 7.5%. The synergy of lime plus fertilizer application decreased the C: N ratio more strongly: applying $N_{18.8}P_{6.5}$, $N_{37.5}P_{13}$, and $N_{75}P_{26}$ under limed conditions lowered the C: N ratio by 11.7%, 13.4%, and 17.3%, respectively, over the control in unliming.

4.2 Objective 2: To determine the influence of lime–fertilizer combinations on sorghum yield components and physiological performance

4.2.1 Sorghum grain yield as influenced by lime, inorganic N and P doses, and their interaction

Sorghum grain yield (SGY) responded expectedly and positively to both lime and fertilizer treatments in all three sites of study, with increased magnitude indicating treatment intensity levels in general. $N_{75}P_{26}$ induced significant increases in yield in Kakamega, Siaya 1, and Siaya 2 at the highest fertilizer rate, and these were statistically significant ($p < .001$). Concurrent trends were also witnessed with $N_{37.5}P_{13}$ and $N_{18.8}P_{6.5}$, both of which raised yield at all locations, significance being achieved in both cases. The response to yield under $N_{37.5}P_{13}$ was particularly notable in Siaya 1 and Siaya 2, while Kakamega was relatively less, though still significant.

Used alone, lime raised the grain yield in Siaya 1 and Siaya 2 significantly ($p < .001$), while in Kakamega, the same but statistically non-significant response was recorded. These results indicated that liming improved the productivity of sorghum significantly where lower initial yields or more acidic soils. The fertilizer-lime interactions were of low order but also positively tended. The lime × fertilizer interaction was significant at intermediate ($N_{37.5}P_{13}$) and high ($N_{75}P_{26}$) fertilizer levels in Siaya 1, suggesting synergistic action on both the combination with lime and application of nutrients. There were no statistically significant interaction effects in Kakamega or Siaya 2, suggesting predominantly additive responses in these areas.

Generally, the sorghum grain yield improved as fertilizer application increased uniformly, and lime contributed to extra yield benefit always, either directly or by maximizing the impact of the fertilizer. These results confirm the agronomic benefit of simultaneous nutrient and pH management, especially in stress-susceptible systems through soil acidity or constricted nutrient availability.

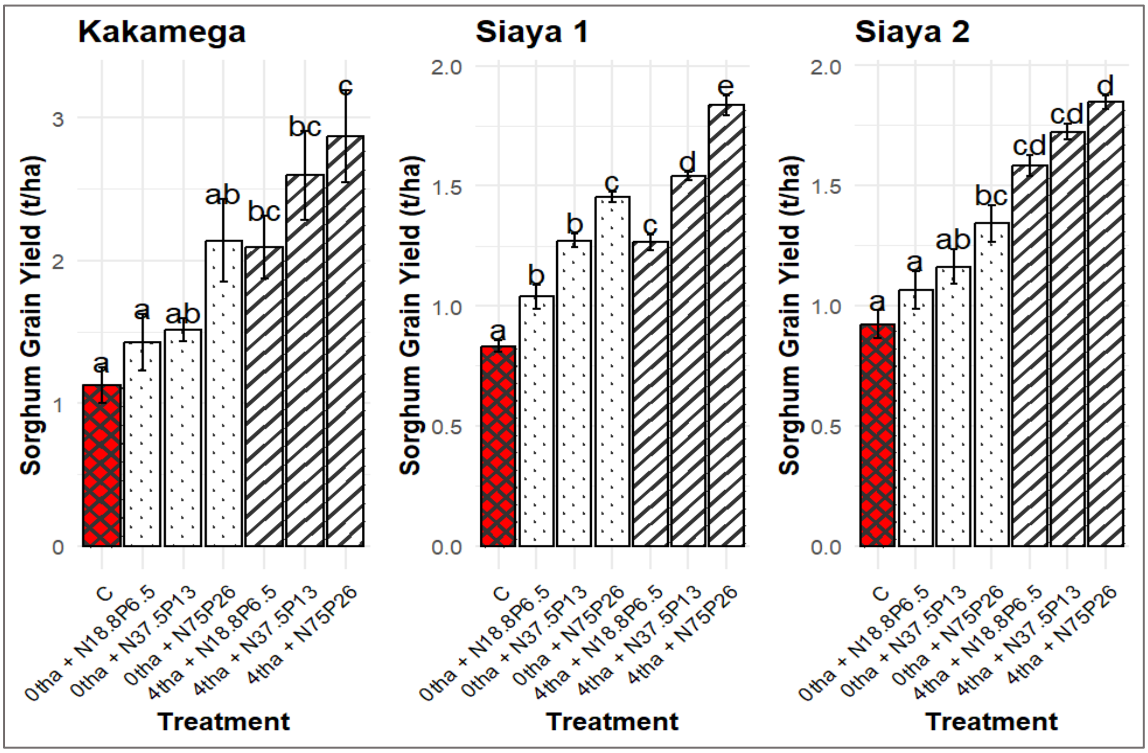


Figure 4.4: Means of grain yield relative to baseline treatment in response to varying doses of N and P fertilizer and their interactions in the study sites over the seasons.

Note: Treatments labeled with red capital 'C' represent control plots with no lime or fertilizer applied.

The highest SGY per site were 2.57, 1.32, and 1.98 t ha^{-1} observed in Kakamega during 2018-LR and in Siaya 1 and site 2 during 2017-LR season as summarized in Appendix IV. Micro-dose fertilizer with lime showed no significant difference with No lime+$N_{75}P_{26}$ in Kakamega in 2016-LR and 2018-LR, and in Siaya 2 in 2017-LR and 2018-LR cropping period. As summarized in Appendix III, mean SGY ranged between 1.14-2.57 t ha^{-1} across the sites and seasons, with the highest recorded in the Kakamega study site in the 2018-LR season. The highest combination of $N_{75}P_{26}$ produced significantly ($p \leq 0.001$) higher SGY in all three experimental sites across all cropping seasons. Increase in grain yield ranged between 27% to 39% in response to the micro-dose fertilizer of $N_{18.8}P_{6.5}$. Control treatments gave the lowest grain yields in all sites through all the seasons, and the recommended fertilizer dose of $N_{75}P_{26}$ recorded the highest grain yield across all sites and in all seasons. However, the use of $N_{37.5}P_{13}$ and $N_{18.8}P_{6.5}$ fertilizer doses recorded no significant difference in the three sites in the 2018-LR cropping period. The traditionally recommended level of $N_{75}P_{26}$ caused a grain yield increase between 58% (Kakamega in 2016-LR and 2018-LR) and 53% in Siaya 1. In Siaya 1 during the 2018-LR cropping season, grain yields were not significantly different in micro-dose fertilizer levels of $N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$, which represented sorghum grain yields of 1.08 kg ha^{-1} and 1.39 kg ha^{-1}, respectively. Likewise, there was no significant difference in grain yield in Siaya 1 and Siaya 2 when $N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$ were applied.

Tukey's HSD test results, summarized in Table 4.3, revealed that across all three sites and seasons, lime application consistently improved SGY. Similarly, fertilizer treatments had a significant positive impact on SGY in every location. The study found that lime application and fertilizer treatments significantly improved sorghum yield (SGY) across all three sites and seasons. The highest fertilizer dose ($N_{75}P_{26}$) consistently produced the greatest yields, with significant increases in Kakamega, Siaya 1, and Siaya 2. The intermediate dose of $N_{37.5}P_{13}$ generally yielded better than N_0P_0 and $N_{18.8}P_{6.5}$, but the means varied by site. The highest combination of $N_{75}P_{26}$ produced significantly higher SGY in all three experimental sites across all cropping seasons. The recommended fertilizer dose of $N_{75}P_{26}$ recorded the highest grain yield across all sites and in all seasons. However, the use of $N_{37.5}P_{13}$ and $N_{18.8}P_{6.5}$ fertilizer doses recorded no significant difference in grain yield in the 2018-LR cropping period.

Table 4.3: Pairwise comparative analysis of sorghum biomass and grain yields under different lime and fertilizer treatments in Kakamega and Siaya sites

Site	Stats	0t Vs. 4t	N_0P_0 Vs. $N_{18.8}P_{6.5}$	$N_{18.8}P_{6.5}$ Vs. $N_{37.5}P_{13}$	$N_{75}P_{26}$ Vs. $N_{18.8}P_{6.5}$	$N_{37.5}P_{13}$ Vs. N_0P_0	$N_{75}P_{26}$ Vs. N_0P_0	$N_{37.5}P_{13}$ Vs. $N_{75}P_{26}$
		……………………. Sorghum Biomass Yield (t ha^{-1}) ………………………						
Kakamega	*Est.*	3.8	-2.56	1.24	4.09	3.8	6.65	2.85
	Pr(>|t|)	<0.001***	≤0.05*	NS	≤0.001***	≤0.001***	≤0.001***	≤0.01**
Siaya 1	*Est*	-1.58	2.46	-2.48	-4.11	-4.94	-6.58	-1.63
	Pr(>|t|)	0.013*	≤0.001***	≤0.001***	≤0.001***	≤0.001***	≤0.001***	≤0.001***
Siaya 2	*Est*	-2.71	2.01	-1.45	-2.79	-3.45	-4.8	-1.35
	Pr(>|t|)	≤0.001***	≤0.01**	NS	≤0.001***	≤0.001***	≤0.001***	NS
		……………………… Sorghum Grain Yield (t ha^{-1}) ……………………………						
Kakamega	*Est.*	0.77	-0.64	0.3	0.74	0.93	1.38	0.45
	Pr(>|t|)	<0.001***	≤0.01**	NS	≤0.01**	<0.001***	<0.001***	NS
Siaya 1	*Est*	-0.25	0.32	-0.25	-0.49	-0.57	-0.81	-0.24
	Pr(>|t|)	0.002**	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
Siaya 2	*Est*	-0.5	0.4	-0.12	-0.27	-0.52	-0.67	-0.15
	Pr(>|t|)	≤0.001***	≤0.001***	NS	≤0.05*	≤0.001***	≤0.001***	0.64

The study of grain yield over control (GYOC) was carried out across the study sites with specific emphasis on trends in the performance of lime and fertilizer N and P treatments on GYOC (Table 4.4). As for the application of lime at 4t Lime ha^{-1}, results were quite varied. At Kakamega and Siaya 2, however, lime reduced GYOC by -6.48 and -6.47, respectively, although this was only significant at Siaya 2. On the other hand, GYOC at Siaya 1 increased significantly by +8.42% ($p < .001$), showing that lime has positive effects in this site. The N and P treatment, especially $N_{75}P_{26}$, greatly improved GYOC over all sites. In Kakamega, Siaya 1, and Siaya 2, $N_{75}P_{26}$ introduced a yield increase of 29.54%, 37.47%, and 29.35% boosts, respectively, which were all highly significant ($p < .001$). The treatment of $N_{37.5}P_{13}$ was also effective in boosting GYOC across sites, although it was milder as it ranged from 13.75 to 24.51%. However, these improvements were not observed in situations when lime was incorporated together with other N and P treatments. When a combination of lime was applied with $N_{37.5}P_{13}$ or $N_{75}P_{26}$ at Kakamega and Siaya, 2, on the other hand, the GYOC turned negative, though to a high degree, on average, there was a lower GYOC.

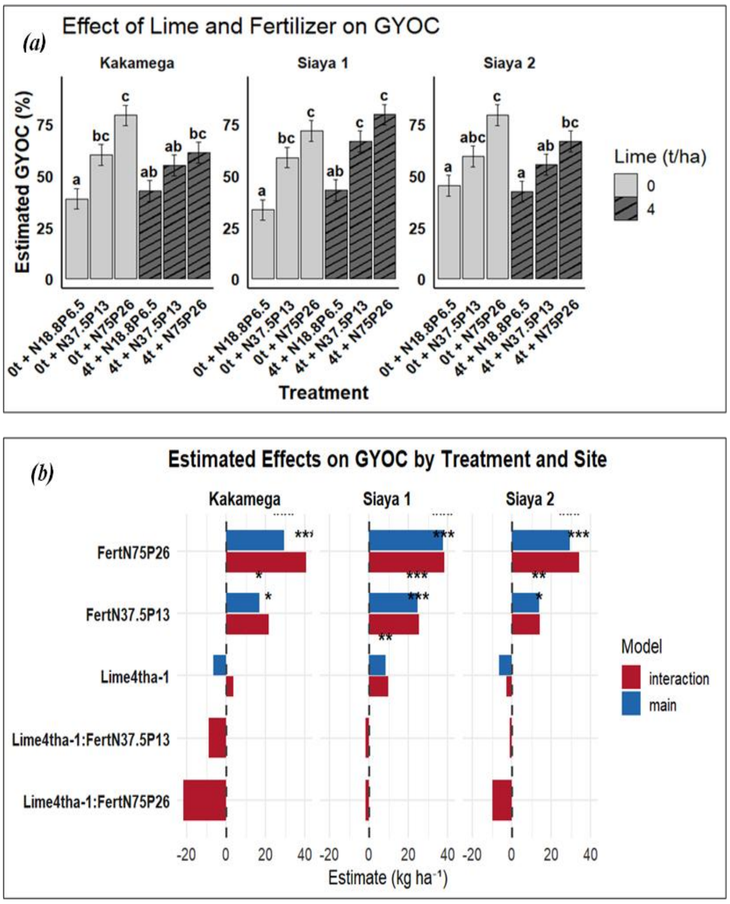


Figure 4.5: Means of (a) GYOC and (b) mean changes in response to varying doses of N and P fertilizer in Siaya site 1

As summarized in Figure 4.5, results for simultaneous pairwise comparison using Tukey’s HSD for GYOC at the three experimental sites showed that the treatment of

$N_{75}P_{26}$ fertilizer produced the highest grain yield. In each case, $N_{75}P_{26}$ significantly surpassed the two: $N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$, which indicated that these two doses were superior in improving the yield in sorghum grains. Additionally, at all sites, $N_{37.5}P_{13}$ produced significantly more grain than $N_{18.8}P_{6.5}$, suggesting a consistent treatment ranking with

Table 4.4: Pairwise comparative analysis of harvest index and grain yield over control under different lime and fertilizer treatments in Kakamega and Siaya sites

		0t Vs. 4t	N_0P_0 Vs. $N_{18.8}P_{6.5}$	$N_{18.8}P_{6.5}$ Vs. $N_{37.5}P_{13}$	$N_{75}P_{26}$ Vs. $N_{18.8}P_{6.5}$	$N_{37.5}P_{13}$ Vs. N_0P_0	$N_{75}P_{26}$ Vs. N_0P_0	$N_{37.5}P_{13}$ Vs. $N_{75}P_{26}$
		Harvest Index						
Kakamega	***Est***	-0.05	0.03	0	-0.02	-0.02	-0.04	-0.02
	Pr(>|t|)	<0.001***	NS	NS	NS	NS	≤0.05*	NS
Siaya 1	***Est***	0.01	-0.04	0.02	0.03	0.06	0.07	0.01
	Pr(>|t|)	NS	≤0.01**	0.225	≤0.05*	<0.001***	<0.001***	1
Siaya 2	***Est***	-0.01	0.01	0.02	0.03	0.01	0.02	0.01
	Pr(>|t|)	≤0.05*	NS	NS	≤0.05*	NS	NS	NS
		Grain Yield Over Control						
Kakamega	***Est***	-6.48		16.99	29.54			12.55
	Pr(>|t|)	NS		0.007**	<0.001***			NS
Siaya 1	***Est***	-8.42		-24.51	-37.47			-12.96
	Pr(>|t|)	0.091NS		<0.001***	<0.001***			<0.001***
Siaya 2	***Est***	6.47		-13.75	-29.35			-15.6
	Pr(>|t|)	NS		≤0.01**	≤0.001***			≤0.01**

Significance levels are represented as** $p \leq .01$, *** $p \leq .001$, * $p \leq .05$ and "NS" for non-significance

$N_{75}P_{26}$ is the most effective, followed by $N_{37.5}P_{13}$, then $N_{18.8}P_{6.5}$.

Appendix III shows that there was a significant (p<0.05) difference in GYOC between limed and unlimed treatments across the study sites over the growing periods, except in Siaya 2 during the 2017-LR growing period. Mean GYOC ranged between 40.0-70.3%. Liming yielded higher GYOC values than experiments without lime. As high as a 207% difference in GYOC between limed and unlimed soils was observed in Kakamega Site in 2018-LR, where GYOC rose from 19.64-60.3%. Results showed that GYOC were significantly different in Siaya 2 in 2016-LR and 2017-LR cropping seasons and in Kakamega during 2018-LR season, where the mean GYOC were 64.25, 56.29, and 39.97, respectively (APPENDIX III & IV). Means of GYOC were observed to be higher in limed than in unlimed plus fertilizer doses at all levels.

GYOC was noted to increase with increasing fertilizer N and P doses as shown in APPENDIX IV. The difference between the fertilizer doses on GYOC was highly significant (p<0.001), with the fertilizer dose of $N_{75}P_{26}$ consistently recording the highest GYOC. Means of sorghum GYOC ranged from 23.38-93.72% across all sites through the cropping periods. All fertilizer treatment doses recorded significantly different (<0.001) GYOC.

4.2.2 Effect of lime, inorganic N and P doses, and their interaction on sorghum biomass yield

Comparison of the effects of lime treatment on the sorghum biomass yield (SBY) at the three sites is presented in Figure 4.6. SBY also responded similarly and positively to both lime and fertilizer applications across all three sites, with effect sizes tending to increase with the intensity of nutrient application. While the maximum application of

P ($N_{75}P_{26}$) yielded the greatest increase in SBY across all sites and treatments, the most significant impact was observed at Kakamega, followed by Siaya 1, then Siaya 2. These increases were all significant ($p < .001$). Likewise, application of the intermediate fertilizer rate ($N_{37.5}P_{13}$) enhanced SBY at all locations, although not as much as $N_{75}P_{26}$. Even the lowest fertilizer treatment ($N_{18.8}P_{6.5}$) resulted in significant ($p \leq .01$) SBY increased at all locations. Application of lime alone also increased SBY at all locations, with very significant effects at Kakamega and Siaya 1 and a mid-level significant increase at Siaya 2 ($p < .05$).

The interaction between fertilizer application and lime was generally negative, or near zero, indicating that fertilizer and lime had generally additive but not synergistic effects on P balance. None of the interactions between the lime × fertilizer was statistically significant, and this implies that there was little added benefit in P balance above the individual main effects of fertilizer or lime alone. In general, SBY response showed a monotonic and dose-dependent rise as a function of input nutrition, indicating the key role played by P application in enhanced soil P functioning under varying agroecological conditions. The greater effect sizes and significance values for Kakamega most probably resulted from its relatively lower initial P concentration or greater amendment responsiveness.

Therefore, findings of this study revealed that lime application enhanced SBY at all three sites, with a better outcome in the Kakamega site. The results, which are shown as the N_0P_0 treatment, implied a lack of availability of N or P, resulting in somewhat considerable declines in SBY across all the sites, though the extent to which the reduction affected SBY could otherwise be viewed as most severe in Siaya 2. $N_{37.5}P_{13}$

treatment effectiveness was also shown to be significant but inconsistent, where the best result showing at Siaya 1 and no effectiveness at all at Siaya 2.

A remarkable degree of heterogeneity was noted in the response of SBY to the different fertilizer doses across the experimental sites. Higher doses of fertilizer ($N_{75}P_{26}$ and $N_{37.5}P_{13}$)

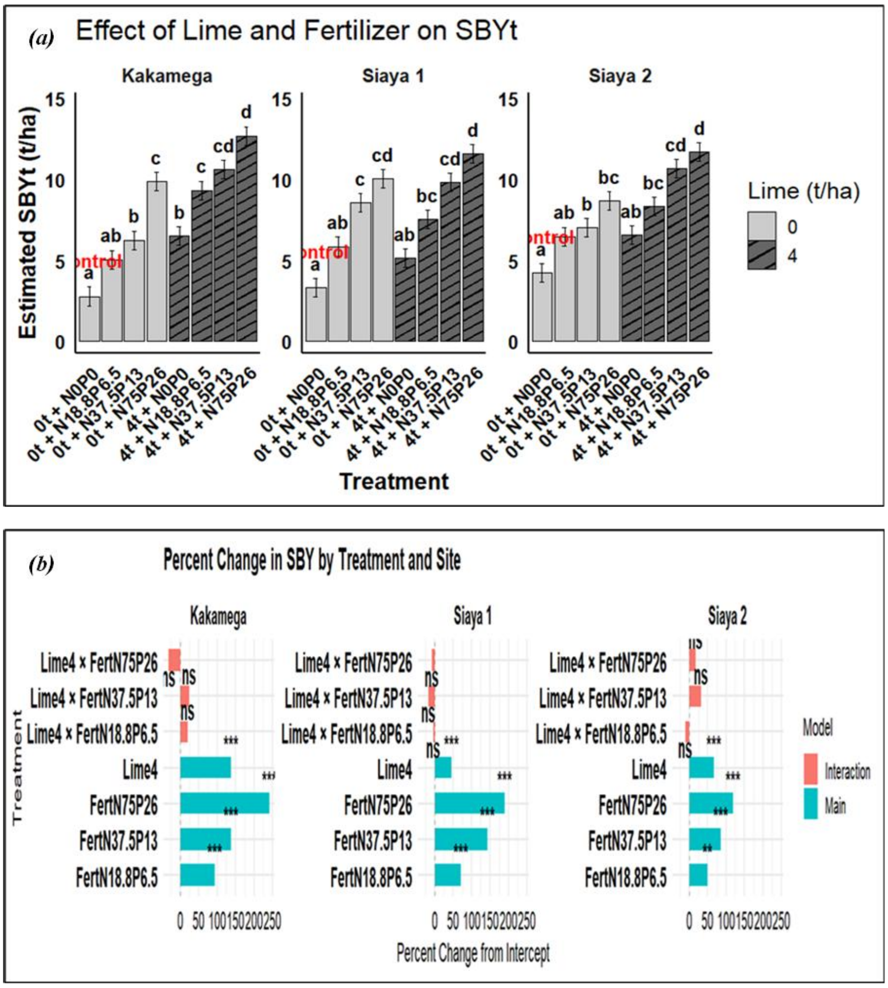


Figure 4.6: Panel *(a)* shows estimated sorghum biomass yield (SBYt; t ha^{-1}), *(b)* changes in SBY (%) across three sites (Kakamega, Siaya 1, and Siaya 2) under varying fertilizer and lime treatments.

†Bars represent mean values with error bars denoting standard errors; letters above bars indicate statistically significant differences ($p < .05$) within sites. Panel *(b)* displays the percent change in SBYt relative to the intercept, highlighting site-specific responses to fertilizer levels applied with lime. Significance levels are represented as**$p < .01$, ***$p < .001$, *$p < .05$, and "ns" for non-significance. The first bar in every panel

marked red represents the control.

generally showed similar effects when compared directly. At the Kakamega site, $N_{75}P_{26}$ improved phosphorus content and enhanced SBY. Siaya 1 and Siaya 2, however, showed a noticeably diminished amount of phosphorus retention at the higher doses, which also correlated with a low SBY at these sites. In contrast, moderate levels of fertilizer treatment ($N_{18.8}P_{6.5}$) showed better results in SBY than that of the control (N_0P_0) for both Siaya 1 and Siaya 2. Even in this case, prospects of achieving significant SBY improvement were not envisaged within the treatments when these two were compared in Kakamega. The highest application ($N_{75}P_{26}$) was observed to decrease the P retention content and eventual SBY at both Siaya 1 and Siaya 2. Nevertheless, this dose had the contrary effect, increasing the soil P and SBY in Kakamega.

SBY, as summarized in Appendix IV and illustrated in Figure 4.6, showed significant differences due to varying doses of fertilizer across the seasons. A mean of 10.5 t ha^{-1} was recorded in Siaya 2 in the 2018-LR season, which was the highest across the study sites and seasons, with the lowest mean being 6.5 t ha^{-1} achieved in Kakamega site in the 2017-LR season. SBY increased with an increase in fertilizer N and P doses, as shown in Figure 4.5. Results showed that all SBY yields at the three fertilizer levels differed significantly ($p<0.001$), with $N_{37.5}P_{13}$ showing the highest yields and N_0P_0 yielding the lowest biomass Figure 4.7 (b). A difference of 62% in yield was observed between fertilizer dose $N_{37.5}P_{13}$ and treatment without fertilizer in Siaya 1 during 2017-LR, where the yield was 9 and 4 t ha^{-1}, respectively. The lowest mean SBY achieved was 5.8 t ha^{-1} in Siaya 2 during the 2016-LR season.

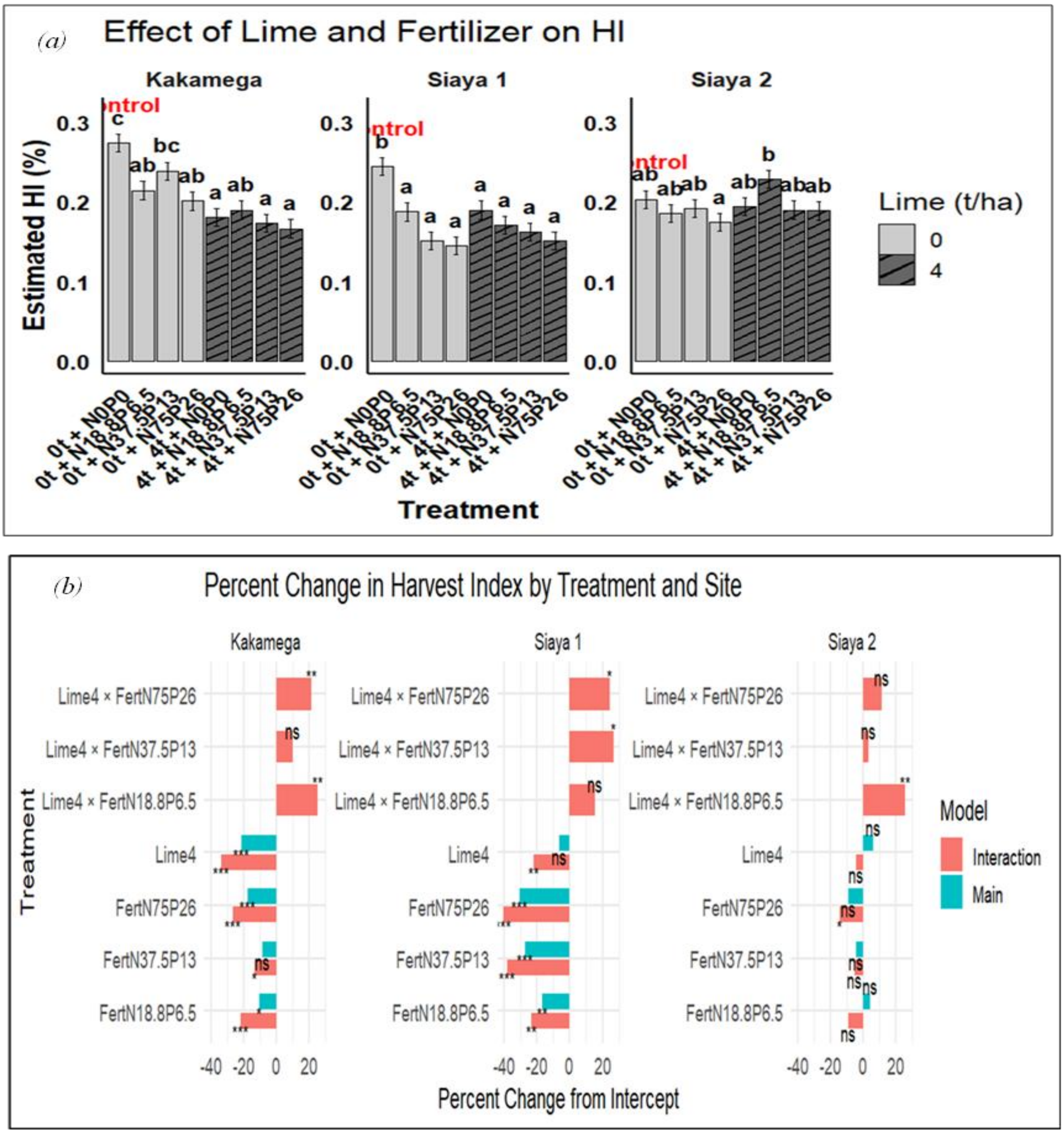


Figure 4.7 Means of (a) HI and mean changes (b) in response to varying doses of N and P fertilizer in Siaya site 1

†Bars represent mean values with error bars denoting standard errors; letters above bars indicate statistically significant differences ($p < .05$) within sites. Panel *(b)* displays the percent change in HI relative to the intercept, highlighting site-specific responses to fertilizer levels applied with lime. Significance levels are represented as**$p < .01$, ***$p < .001$, *$p < .05$, and "ns" for non-significance. The first bar in every panel marked red represents the control.

4.2.3 Effect of lime, inorganic N and P doses, and their interaction on sorghum harvest index

The decrease in harvest index (HI) was observed after the administration of fertilizers, where they were used more intensively. At Kakamega, in all the intensities of fertilizer, there was a reduction of HI with the most pronounced results of $N_{75}P_{26}$ ($p<.001$). The same prototype applied with Siaya 1, with sudden, sharp drops in all directions, with the steepest at the top rate. Siaya 2 followed suit but more mildly; only $N_{75}P_{26}$ had a significant effect ($p = .037$), and the overall reduction was less striking.

Lime alone had an inconsistent pattern. It lowered HI markedly in Kakamega ($p < .001$), had a borderline negative impact in Siaya 1 ($p = .009$), and was nonsignificant with no consistent direction in Siaya 2. The pattern indicates that lime may have diverted biomass to vegetative growth, particularly where there was nutrient restriction.

Several lime × fertilizer combinations notably softened the HI decline. In Kakamega, the interactions with $N_{18.8}P_{6.5}$ and $N_{75}P_{26}$ each yielded modest but significant gains ($p < .01$), partly offsetting earlier losses. In Siaya 1, similar recoveries occurred with mid and high rates, again statistically supported. Siaya 2 showed one significant bump under lime × $N_{18.8}P_{6.5}$ ($p = .005$), though other interactions were weak.

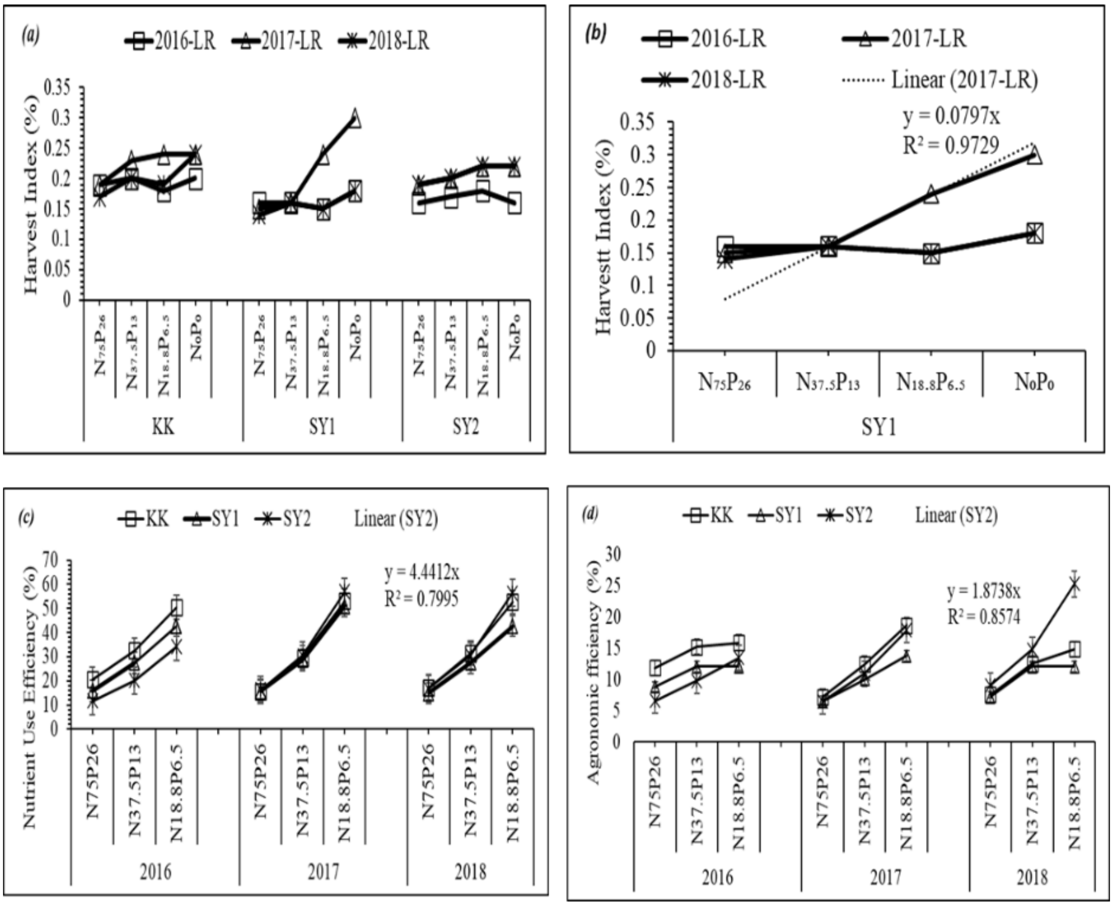


Figure 4.8: Trends of (a) NUE, (b) AE, (c) HI, and (d) linear regression of HI in response to varying doses of N and P fertilizer in the respective sites over the seasons

4.2.4 Effect of lime, inorganic N and P doses, and their interaction on sorghum agronomic efficiency

Across the three study sites, lime and fertilizer treatments significantly influenced sorghum agronomic efficiency (AE), though with varying effects (Table 4.5). Lime application at 4t Lime ha^{-1} consistently improved AE across all sites. In Kakamega, lime increased AE by 42.7%

($p < .001$) in the main effects model, and by 76.9% ($p < .001$) in the interaction model. At Siaya 1, AE rose by 30.7% ($p < .001$) with lime application in the main effects model, while the interaction model showed an even greater increase of 46.2% ($p < .001$). Siaya 2 saw the most significant response to lime, with a 43.4% improvement ($p < .001$) in the main effects model and 76.3% ($p < .001$) in the interaction model.

The impact of fertilizer treatments, however, was less consistent and showed greater variability between the sites. At the moderate fertilizer level ($N_{37.5}P_{13}$), Kakamega experienced a 22.7% reduction in AE ($p < .001$) in the main effects model, though the impact was less pronounced in the interaction model ($p = .146$). In Siaya 1, $N_{37.5}P_{13}$ reduced AE by 11.3% ($p < .01$) in the main effects model, while the interaction of lime with $N_{37.5}P_{13}$ further reduced AE by 13.1% (p > .05), though this interaction effect was not statistically significant. In Siaya 2, $N_{37.5}P_{13}$ had the largest negative effect, with AE decreasing by 45.3% ($p < .001$) in the main effects model, and by an additional 30.1% ($p < .05$) in the interaction model. This suggests Siaya 2 was more sensitive to moderate fertilizer levels compared to the other sites.

The highest fertilizer treatment ($N_{75}P_{26}$) caused the most substantial reductions in AE across all locations. In Kakamega, AE dropped by 56.0% ($p < .001$) in the main effects model, though the interaction model showed a smaller reduction of 35.2% ($p < .001$). In Siaya 1, $N_{75}P_{26}$ led to a 46.9% decline in AE ($p < .001$), with an additional 25.7% reduction when combined with lime ($p < .01$). At Siaya 2, $N_{75}P_{26}$ produced the steepest decline in AE, reducing it by 73.9% ($p < .001$) in the main effects model, with an additional 54.7% reduction ($p < .001$) when lime was applied.

Appendix IV summarizes the response of AE to changes in fertilizer doses across individual sites over the seasons. AE were significantly different in all study sites across the seasons, with observations showing lower AE values with higher doses of fertilizer N and P. Mean AE ranged from 6-19% across the study sites in the cropping seasons. The lowest AE (6%) was reported when the $N_{75}P_{26}$ fertilizer dose was used, whereas the highest AE was recorded in the application of $N_{18.8}P_{6.5}$ fertilizer doses. It was observed that application of $N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$ fertilizer doses did not show significant differences in AE in Kakamega and Siaya 1 in the 2016-LR cropping period and in all study sites during the 2018-LR period. Siaya 2 recorded the highest difference (64%) in AE in response to application of the lowest and highest doses of fertilizer N and P during the 2018-LR season.

Table 4.5: Means of NUE of sorghum as influenced by the interaction of lime and fertilizer during the cropping period across the sites

Treatment	Kakamega (ME)	Kakamega (Int)	Siaya 1 (ME)	Siaya 1 (Int)	Siaya 2 (ME)	Siaya 2 (Int)
			------------------- **Agronomic Efficiency** --------------------------			
4 t ha⁻¹	↑ 43% ***	↑ 77% ***	↑ 31% ***	↑ 46% ***	↑ 43% ***	↑ 84% ***
$N_{37.5}P_{13}$	↓ 23% ***	↓ 12%	↓ 11% **	↓ 5%	↓ 3%	↓ 35% ***
$N_{75}P_{26}$	↓ 56% ***	↓ 35% ***	↓ 47% ***	↓ 37% ***	↓ 74% ***	↓ 54% ***
4 t + $N_{37.5}P_{13}$	—	↓ 27% **	—	↓ 15%	—	↓ 84%
4 t + $N_{75}P_{26}$	—	↓ 57% ***	—	↓ 26% **	—	↓ 64% ***
			------------------------ **Nutrient Uptake Efficiency** ----------------------------			
4 t ha⁻¹	↑ 24% ***	↑ 44% ***	↑ 13% ***	↑ 22% ***	↑ 18% ***	↑ 32% ***
$N_{37.5}P_{13}$	↓ 45% ***	↓ 39% ***	↓ 41% ***	↓ 39% ***	↓ 49% ***	↓ 46% ***
$N_{75}P_{26}$	↓ 74% ***	↓ 64% ***	↓ 70% ***	↓ 66% ***	↓ 76% ***	↓ 68% ***
4 t ha⁻¹ + $N_{37.5}P_{13}$	—	↓ 19% ***	—	↓ 18%	—	↓ 13%
4 t ha⁻¹ + $N_{75}P_{26}$	—	↓ 33% ***	—	↓ 15% ***	—	↓ 129%

*Note: Directional arrows (↑/↓) represent increases or decreases relative to the comparison group. Significance codes: ***p < 0.001, **p < 0.01, *p < 0.05, NS = Not Significant*

Means of agronomic efficiency (AE) showed significant differences in all seasons across the sites except in 2017-LR in Siaya 1 (Table 4,6). These means ranged between 9.95 and 16.40%. Under treatments with or without lime, higher doses of fertilizer recorded lower mean AE values in all study sites over the seasons. Application of higher doses of fertilizer was shown not to significantly impact differently on means of AE whether with lime or no lime application. This observation was reported in Kakamega during 2016-LR and 2018-LR, where means of AE did not report significant differences between $L_0N_{37.5}P_{13}$ and $L_0N_{18.8}P_{6.5}$ and between $L_0N_{75}P_{26}$ and $L_0N_{37.5}P_{13}$. respectively. Similarly, in Siaya 1, during 2016-LR, means of AE did not vary significantly between $L_1N_{37.5}P_{13}$ and $L_1N_{18.8}P_{6.5}$, nor between $L_0N_{37.5}P_{13}$ and

$L_0N_{18.8}P_{6.5}$, while during 2018-LR, application of $L_1N_{37.5}P_{13}$ and $L_1N_{18.8}P_{6.5}$ did not impart a significant difference on the means of AE. Also, a significant difference was not observed in mean AE in Siaya 2 during 2018-LR upon use of $L_0N_{37.5}P_{13}$ and $L_0N_{18.8}P_{6.5}$.

Table 4.6: Pairwise comparative analysis of agronomic and nutrient use efficiency under different lime and fertilizer treatments in Kakamega and Siaya sites

	------ Agronomic Efficiency (%) ---			---- Nutrient Use Efficiency (%) -----		
	N37.5P13 Vs. N18.8P6.5	N75P26 Vs. N18.8P6.5	N75P26 Vs. N37.5P13	N37.5P13 Vs. N18.8P6.5	N75P26 Vs. N18.8P6.5	N75P26 Vs. N37.5P13
	Kakamega					
Estimate	-3.08	-7.607	-4.527	-20.818	-34.247	-13.429
Std.Error	1.32	1.32	1.32	2.357	2.357	2.357
tvalue	-2.333	-5.763	-3.43	-8.831	-14.528	-5.697
Pr(>|t|)	0.071.	<0.001***	0.004**	<0.001***	<0.001***	<0.001***
	Siaya Site 1					
Estimate	1.241	5.131	3.891	17.633	29.971	12.338
Std.Error	0.781	0.781	0.781	1.368	1.368	1.368
tvalue	1.588	6.57	4.981	12.887	21.904	9.017
Pr(>|t|)	0.356	<0.001***	<0.001***	<0.001***	<0.001***	<0.001***
	Siaya Site 2					
Estimate	7.03	11.462	4.432	22.103	34.155	12.052
Std.Error	1.511	1.511	1.511	2.222	2.222	2.222
tvalue	4.652	7.585	2.933	9.948	15.373	5.425
Pr(>|t|)	≤0.001***	≤0.001***	≤0.05*	≤0.001***	≤0.001***	≤0.001***

Response of nutrient uptake efficiency to varying treatments is summarized in Table 4.6. The application of a fertilizer rate at $N_{75}P_{26}$ exhibited an even greater effect on NUE, causing a marked negative effect upon its application. At the Kakamega site, NUE was negatively affected by 73.9% ($p < .001$) in the main effects model and 63.8% ($p < .001$) in the interaction model. Siaya 1 experienced a loss of another 70.3% ($p < .001$) in NUE in the main effects model and 65.5% ($p < .001$) damage to NUE from the interaction model. Siaya 2 had the worst performance with NUE negatively impacted by 75.8% ($p < .001$) in the main effects model and 68.3% ($p < .001$) in the interaction model. These numbers reinforce the fact that NUE was impaired the most by $N_{75}P_{26}$, especially in the overall performance at Siaya 2.

The overall performance of NUE was influenced by the lime and fertilizer reaction. At Kakamega, lime and $N_{37.5}P_{13}$ application caused another reduction of 18.6% ($p < .001$), and the combination of lime with $N_{75}P_{26}$ reduced NUE by 32.5% ($p < .001$). Similarly, at Siaya 1, NUE was reduced due to lime treatment with $N_{37.5}P_{13}$ reducing NUE by another 8.4% ($p < .05$) and $N_{75}P_{26}$ -14.9% ($p < .001$). Siaya 2 yielded the lowest performance with the lime and $N_{37.5}P_{13}$ reducing NUE by 12.3% ($p > .05$), and the lime and $N_{75}P_{26}$ had the performance increase of 23.1% ($p < .05$) with NUE performance.

Pairwise comparison using Tukey's HSD, as illustrated in Table 4.7revealed that in each of the three experimental sites, $N_{18.8}P_{6.5}$ always showed a higher NUE than both $N_{37.5}P_{13}$ and $N_{75}P_{26}$. NUE consistently followed the order $N_{18.8}P_{6.5}$>$N_{37.5}P_{13}$>$N_{75}P_{26}$. The highest difference in NUE due to micro-dose and $N_{75}P_{26}$ was 234% as observed in Siaya 2 in the 2018-LR season. Despite the fact that both results presented the treatments in order of increasing NUE, the separation between the various treatments was larger in the case of the Kakamega site. NUE decreased with an increase in fertilizer dose. From this case at Kakamega, $N_{37.5}P_{13}$ and $N_{75}P_{26}$ yielded a significantly lower NUE than did $N_{18.8}P_{6.5}$, while $N_{75}P_{26}$ was significantly lower in NUE than $N_{37.5}P_{13}$ and indicated larger disparities between the treatments. Still, the main features from Siaya 1 and Siaya 2 were quite similar to those described above, although the importance of the $N_{37.5}P_{13}$- $N_{75}P_{26}$ range was not present at Kakamega. Relative to Kakamega, we can see that at both Siaya 1 and Siaya 2 for $N_{37.5}P_{13}$, it was significantly higher than plants receiving $N_{75}P_{26}$, even though the contrast appeared to be not as great as in Kakamega.

Appendix IV summarizes results obtained for mean fertilizer NUE by sorghum during the growing seasons in the study sites. Means of NUE were highly significant (p<0.001) in limed over unlimed interaction with fertilizer doses. A high mean of 34.56% NUE was observed in Siaya 2 in the 2017-LR season. The lowest mean NUE was found to be 21.91%. Under fertilizer treatments, as low as 15% and a peak of 57% were realized.

4.3 Influence of lime on nutrients N and P uptake by sorghum grain and stover

4.2.5 Effect of lime, inorganic N and P doses, and their interaction on sorghum grain nitrogen uptake

At all three locations, grain nitrogen uptake reacted to application of lime and fertilizers, but with differences in magnitude and significance as summarized in Table 4.8. Appendix VI shows nutrient N and P uptake by sorghum grain across the individual sites over the season. Grain N ranged between 0.60-2.05% across the seasons in all study sites. Up to a 15% difference in grain N was reported between the control and application of $N_{75}P_{26}$ doses as observed in Siaya 1 in the 2018-LR season. In Kakamega, where GN increased by 9.8% due to application of lime under the main effect model ($p < .01$), the interaction effect (11.0%) was insignificant. $N_{75}P_{26}$ had the strongest fertilizer response, with a 10.5% increase ($p < .05$) under both main and interaction effects. Lower fertilizer rates (N_0P_0 and $N_{37.5}P_{13}$) did not result in significant differences from the constant. Siaya 1 exhibited highly consistent and statistically significant responses to all main treatments. Lime increased GN by 7.7% ($p < .001$), and the interaction model raised this to 9.2% ($p < .001$). The main fertilizer effects were also robust: $N_0P_0N_0P_0$ reduced uptake by 5.7% ($p < .001$), while $N_{37.5}P_{13}$ and $N_{75}P_{26}$ improved GN by 4.9% and 9.0%, respectively (both $p < .001$). Their interaction effects remained significant, particularly for $N_{37.5}P_{13}$ (6.0%, $p < .01$) and $N_{75}P_{26}$ (8.5%, $p < .001$). In contrast, Siaya 2 showed no statistically significant responses to either lime or fertilizer under either modeling approach. Though numerically higher gains were recorded with lime (17.7%) and $N_{75}P_{26}$ (10.2%), these values did not attain significance, likely due to higher variability as suggested by the larger standard errors.

Pairwise comparison as summarized in Table 4.9 showed that lime application (0t → 4t) increased grain nitrogen uptake at all sites by 15%, 14%, and 21% for Kakamega, Siaya 1, and Siaya 2, respectively ($p < .001$). First, enrichment from N_0P_0 to $N_{18.8}P_{6.5}$ resulted in a positive but predominantly nonsignificant reaction, Sega Siaya 1 alone exhibiting a small but significant 11% response ($p < .05$). Subsequent enrichment with $N_{18.8}P_{6.5}$ to $N_{37.5}P_{13}$ produced small and nonsignificant increases (6%, 9%, and 8%).

Importantly, the change from $N_{75}P_{26}$ to $N_{18.8}P_{6.5}$ generated dramatic declines in GN intake at each of the three sites—16% at Kakamega, 17% at Siaya 1 ($p < .001$), and 12% at Siaya 2 ($p < .05$)—a measure of decreased efficiency at the higher rates versus the moderate rate.

In contrast, N_0P_0 to $N_{37.5}P_{13}$ gains were notable for all the sites: 12% for Kakamega ($p < .05$), 20% for Siaya 1 ($p < .001$), and 16% for Siaya 2 ($p < .01$). The greatest and most reliable gains were for N_0P_0 to $N_{75}P_{26}$, whose GN uptake increased by 22%, 27%, and 20%, respectively (ps < .001). There was, however, a decrease from $N_{37.5}P_{13}$ to $N_{75}P_{26}$, with a significant 11% decrease at Kakamega (p < .05) as well as infinitesimal (significant) drops at the other stations.

Table 4.7: Comparison of grain Nitrogen and Phosphorus uptake under different fertilizer and lime treatments at two lime levels (0t vs. 4t)

Site	Contrast	Grain N Uptake (%)	Grain P Uptake (%)
Kakamega	No Lime → Lime (0t → 4t)	↑ 0.15 (15%) ***	↑ 0.08 (8%) ***
	N_0P_0 → $N_{18.8}P_{6.5}$	↑ 0.06 (6%) n.s.	↑ 0.04 (4%) n.s.
	$N_{18.8}P_{6.5}$ → $N_{37.5}P_{13}$	↑ 0.06 (6%) n.s.	↑ 0.06 (6%) *
	$N_{75}P_{26}$ → $N_{18.8}P_{6.5}$	↓ 0.16 (16%) ***	↓ 0.10 (10%) ***
	$N_{37.5}P_{13}$ → N_0P_0	↑ 0.12 (12%) *	↓ 0.10 (10%) ***
	$N_{75}P_{26}$ → N_0P_0	↑ 0.22 (22%) ***	↓ 0.14 (14%) ***
	$N_{37.5}P_{13}$ → $N_{75}P_{26}$	↓ 0.11 (11%) *	↑ 0.04 (4%) n.s.
Siaya 1	No Lime → Lime	↑ 0.14 (14%) ***	↑ 0.05 (5%) ***
	N_0P_0 → $N_{18.8}P_{6.5}$	↑ 0.11 (11%) *	↑ 0.03 (3%) n.s.
	$N_{18.8}P_{6.5}$ → $N_{37.5}P_{13}$	↑ 0.09 (9%) *	↑ 0.03 (3%) n.s.
	$N_{75}P_{26}$ → $N_{18.8}P_{6.5}$	↓ 0.17 (17%) ***	↓ 0.06 (6%) ***
	$N_{37.5}P_{13}$ → N_0P_0	↑ 0.20 (20%) ***	↓ 0.05 (5%) ***
	$N_{75}P_{26}$ → N_0P_0	↑ 0.27 (27%) ***	↓ 0.08 (8%) ***
	$N_{37.5}P_{13}$ → $N_{75}P_{26}$	↓ 0.08 (8%) *	↑ 0.03 (3%)
Siaya 2	No Lime → Lime	↑ 0.21 (21%) ***	↑ 0.06 (6%) ***
	N_0P_0 → $N_{18.8}P_{6.5}$	↓ 0.08 (8%) n.s.	↑ 0.03 (3%) n.s.
	$N_{18.8}P_{6.5}$ → $N_{37.5}P_{13}$	↑ 0.08 (8%) n.s.	↑ 0.02 (2%) n.s.
	$N_{75}P_{26}$ → $N_{18.8}P_{6.5}$	↓ 0.12 (12%) *	↓ 0.04 (4%) **
	$N_{37.5}P_{13}$ → N_0P_0	↑ 0.16 (16%) **	↓ 0.05 (5%) ***
	$N_{75}P_{26}$ → N_0P_0	↑ 0.20 (20%) ***	↓ 0.07 (7%) ***
	$N_{37.5}P_{13}$ → $N_{75}P_{26}$	↓ 0.04 (4%) n.s.	↑ 0.02 (2%) n.s.

Note. Arrows indicate direction of change. Significance codes: *p* < .05 (*), *p* < .01 (*), *p* < .001 (**), † = marginal (p ≈ .10), n.s. = not significant.

4.2.6 Effect of lime, inorganic N and P doses, and their interaction on sorghum grain phosphorus uptake

As summarized in Table 4.7, grain phosphorus uptake (GP) also rose with the addition of fertilizer at all the locations, albeit with differences in the degree of improvement. At the maximum level of application ($N_{75}P_{26}$), all three locations experienced rises, with Kakamega showing the highest, followed by Siaya 1, then Siaya 2. At mid-level application ($N_{37.5}P_{13}$), there was a pronounced peak in Kakamega and Siaya 1, while that of Siaya 2 was tiny. $N_{18.8}P_{6.5}$ gave smaller upticks that didn't quite reach significance anywhere. Lime alone also raised GP levels across the board. The response was strongest and statistically firm in Kakamega and Siaya 2. In Siaya 1, lime still helped, though its edge narrowed after accounting for interaction terms. As for the lime × fertilizer combinations, none stood out. Across all three sites, interaction terms hovered near zero with wide uncertainty, implying that lime and fertilizer mostly worked independently to enhance P uptake rather than in synergy. It was imperative that, as fertilizer P doses increased, more of it was partitioned to GP.

Table 4.8: Main and interaction effects of lime and fertilizer doses on sorghum stover nitrogen and phosphorus uptake as influenced by lime and varying fertilizer doses during the cropping periods across the experimental sites

Site	Contrast	Stover N Uptake (%)	Stover P Uptake (%)
Kakamega	No Lime → Lime (0t → 4t)	↑ 0.10 (12%) ***	↑ 0.02 (29%) ***
	N_0P_0 → Constant	↓ 0.07–0.11 (9–13%) **	↓ 0.02–0.00 (29–1%) **
	$N_{37.5}P_{13}$ → Constant	↑ 0.04–0.05 (5–6%) n.s.	↑ 0.01 (14%) n.s.
	$N_{75}P_{26}$ → Constant	↑ 0.07–0.08 (9–10%) **	↑ 0.01 (14%) **
	4t + N_0P_0 → N_0P_0	—	—
	4t + $N_{37.5}P_{13}$ / $N_{75}P_{26}$ → Control Treatment	—	—
Siaya 1	No Lime → Lime	↑ 0.09–0.10 (15–17%) *	↑ 0.01 (20%) ***
	N_0P_0 → Constant	↓ 0.02 (3%) n.s.	~0.00 ↓ (1%) n.s.
	$N_{37.5}P_{13}$ → Constant	↑ 0.04–0.06 (7–10%) n.s.	↑ 0.01 (20%) n.s.
	$N_{75}P_{26}$ → Constant	↑ 0.07–0.08 (11–13%) *	↑ 0.01 (20%) **
	4t + N_0P_0 → N_0P_0	—	—
	4t + $N_{37.5}P_{13}$ / $N_{75}P_{26}$ → Control Treatment	—	—
Siaya 2	No Lime → Lime	↑ 0.03–0.05 (5–8%) ***	↑ 0.06–0.07 (24–28%) ***
	N_0P_0 → Constant	↓ 0.09–0.14 (14–22%) ***	↓ 0.03 (12%) n.s.
	$N_{37.5}P_{13}$ → Constant	↑ 0.05–0.06 (8–9%) **	↑ 0.02 (8%) n.s.
	$N_{75}P_{26}$ → Constant	↑ 0.10–0.11 (16–17%) ***	↑ 0.04 (16%) *
	4t + N_0P_0 → N_0P_0	↑ 0.11 (17%) **	↓ 0.00 (1%) n.s.
	4t + $N_{37.5}P_{13}$ → $N_{37.5}P_{13}$	↓ 0.02 (3%) n.s.	↑ ~0.00 (1%) n.s.
	4t + $N_{75}P_{26}$ → $N_{75}P_{26}$	↓ 0.01 (2%) n.s.	↓ 0.00 (1%) n.s.

Note. Arrows indicate direction of change. Values in parentheses indicate percent change. Significance codes: $p < .05$ (), $p < .01$ (), $p < .001$ (**), n.s. = not significant, ~ = approximate estimate. Dashes (—) indicate unavailable data for that contrast at the site.

4.2.7 Effect of lime, inorganic N and P doses, and their interaction on sorghum stover nitrogen and phosphorus uptake

Stover nitrogen uptake (SN) steadily improved with rising fertilizer levels across all three sites, though the scale and reliability of gains depended on context (Table 4.8). In Siaya 2, every fertilizer dose—from low to high—brought a sharp and statistically firm increase in SN. That made it the most responsive site overall. Kakamega also showed clear, significant gains at all levels, especially under $N_{75}P_{26}$, though the absolute values were slightly lower. Siaya 1 was more cautious: $N_{75}P_{26}$ nudged SN upward, but lower doses did little, and statistical support was weak. Lime provided the maximum return in Kakamega and Siaya 2. It gave the highest P uptake in Kakamega, and even higher in interaction with fertilizer, although the interactions were slightly negative, indicating that yields were in decline. Siaya 2 registered the same: lime-enhanced uptake on its own and in combination, but the lime × fertilizer effects reduced the main effects a little. In Siaya 1, lime added a modest increase in the base model, but the benefit disappeared once interactions were considered. None of the interaction terms, however, reached significance.

In this study, Tukey's HSD post hoc test was used to evaluate the effect of different fertilizer treatments on phosphorus (P) content at the three sites. Stover phosphorus uptake (SP) steadily improved with rising fertilizer levels across all three sites, though the scale and reliability of gains depended on context. In Siaya 2, every fertilizer dose—from low to high—brought a sharp and statistically firm increase in SP. That made it the most responsive site overall. Kakamega also showed clear, significant ($p<0.001$) gains at all levels, especially under $N_{75}P_{26}$, though the absolute values were slightly lower. Siaya 1 showed that treatment with the higher recommended rates of $N_{75}P_{26}$

raised the SP, but lower doses increased it minimally, and statistical support was weak. Lime provided the maximum return in Kakamega and Siaya 2. It gave the highest P uptake in Kakamega, and even higher in interaction with fertilizer—although the interactions were slightly negative, indicating that yields were in decline. Siaya 2 registered the same: lime-enhanced uptake on its own and in combination, but the lime × fertilizer effects reduced the main effects a little. In Siaya 1, lime added a modest increase in the base model, but the benefit disappeared once interactions were considered. In fact, none of the interaction terms reached significance there.

Figure 4.9 illustrates the effect of fertilizer and lime application on soil nitrogen (SN) in the experimental sites. The level of sorghum stover N increased with the application of lime as well as higher levels of fertilizer in as shown in Figure 4.9 (a). The SN percentages increased as the rates of fertilizer with lime increased, as with 4 t/ha of lime (blue bars) versus the no-lime control (red bars).

It was observed that there were statistically significant treatment differences, especially in Kakamega and Siaya 2, where the higher fertilizer with lime rates had the greatest increases.

Figure 4.9 (b) reinforces these patterns by quantifying percent changes in SN relative to the intercept. Combined lime and fertilizer treatments (e.g., Lime4 × $N_{37.5}P_{13}N_{75}P_{26}$) produced the greatest positive shifts in SN, especially in Kakamega and Siaya 2, with significance levels ranging up to **p < .001. Conversely, principal effects of fertilizer registered lower gains only, and in others, the changes were not significant. In general, interaction effects indicate a synergistic benefit of lime and fertilizer on soil nitrogen enhancement, with site-specific responsiveness being more common in Kakamega.

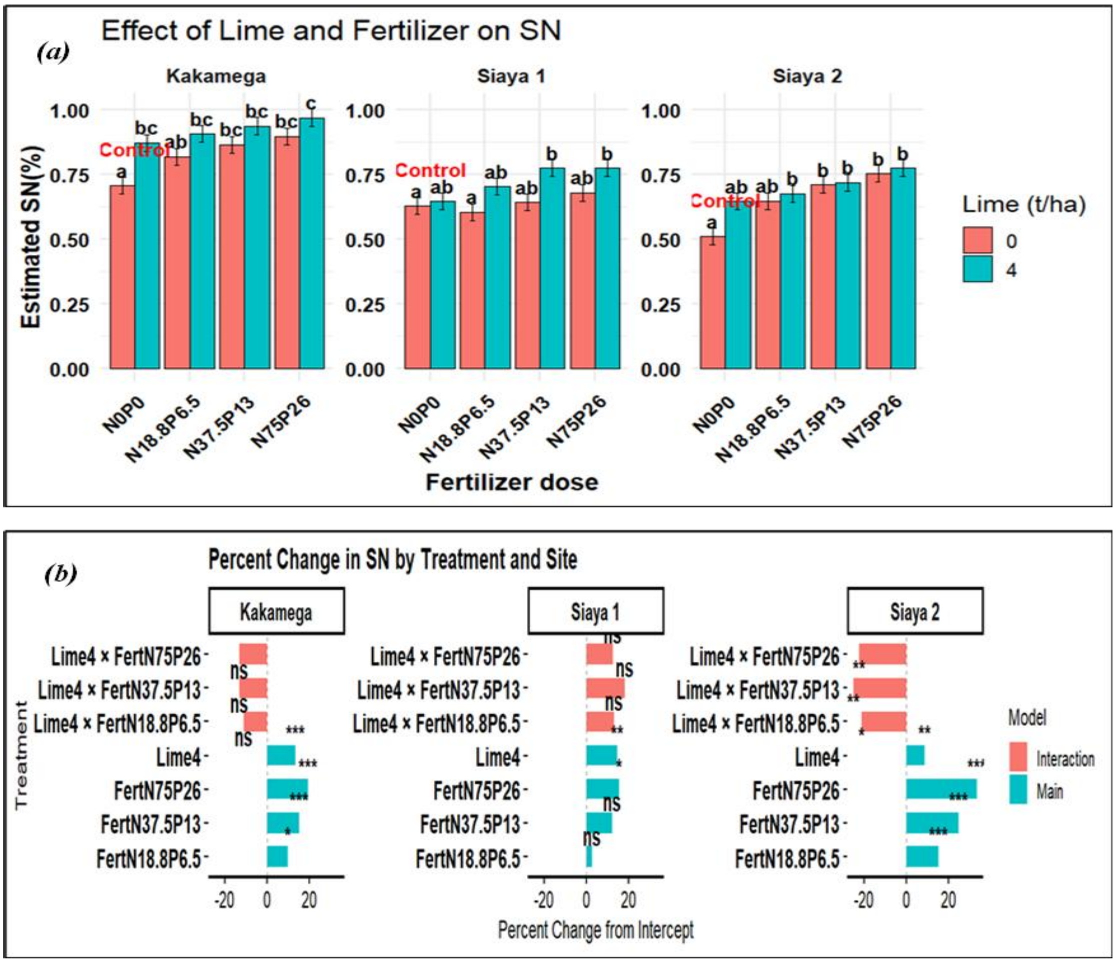


Figure 4.9*: Effect of Lime and Fertilizer on Soil Nitrogen Content Across Three Sites*

†*Note.* Panel *(a)* shows estimated soil nitrogen (%) under lime and fertilizer treatments across three study sites, revealing significant treatment-by-site interactions. Panel *(b)* illustrates the relative percent change in soil nitrogen compared to the intercept, highlighting site-specific responses and significance thresholds (**p* < .05, ****p** < .01, *** ***p*** < .001).

As summarized in Figure 4.10, fertilizer application increased nutrient uptake in sorghum tissue. The effect was strong. Site-specific linear regression showed clear trends. This applied to both nitrogen (N) and phosphorus (P). The trends were seen in grain and stover fractions. Kakamega had the highest slopes and R^2 values. This was true for all nutrient forms. Grain N uptake was especially responsive, where the slope was 0.016 and the R^2 value was 0.991. This showed high responsiveness to fertilizer application. Siaya 1 and Siaya 2 followed similar patterns, though with comparatively lower intercepts and marginally flatter slopes, suggesting site-dependent nutrient recovery efficiency. Regression fits were strong across all sites and nutrients ($R^2 \geq 0.85$), affirming linearity in the nutrient response curves within the studied application range. The measurements of phosphorus uptake were in agreement. However, they showed less pronounced gradients than nitrogen. There was natural heterogeneity in plant uptake dynamics. The same applied to the translocation of nutrients. These findings highlight an important point. Nutrient management practices must suit specific site conditions. This helps improve nutrient use efficiency. It is especially important in smallholder sorghum systems.

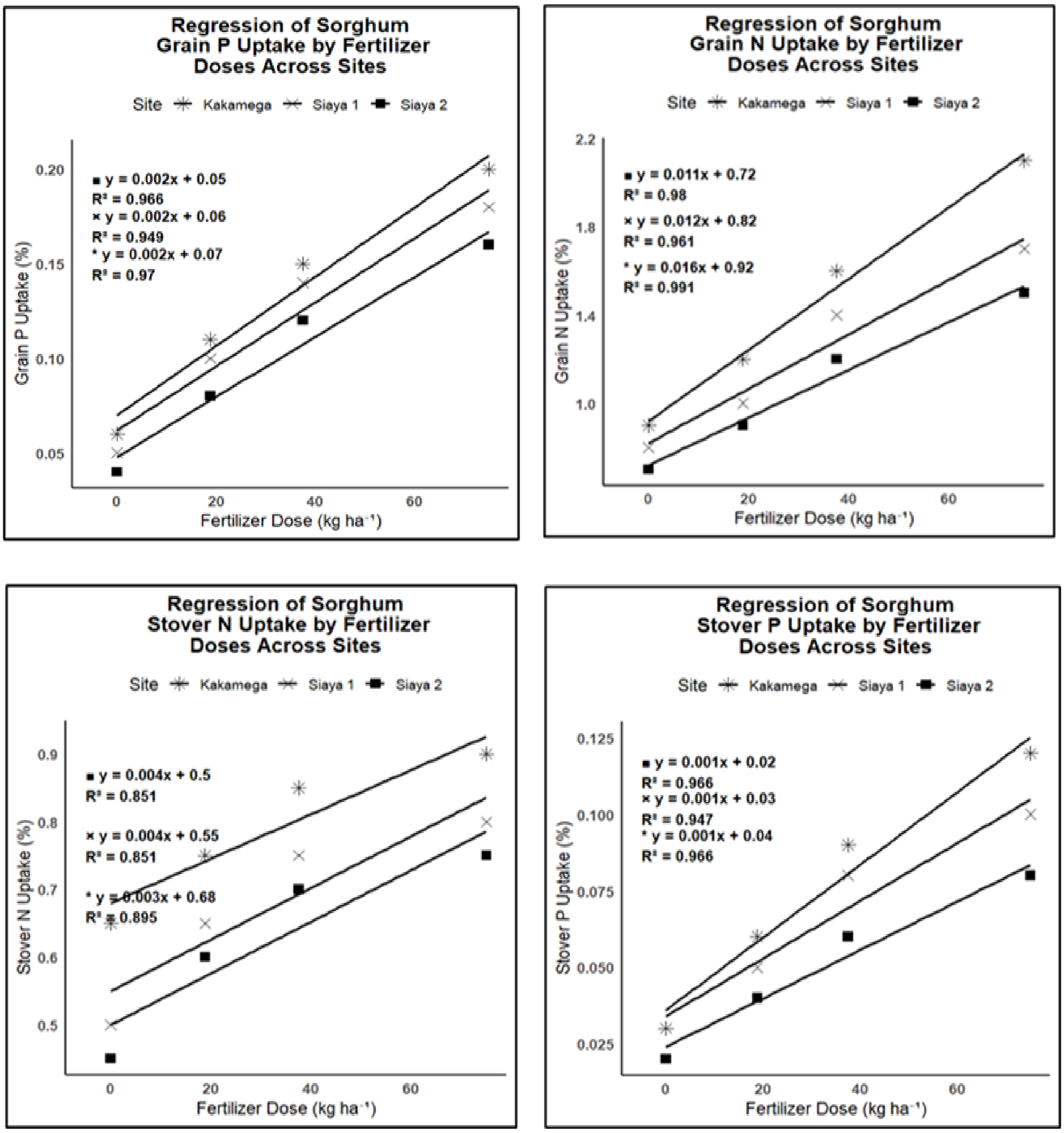


Figure 4.10: Linear regression of *Sorghum bicolor* grain and stover N and P uptake (%) in response to fertilizer dose across Kakamega, Siaya 1, and Siaya 2.

Site-specific equations and R^2 values are symbol-coded and positioned along the left margin.

4.4 Objective 3: To evaluate the relationships among soil chemical properties and sorghum performance metrics

4.4.1 Correlation of soil chemical properties and sorghum yield as influenced by lime and varying inorganic N and P doses

Pearson correlation analysis revealed that a number of statistically significant correlations existed among lime application, fertilizer use, soil chemical properties, and sorghum yield parameters. Soil pH, available P, total N, and soil organic carbon (SOC) were positively correlated with lime application, and exchangeable Al was negatively correlated at $p < .001$. Fertilizer application showed strong positive associations with sorghum biomass yield (SBY, t ha^{-1}), grain yield (SGY), N, and SOC ($p < .001$), and a moderate negative correlation with the carbon-to-nitrogen ratio (CNR; $p < .001$). SBY and SGY were positively associated with each other and also with pH, P, N, and SOC, while negatively correlated with Al and CNR (all $p < .001$). It is important to note that SOC had a high correlation with total N ($p <.001$), whereas CNR had significant negative correlations with N and SOC ($p <.001$). Al showed strong and negative correlations with P, N, and SOC ($p <.05$ or even less), consistent with the antagonistic effect of Al in acidic soils.

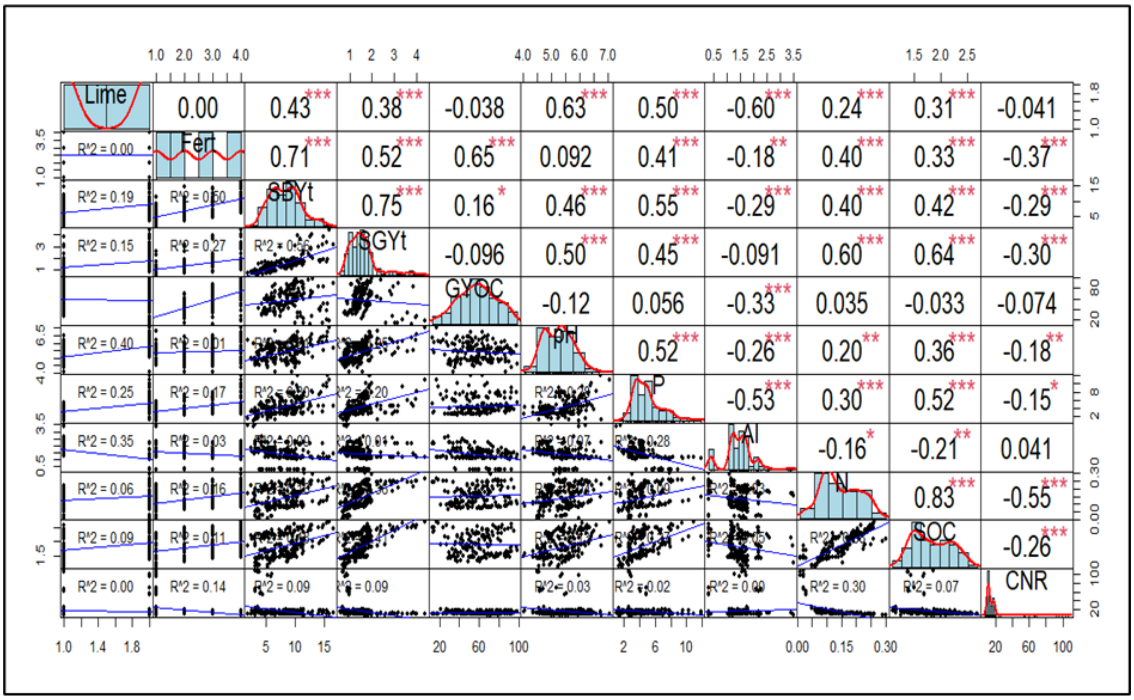


Figure 4.11: Chart showing the correlation of yield and soil chemical parameters under lime varying inorganic N and P doses across the sites and seasons.

Coefficients (*r*); 0.10≤0.30=small; 0.30≤0.50=medium; ≥0.50=large. * *p* <0.05, ** *p* <0.01, *** *p* <0.001

4.4.2 Correlation of soil chemical properties and nutrient N and P uptake as influenced by lime and varying inorganic fertilizer N and P doses

A detailed analysis of nutrient N and P uptake in sorghum grain and stover as a result of lime and fertilizer N and P application is summarized in Figure 4.13. The results established significant statistical relationships that demonstrate the importance of lime and fertilizer management for the sustenance of soil productivity, particularly in the improvement of nutrient use efficiency. The simultaneous nutrient uptake across plant components was evidenced by a moderate yet significant (*$p<0.001$*) relationship between grain nitrogen (GN) and grain phosphorus (GP), grain nitrogen GN and stover nitrogen (SN), as well as GP and SP. The data showed P availability leading to better N assimilation and distribution throughout the plant, as it positively and significantly (*$p < 0.001$*) linked GP with both SN and SP.

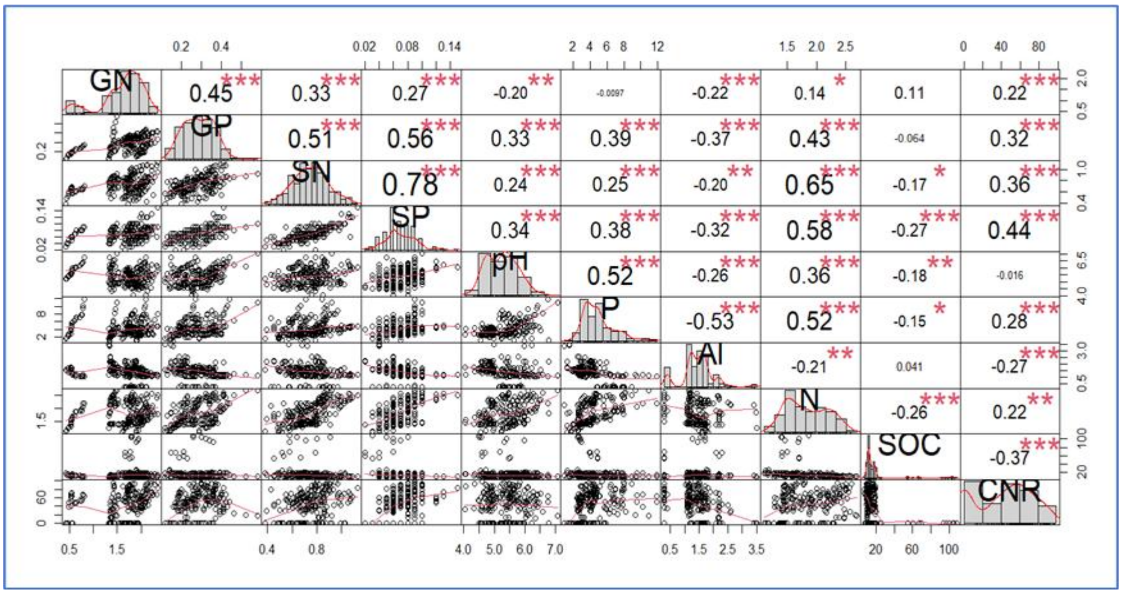


Figure 4.12: Correlation of soil chemical properties with nutrient N and P uptake by sorghum grain and stover in the study sites during the cropping seasons as influenced by lime and fertilizer doses

The use of lime applications affected soil chemistry through multiple positive and significant (*$p < 0.001$*) correlations between GN, GP, SN, SP, pH, and P, except for the insignificant correlation between GN and P. However, soil pH showed a contrasting negative and significant (*$p<0.001$*) correlation with exchangeable Al.

The essential role of plant-derived P in enhancing simultaneous N and P dynamics appeared through moderate to strong positive yet significant (*$p < 0.001$*) relationships between available soil P content and GP, SN, and SP. Soil N, together with SOC, played significant roles in the uptake of nutrients by sorghum. Results showed that soil N co-varied positively and significantly ($p < 0.001$) with GP and both SN and SP. Similarly, soil OC linked positively with GN and GP and SN, and SP. Soil exchangeable Al showed a negative and significant (*$p<0.001$*) association with GP and SN and SP, an indication that it suppressed nutrient absorption.

The study findings revealed that soil N displayed positive and significant ($p<0.001$) relations with GP, SN, and SP, while SOC showed similar correlations to GN, GP, SN, and SP. The exchangeable soil Al had a negative and significant ($p < 0.001$) relationship with GP, SN, and SP, indicating its inhibitory impact on nutrient acquisition.

4.4.3 Correlation of soil chemical properties with yield assessment indices of grain sorghum under lime and inorganic N and P doses

Pearson correlation analysis was adopted to study the correlation between lime and fertilizer application, sorghum harvest index (HI), agronomic efficiency (AE), nutrient uptake efficiency (NUE), and soil factors such as pH, available phosphorus (P), exchangeable aluminum (Al), soil organic carbon (SOC), and carbon-to-nitrogen ratio (CNR).

As summarized in Figure 4.16, lime addition was significantly ($p < 0.001$) and positively correlated with higher pH and extractable phosphorus, and with exchangeable Al declines. Lime addition was also very ($p < 0.001$) highly significantly ($p < 0.001$) correlated with AE, NUE, and SOC, indicating that lime addition increases the efficiency of nutrient uptake and chemical fertility of the soil. Lime was negatively and significantly ($p < 0.001$) associated with aluminum and HI, implying that liming may reduce Al toxicity and shift biomass partitioning. Fertilizer application was strongly ($p < 0.001$) correlated with AE and NUE, but in both instances negatively, and also had strong ($p < 0.001$) correlations with available P and SOC. Interestingly, there was a significant ($p = 0.01$) negative correlation with exchangeable Al, indicating indirect suppression of acidification by input conditions of nutrients. Fertilizer application was negatively and significantly ($p < 0.001$) associated with harvest index and CNR.

Harvest index (HI) was also significantly ($p < 0.001$) positively correlated with AE and NUE, demonstrating that nutrient use dynamics are associated with efficient biomass to grain conversion. It was not correlated significantly, however, with soil pH, P, or SOC ($p > 0.05$), suggesting that HI could be more sensitive to physiological than immediate soil chemical aspects.
Agronomic efficiency (AE) was significantly ($p < 0.001$) positively related to NUE and soil pH, and negatively and significantly ($p < 0.001$) associated with exchangeable Al, supporting the idea that both lime and fertilizer influence efficiency primarily through changes in soil acidity.
Nutrient uptake efficiency (NUE) was significantly ($p < 0.001$) correlated with AE, liming, and pH soil ($p = 0.02$), but not significantly correlated with Al, P, or SOC ($p > 0.05$), suggesting a more intricate interaction possibly mediated by root uptake processes. Among soil indices, pH was significantly ($p < 0.001$) associated with

available P, SOC, and inversely with Al. Available P also correlated significantly ($p < 0.001$) with SOC and negatively with Al. Exchangeable Al had significant ($p < 0.001$) negative relationships with lime, AE, and pH. SOC showed significant ($p < 0.001$) positive correlations with both lime and fertilizer, and with available P. Lastly, the C: N ratio showed weaker but statistically significant ($p < 0.05$) correlations with HI, pH, and available P, while its associations with lime and Al were not significant.

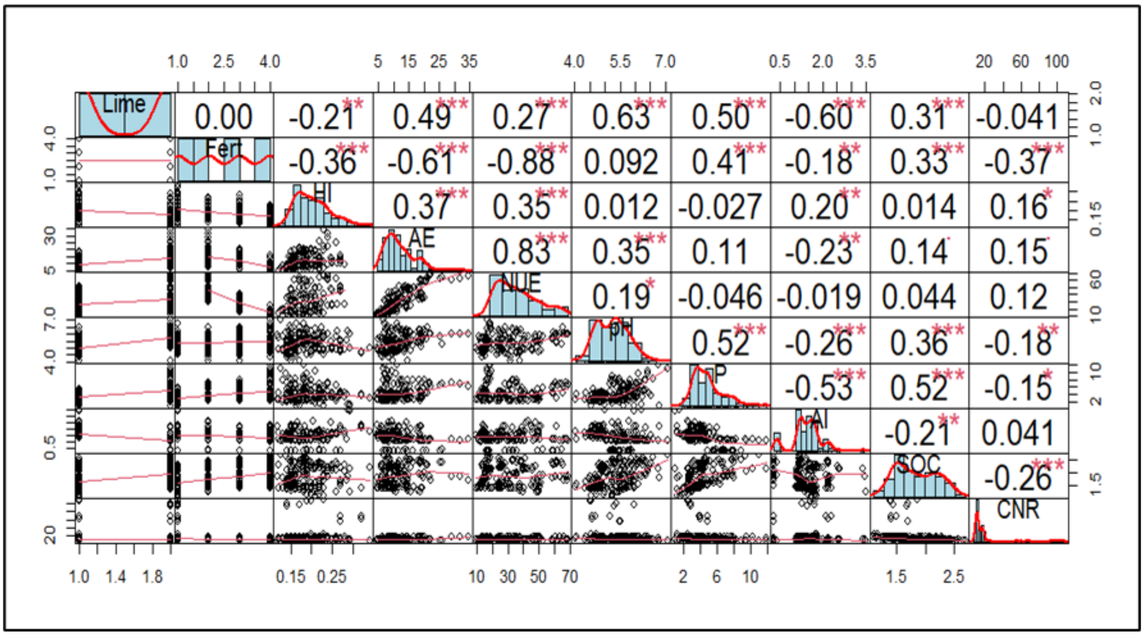


Figure 4.13: Correlation of soil chemical properties with yield assessment indices of grain sorghum as influenced by lime and fertilizer doses.

†Asterisks following correlation values represent the effect sizes; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Effect sizes were labelled following Funder's (2019) recommendations

Soil phosphorus established significant (*$p < 0.01$*) associations mainly with plant HI, AE, and NUE, indicating its vital functions in both development structure and biochemical processes. The study showed that Al toxicity was observed to have a negative correlation between both AE (*$p < 0.001$*) and NUE (*$p < 0.05$*). This reinforced the positive impact of lime application in reducing the effects of Al toxicity in acidic soils.

4.4.4 Correlation of yield and nutrients N and P uptake by sorghum grain and stover as influenced by lime and fertilizer doses

Pearson correlation was used to assess relationships between lime and fertilizer application, sorghum biomass yield (SBY), grain yield (SGY), grain yield over control (GYOC), and measures of nutrient uptake, e.g., grain nitrogen (GN), grain phosphorus (GP), stover nitrogen (SN), and stover phosphorus (SP) (Figure 4.14). Application of lime was significantly ($p < 0.001$) correlated with biomass production, grain yield, and all nutrient uptake parameters (GN, GP, SN, and SP), with the highest correlation with stover P. Application of fertilizer was significantly ($p < 0.001$) correlated with all the result variables, such as SBY, SGY, GYOC, and all nutrient uptake parameters. SBY was significantly ($p < 0.001$) correlated with SGY and all nutrient uptake parameters except grain N, indicating that overall plant growth is tightly linked to P uptake and nutrient remobilization efficiency. Its positive association with GYOC was marginally significant ($p = 0.04$). SGY was also significantly ($p < 0.001$) associated with grain P, stover N, and stover P. However, the correlation with grain N was not statistically significant ($p = 0.67$), suggesting that N content in the grain may not directly reflect yield magnitude. Grain yield over control (GYOC) exhibited significant ($p = 0.01$) correlations with grain N and both stover nutrient uptakes (SN and SP), but not with grain P ($p = 0.22$) or SGY itself ($p = 0.23$), highlighting that improvements relative to the control may be more strongly tied to vegetative nutrient retention. Of the nutrient uptake indices, grain P was significantly correlated ($p < 0.001$) with grain N and stover nutrients. Stover P and stover N were significantly intercorrelated ($p < 0.001$), implying correlated nutrient allocation patterns in vegetative tissues.

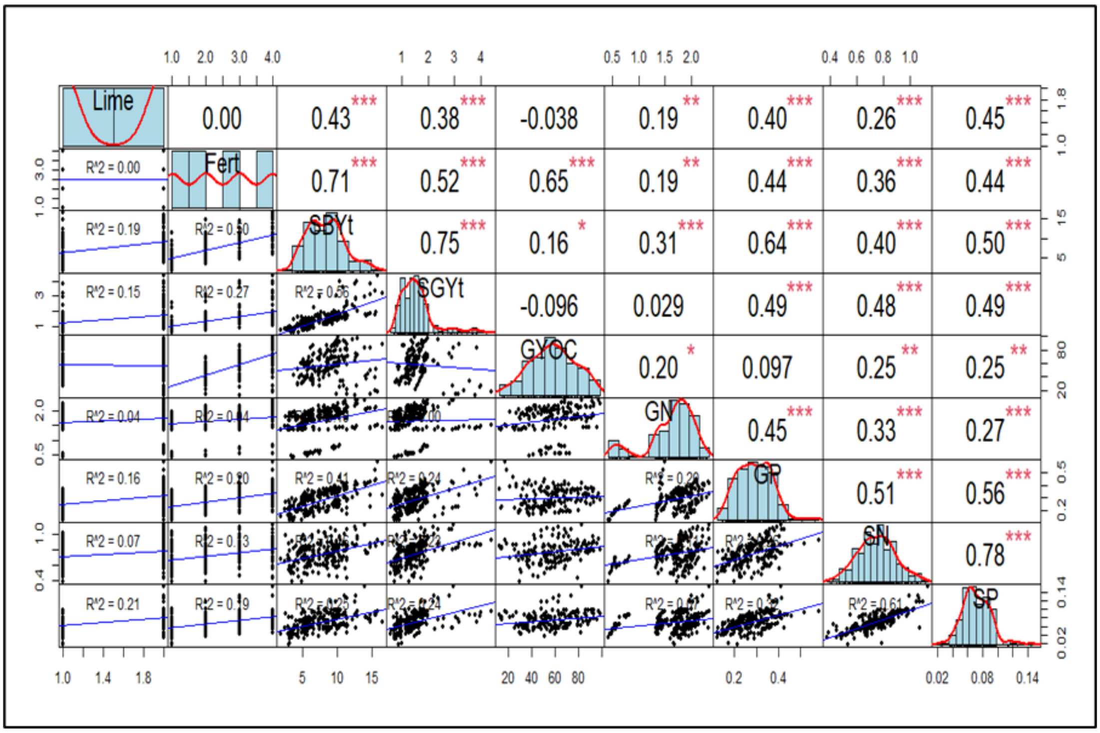


Figure 4.14: Correlation of yield and nutrients N and P uptake by sorghum grain and stover as influenced by lime and fertilizer doses.

†Asterisks following correlation values represent the effect sizes; * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$. Effect sizes were labelled following Funder's (2019) recommendations

4.5 Objective 4: To evaluate the economic efficiency of lime–fertilizer combinations in enhancing sorghum productivity.

4.5.1 Gross Marginal analysis of sorghum as influenced by lime and fertilizer doses

Gross margin (GM) was highly affected by lime × fertilizer treatments across all sites and seasons ($p < .001$) (Fig.4.15). All the treatments with lime had higher values of GM than those without lime. The highest gross margin was achieved under the 4 t ha^{-1} lime + $N_{75}P_{26}$ treatment in Kakamega during the long rains season of 2016 and was valued at 94,983 KES ha⁻¹.In Siaya 2, the same treatment yielded 70,112 KES ha⁻¹ during the 2017 long rains season. Several other treatments also exceeded the profitability threshold of 50,000 KES ha⁻¹, including 4 t ha⁻¹ lime + $N_{37.5}P_{13}$ and, in some instances, 0 t ha⁻¹ lime + $N_{75}P_{26}$. Lime treatment with moderate fertilizer rate application levels ($N_{37.5}P_{13}$ and $N_{18.8}P_{6.5}$) generated middle-level gross margins ranging from 35,000 to 65,000 KES ha⁻¹ by site and season. The control (0 t ha⁻¹ lime + N_0P_0) recorded the least and increasingly had gross margins below 20,000 KES ha⁻¹.

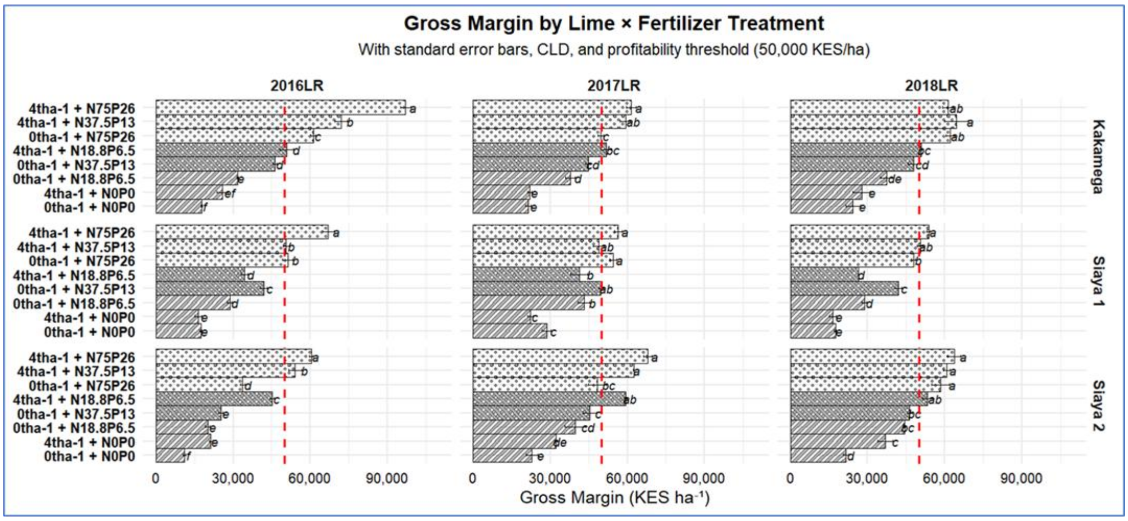


Figure 4.15: Gross Margin by Lime × Fertilizer Treatment

Mean gross margin (KES ha⁻¹) ± standard error for eight lime × fertilizer treatments at Kakamega and Siaya across the 2016-LR, 2017-LR, and 2018-LR seasons. The dashed red line indicates the profitability threshold (50,000 KES ha⁻¹). Different letters denote statistically significant differences among treatments (Tukey's HSD, $p < .05$).

4.5.2 Benefit-cost ratio for sorghum productivity under lime and fertilizer doses in acidic soils of western Kenya

A summary of the Benefit-Cost Ratio (BCR) is presented in Fig. 4.16. BCR was considerably affected by lime × fertilizer treatments at each location and season (p <

.001). Treatment 4 t ha^{-1} lime plus $N_{75}P_{26}$ consistently produced the highest values of BCR, far above the critical threshold at 2.0 in all combinations of site and season. For Kakamega, the treatment provided BCR values close to or in excess of 3.5, whereas for Siaya 1 and Siaya 2, BCR values ranged from 2.5 to 3.2 as per season.

Other treatments also exceeded the BCR threshold of 2.0 in some cases. Particularly, 4 t ha^{-1} lime + $N_{37.5}P_{13}$ and 0 t ha^{-1} lime + $N_{75}P_{26}$ both achieved the viability threshold in more than one site-season combination, especially during the 2018 long rains season. The 4 t ha^{-1} lime + $N_{18.8}P_{6.5}$ treatment also achieved or surpassed the threshold in certain cases, although less consistently across sites.

In contrast, treatments involving reduced fertilizer rate and non-lime, like 0 t ha^{-1} lime + $N_{18.8}P_{6.5}$ and 0 t ha^{-1} lime + $N_{37.5}P_{13}$, also had BCR values less than 2.0. The control treatment, 0 t ha^{-1} lime + N_0P_0, yielded the lowest BCR values at both locations and times that were often less than 1.0.

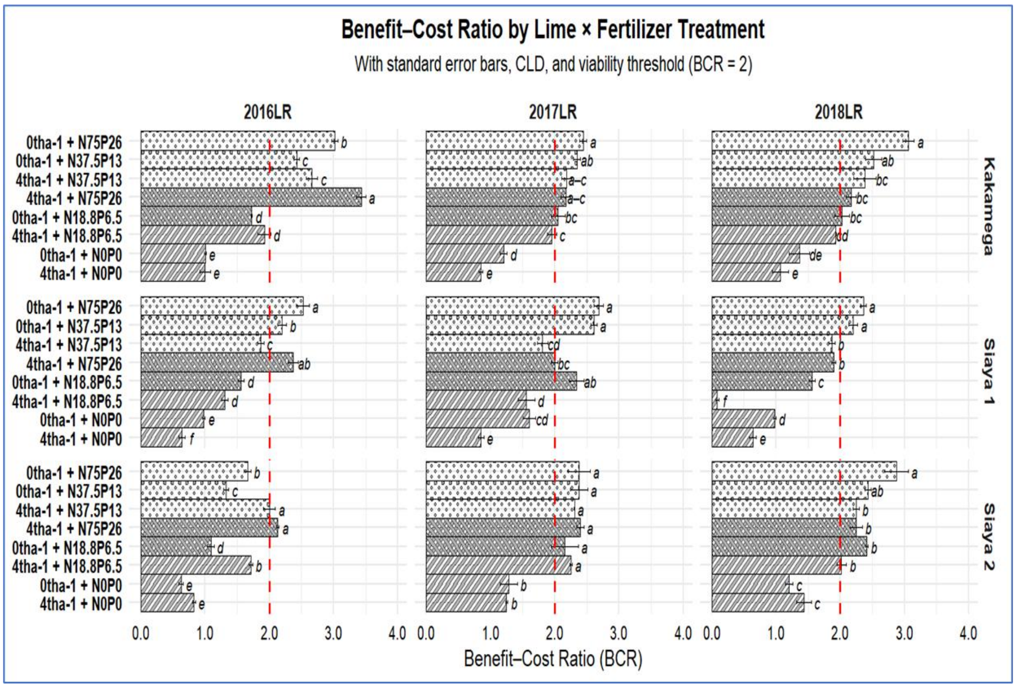


Figure 4.16. Benefit–Cost Ratio by Lime × Fertilizer Treatment

†Mean benefit–cost ratio (BCR) ± standard error for eight lime × fertilizer treatments at Kakamega and Siaya across the 2016-LR, 2017-LR, and 2018-LR seasons. The dashed red line marks the viability threshold (BCR = 2.0). Treatments combining 4 t ha^{-1} lime with full fertilizer rate ($N_{75}P_{26}$) significantly exceeded this threshold ($p < .001$), whereas the control (0 t ha^{-1} + N_0P_0) remained below 1.0.

CHAPTER FIVE

DISCUSSION

5.1 Objective 1: To assess the effects of lime and NP fertilizer rates on selected soil chemical properties of acidic soils in western Kenya

5.1.1 Effect of liming and inorganic nutrients N and P on soil pH changes

The consistent reduction in hydrogen ion concentration [H^+] across all study sites following lime application at 4 t ha^{-1} reflects the fundamental chemical reaction of lime (commonly $CaCO_3$) in acidic soils. When applied, lime underwent the following neutralization reaction:

$$CaCO_3 + 2H^+ \rightarrow Ca^{2+} + CO_2 + H_2O$$

Calcium oxide (CaO)-based agricultural lime, which was manufactured in Koru, was vital in the process of adjusting the acidity of soils in most Kenyan agro-ecological set-ups. When used, CaO reacted with soil moisture to produce calcium hydroxide ($Ca(OH)_2$), which neutralized hydrogen ions (H^+) and increased the pH of the soil; this process was well-reported in the acid soil management literature by Muindi (2015a). The resulting calcium ions (Ca^{2+}) pushed out exchangeable aluminum (Al^{3+}) and hydrogen ions in the soil colloids and hence, made the soil lose exchangeable acidity and probably increased its cation exchange capacity (CEC). These pH changes also enhanced the availability of phosphorus (P) by decreasing the activity of Al^{3+}, which otherwise bound P in insoluble forms. The field studies conducted in Western Kenya revealed that liming significantly increased the supply of P and crop uptake, both with phosphorus fertilizer applied in moderate amounts (Opala et al., 2015; Kisinyo et al., 2014). These findings affirm the use of locally available agricultural lime as an affordable and technically viable amendment in the management of acidity in soil and in supplementing the use of nutrients in the smallholder farming systems.

Additionally, higher pH likely supported microbial activity, notably nitrifiers that oxidize ammonium (NH_4^+) to nitrate (NO_3^-)—more plant-soluble; a stimulation of such microbes could also have enhanced decomposition of organic matter, thereby elevating mineral N availability for sorghum assimilation (Dereje et al., 2019). Al^{3+} is toxic to roots when the pH is low. By precipitating Al as the insoluble $Al(OH)_3$ with lime, toxicity and root growth, and nutrient absorption (Enesi et al., 2023) are enhanced.

The highest increase in pH values (4.50 to 6.19 at Siaya 2) is related to the power of lime in a highly acidic, poorly buffered soil. The lesser pH rise at Kakamega (6%) was due to greater initial pH and more clay, which did not allow for a sudden pH change.

Notably, fertilizer-only application produced little or irregular influence on pH. High rates of nitrogen (e.g., $N_{75}P_{26}$) could have caused slight acidification via nitrification and proton release in some cases, but this was not statistically significant in the short term. This is consistent with Li et al. (2019), who explained that ammonium-type fertilizers can gradually reduce soil pH over time.

5.1.2 Effect of liming and inorganic nutrients N and P on available soil Phosphorus

The site-specific increases in fertilization and lime application observed are consistent with what has been established in acid soil management. Specifically, the marked increase in available phosphorus at Kakamega after combined fertilizer and lime treatment is a manifestation of the synergy in pH correction and nutrient supplementation. This is in line with Kisinyo *et al.* (2013), who established that the application of lime effectively reduces exchangeable aluminum and improves phosphorus availability in Siaya acid soils of western Kenya. In contrast, non-improvement of phosphorus at Siaya 1 following treatment reveals ongoing P fixation or low initial fertility. This is supported by research carried out by Haynes (1982), which indicated that liming does not always favor P availability in highly weathered soils because of precipitation of amorphous Al-hydroxyl polymers that continue to adsorb phosphate.

In Siaya 2, the beneficial impact of lime alone to constrain P decline is a sign of its function to relieve aluminum toxicity and to sustain P solubility—a process extensively proven in the review of Haynes (1982) and clarified by Muindi et al. (2015b), which stated that lime-Al-P interactions notably limit P adsorption and enhance extractable P in Kenyan highland soils. In contrast, for Siaya 1, the effects of lime and fertilizer treatments were generally less pronounced. These results showed the benefits of liming in combination with microdose fertilizer, especially in Kakamega, to optimize soil P levels and argue that soil management schemes would have to be adapted to location to ensure optimized availability of soil P. Liming of acid soils increased soil pH with resultant freedom of phosphate ions (PO_4^{3-}, HPO_4^{3-}, and $H_2PO_4^{3-}$) which had been precipitated with Al thus, making P available for plant uptake. This increase in available soil P could be due to enhanced availability of labile soil P or mineralization of soil organic P at nearly equal levels despite the variably applied doses. Furthermore, this increase, in turn, possibly led to P utilization by sorghum, as discussed later in this thesis. Similar results were observed of lime increasing the soil available P due to the reduced P sorption as was reported by Esilaba *et al.* (2023) and Kisinyo *et al.* (2015).

The influence of 4t Limeha^{-1} against no lime treatment in raising available soil P was apparent from the high soil exchangeable P reported in all study sites. The application of higher P rates resulted in higher residual P levels in the soil, as was reported in section 4.1. Empirical data from our experiments in Siaya 2 and Kakamega data, treatment receiving more P rates under liming conditions had statistically higher residual soil content of P, especially where P > 30 kg ha^{-1}. This is proof of a linear relationship between the rate of application and recovery of residual P after cropping. At elevated P rates, crop uptake reaches physiological limits, leaving excess P in the rhizosphere or bound to soil particles in plant-available forms. This explains why residual P accumulates despite active root absorption. In the present experiment, lime elevated pH and reduced Al toxicity, thereby limiting the formation of insoluble Al-P and Fe-P complexes. This rendered P applied through fertilizer more prone to stay in the soil solution or labile pool at the crop's maturity stage. Acid soils, prevalent in Siaya and Kakamega, tended to fix P owing to the high reactivity of aluminum (Al^{3+}) and iron (Fe^{3+}). Incorporating higher levels of P likely to have started to take up these binding sites, and a larger percentage of P was then retained in available or extractable pools. This indicated a higher proportion of unutilized P during the sorghum growing period under a higher dose of 26 kg ha^{-1} than the micro-dose application of 13kg ha^{-1} and 6.5 kg ha^{-1}. Although a linear upward trend was observed from low to high dose fertilizer P rates, it is deduced that 13kg ha^{-1} and 6.5 kg ha^{-1} or higher were excessive application doses and could have led to surplus soil P not utilized by the sorghum crop. Similarly, post-harvest soil P recorded was low when microdose fertilizer was used, suggesting optimal utilization by sorghum or complete fixation where liming was not done, of available soil P under the microdose rate. In higher doses, the findings indicated that more P fertilizer than sorghum's potential root assimilation resulted in the accumulation of unused P in the soil. This excess P may not have been fully taken up by sorghum during the growing season. Since there was no significant difference between $N_{75}P_{26}$ and $N_{37.5}P_{13}$ doses in their influence on available soil P, the results provided an application option between the recommended and the microdose without compromising on yield. Lack of significant difference with application of 13kg ha^{-1} and 6.5 kg ha^{-1} indicated the likelihood of micro-dose level being optimally assimilated and thus, minimal residual P within the sorghum root zone at harvesting. The results, therefore, affirmed the influence of fertilizer doses on the residual concentration of available soil P. Further, the variable residual P in the study sites is probably due to the difference in varied nutrient uptake efficiency occasioned by variation in soil types, due to the lower clay and sandy nature in Kakamega Acrisols, than Ferralsols of Siaya site Ferralsols which are technically defined by a fine-textured subsurface layer of low silt-to-clay ratio. They also have high contents of kaolinitic clay and iron and aluminum oxides, and low amounts of available calcium or magnesium, and hold water well, as described by Jaetzold et al. (2010). As was reported earlier, AE and HI were pronounced under microdose P6.5 kg $ha^{-1}$and indicated higher P efficiency than the recommended higher doses.

The findings indicate that the use of fertilizer $N_{37.5}P_{13}$ and $N_{75}P_{26}$ rates may have been greater than the sorghum could take in one instance, leading to excess P in the soil. This is evident from the highest value of post-harvest mean soil P at 5.48 mg kg^{-1} under $N_{75}P_{26}$ treatment. Nevertheless, since the research was short-term, no soil pH variation was observed across fertilizer levels, even in the anticipation of acidification with increased N inputs, a sign of the buffer capacity of the soil within a short duration.

Nevertheless, the initial low rhizosphere pH, in turn unaltered by fertilizers, could have played a role in P sorption patterns in soils, especially in acidic soils.

Notably, no yield differences were observed between $N_{75}P_{26}$ and the lower dose of $N_{37.5}P_{13}$, and this shows that microdosing can attain similar productivity without resulting in residual buildup of nutrients. Post-harvest P content in the $N_{18.8}P_{6.5}$ and N_0P_0 treatments also implies increased P utilization and minimal risk of environmental loss. The declining residual P response of the Kakamega site during the 2016 LR season suggests that site-specific factors, such as a high ability for P fixation of Acrisols or temporal limitation on nutrient cycling, prevent short-term P accumulation—regardless of application rate. These results, in general, support the soundness of microdose fertilizer practice that strictly follows crop needs and avoids undesirable chemical alteration of the soil at the initial phase of nutrient management.

The variable residual P in the study sites was probably due to the difference in varied nutrient uptake efficiency occasioned by variation in soil types, as already alluded. There was consistency in the trend of fertilizer N and P doses and the amount recorded in the sorghum root zone P. However, several instances showed that there was no significant difference between the levels of fertilizer N and P doses. For instance, in Siaya 1 in 2016-LR, soil P level showed no significant difference between $N_{75}P_{26}$ and $N_{18.8}P_{6.5}$ application doses. $N_{75}P_{26}$ and $N_{37.5}P_{13}$ doses showed no soil P difference at harvesting, meaning there is a P-dose threshold beyond which assimilation is inhibited. Lack of significant difference with no fertilizer and microdose $N_{18.8}P_{6.5}$application indicated the likelihood of microdose level being optimally assimilated and thus, minimal residual P within the sorghum root zone at harvesting. The results, therefore, affirmed the influence of fertilizer doses on the residual concentration of available soil P.

5.1.3 Effect of liming and inorganic nutrients N and P on exchangeable soil Aluminum

At sites, lime application raised soil pH, which likely led to the precipitation of toxic Al ions as insoluble aluminum hydroxides, thereby reducing exchangeable Al. Low soil exchangeable Al concentration was realized upon treatment with 4t Lime ha^{-1} agricultural, which principally constituted burnt CaO. Similar results were obtained by (Bowo & Zahni, 2023; Chulo et al., 2023; Ejigu et al., 2023; Kibet et al., 2023). Our observations are similar to recent deductions that lime application increases the pH level and reduces toxic aluminum concentration (Abdi, 2024).

In the current experiment, Al remained precipitated and less available in the soil solution, which could be attributed to the lesser differences in exchangeable Al under fertilizer treatments. However, the fertilizers used may not have contributed enough acidity or anions to drive Al to be sufficiently mobilized across all doses, particularly in soils where Al had already been fixed or where baseline soil pH was only slightly acidic. The observed lack of treatment differences may be attributed to the possibility that only a small percentage of the fertilizer applied had compounds with acidifying potential.

5.1.4 Effect of liming and inorganic nutrients N and P on soil Nitrogen

Application of agricultural lime at 4 t ha^{-1} enhanced a continued supply of adequate soil N levels in the experimental treatments. Despite the mechanisms' complexity, lime is simply a buffering mechanism against acidification by ensuring stabilization of soil pH to levels far within microbial populations involved in nitrogen cycling (Basu et al., 2021; Fenice, 2021; Martikainen, 2022; Ramm et al., 2022; Robertson & Groffman, 2024). In the present study, the resultant increase in pH following liming was most likely to have caused long-term alterations in the functionality of microbes, in which case the organic matter breakdown could be accelerated, and the transformation of nitrogen processes accelerated. The fact is that, in addition to the effects of biological processes, lime may have led to improved physical soil properties, such as structure and aggregation, as well as an increment in cation exchange capacity, as evidenced in recent research findings (Junior et al., 2020; Y. Wang et al., 2021). These cumulative effects would have enhanced both the overall supply and duration of nitrogen in the root zone, justifying the use of lime to control acidity in the soil in order to enhance the distribution of nutrients, as was presented in section 4.1.4.

5.1.5 Effect of liming and inorganic nutrients N and P on available soil Organic Carbon

Initial SOC was low in the study sites. It was shown that in all the study sites, using 4t Lime ha^{-1}consistently led to a significant increase in SOC, which agreed with the findings of Wang *et al.* (2021). Lime incorporation into the soil has been identified as one of the leading ways through which SOC can be improved since the concept enhances the pH of these low pH soils. Although there was no addition of external organic matter sources, liming likely led to increased SOC by improving soil pH, reducing aluminum toxicity, enhancing plant productivity, promoting microbial activity, and stabilizing organic carbon. The overall result is greater input and retention of carbon in the soil system, particularly in the surface soils of these study sites, other than Siaya 2. These findings agree with the findings of Trivedi et al.(2021) on improved SOC stabilization, Murugan et al. (2022) on benefits to organic carbon cycles, Hijbeek et al. (2021) on improved biomass outputs and thus SOC, and Murugan et al. (2022) on significantly enhanced growth and yield with subsequent benefits to organic carbon cycles. Lime may have also played a role in cycling phosphorus in that once it effectively raised the soil pH, it may have consequently enhanced the content of phosphorus, which is an essential nutrient in plant production. With improved plant growth comes a better deposition of organic matter and, hence, an improvement in SOC levels. Since SOC is derived from soil organic matter, Crusciol et al. (2017), Chan & Heenan (1999), and Wang et al. (2016), some researchers (Chan & Heenan, 1999; Crusciol et al., 2017; X. Wang et al., 2016) opined that the change in SOM content may take longer, or the degree of change in soil pH could not be sufficient to change the SOC levels. It can be inferred, therefore, that increasing or decreasing crop residue alongside liming determines whether net SOC decreases or increases, thus dictating the balance between SOC gains and losses. In the current study, low pH soils probably inhibit beneficial bacteria, reducing organic matter decomposition and humification needed for stable active SOC. Soil acidification likely reduced microbial and macrofaunal diversity and diminished biological functions essential for soil carbon cycling. When soils are acidic (pH < 5), Al^{3+} becomes soluble and toxic, inhibiting root elongation, nutrient uptake, and biomass production. This results in poor crop growth and less residue returned to the soil, contributing to low SOC. Acidic soils often cause deficiencies in P, Ca, Mg, and other nutrients, stunting plant growth. With limited above- and below-ground biomass, there is less substrate entering the soil organic carbon pool. Bai et al. (2025) observed that acidic soils favor fungi over bacteria, and that fungal-dominated decomposition can lead to higher carbon turnover rather than stable humus formation. This led to the conclusion that acidification stimulated SOC loss by increasing microbial breakdown of labile carbon.

In contrast, reports indicate that liming under specific conditions may elicit reduced SOC under long-term trials of liming acidic Ferralsols (Ernani et al., 2004), acidic Sodosols (Aye et al., 2016), and acidic Tenosol and Chromosol (Grover et al., 2017). The strong positive linear trend from nil treatment to $N_{75}P_{26}$ with an R^2 value of 0.88 showed the responsiveness of these soils to the progressive increase of fertilizer N and P. Lime-fertilizer interaction means slightly increased and ranged from 1.43 to 2.28% across the study sites and seasons. According to Smith (2004), increases in SOC inputs, which are below 15% might make it impossible to detect a change in SOC without a colossal number of samples. The interaction between lime and fertilizer treatments can have complex effects on SOC levels, and the outcomes of which depend on soil type, initial soil conditions, and lime and/or fertilizer used, as well as the management practices. In lime-fertilizer interaction, the contribution of lime could have benefited soil microbial activity and the decomposition of organic matter, potentially leading to increased SOC levels. Further, fertilizers could have contributed to the supply of essential nutrients, which likely led to increased plant growth and root biomass. Root growth could have contributed organic matter to the soil through root exudates as plants took up nutrients from the soil and decaying plant material. This can lead to increased SOC levels in the soil.

The values of R^2 range from 0.59 to 0.63, and the significant F-statistics meant that all the outcomes were quite stable. The fact that there were consistent trends identified through the different modeling strategies increased confidence in the generalizability of these findings for use in soil management practices. These results elucidate the importance of fertilization in building and enhancing SOC stocks, especially under the high input $N_{75}P_{26}$ treatment. Concerning nutrient availability, the data also indicated adverse effects of nutrient depletion under unfertilized conditions. The overall trend aligns with known mechanisms where a lack of nutrient input reduced plant residue accumulation, thereby diminishing SOC. This highlights the necessity of nutrient replenishment to maintain SOC levels and ensure long-term soil productivity.

5.1.6 Changes in soil C: N ratio, soil as influenced by liming and inorganic nutrients N and P

The result that is achieved among increased soil C: N ratio at reduced levels of nitrogen (N) and phosphorus (P) fertilizer application rates indicates a change in organic carbon accumulation to nitrogen mineralization equilibrium. C: N ratios for this research varied from a maximum of 34.25 under low input to a minimum of 10.47 at the Kakamega site, where increased rates of fertilizers were used. These results indicate that nutrient supply influences microbial function and organic matter cycling directly, thereby controlling soil organic matter stoichiometry.
N concentration is a primary driver that promotes microbial degradation and nutrient turnover in sorghum production systems.

In sorghum systems, N availability is a key driver of microbial decomposition and nutrient cycling. Zhou *et al.* (2022) demonstrated that increasing N fertilizer rates in grain sorghum significantly enhanced microbial activity and N uptake, which in turn reduced the soil C: N ratio by accelerating organic matter mineralization and N incorporation into the soil pool.

The 954% dramatic change in the C: N ratio between $N_{75}P_{26}$ and N_0P_0 treatments at Siaya 1 during the 2016 long rains season indicates the responsiveness of soil organic matter processes to fertilizer use. The excess application of N and P likely triggered microbial biomass and enzymatic activity, leading to the degradation of carbon-rich residues and enhanced N availability. This aligns with research conducted by Mishra and Patil (2015), which reported that nutrient management in sorghum intercrops enhanced N-use efficiency and lowered the C: N ratio by enhancing soil biological activity and nutrient turnover.

Besides, the high C: N ratios with low applications of fertilizers can be an indication of surplus accumulation of undecomposed organic residues as a result of N limitation. These microbial communities are carbon-rich but N-poor, and hence decomposition and immobilization of available N is reduced. Such an event has been observed in dryland sorghum production systems, where the nutrient-deficient soils and low levels of fertilizer application led to the accumulation of organic matter but minimal cycling of nutrients (Liman et al., 2018).

N fertilization increases ammonification and nitrification in a chemical soil context, while phosphorus increases microbial ATP production and root exudation, both of which enhance organic matter turnover. Together application of N and P thus decreases the C: N ratio of the soil by increasing the rate of carbon mineralization relative to N immobilization.

5.2 Objective 2: To determine the influence of lime–fertilizer combinations on sorghum yield components and physiological performance

5.2.1 Synergistic effects of lime and inorganic N and P on nitrogen uptake by sorghum grain and stover (chemically-physiologically enhanced)

Experimental results indicated enhanced sorghum grain uptake of N in limed over unlimed soils by 33% likely due to greater ion diffusion flux in the rhizosphere and enhanced mass flow (Gastal & Lemaire, 2002). Chemical availability of ammonium (NH_4^+) and nitrate (NO_3^-) resulting from improved solubility under limed conditions probably resulted in less aluminum toxicity and greater cation exchange, hence facilitating greater nitrogen diffusion to the roots. This likely stimulated physiological processes such as increased protein synthesis and chlorophyll production, which manifested in the form of larger leaves and more robust stems — in line with the higher SBY noted earlier.

Although AE was larger at lower N and P levels, this was not reflected in grain N, indicating that N uptake per se was not determining yield. At higher combination rates of N and P, N uptake appeared depressed, possibly due to physiological saturation of N demand and the emergence of other limiting nutrients per Liebig's law of the minimum (Blessing, 2014). Nitrogen translocation from vegetative tissues to grain may also have plateaued, limiting the partitioning of grain N despite increased uptake.

The uptake of N in sorghum grain was positively related to small amounts of applied fertilizer and yield, but there was no significant difference between the two tested levels, $N_{75}P_{26}$ and $N_{37.5}P_{13}$, indicating that there could be a level of the applied fertilizers beyond which the physiological mechanisms would not favor grain filling in the crop, leading to the accumulation of N in the stems (Gastal & Lemaire, 2002). There was a highly significant ($p<0.001$) difference in grain N uptake across the fertilizer rates, sites, and seasons, where grain N varied between 0.60-2.05% and a maximum increase of 15% at site Siaya 1 (2018-LR).

Depression of pH due to lime also promoted microbial nitrification and mineralization, leading to an increase in bioavailable forms of N. This affected the SN content as well as root proliferation, which improved under most lime-N-P interactions. In case the SN did not show any significant difference (e.g., Siaya 1, 2017-LR and 2018-LR), the site could have been limited to insufficient microbial activity or limited organic matter mineralization on a small scale.

5.2.2 Influence of lime and inorganic N and P on phosphorus uptake by sorghum grain and stover (chemically-physiologically enhanced)

The fertilizer treatment revealed that an increase in N-P levels intensified P uptake, but in other cases, low and moderate doses applied did the same. This observation suggested root plasticity and enzymatic recovery of organic P reserves because of rhizosphere acidification, comparable to those observed by Zhou *et al.* (2022). The effect of organic matter and microbial activity in mineralizing P into absorbable formats becomes the focus of such responses.

The practices by Lim consistently increased grain P concentration across study landscapes by altering the soil pH and the sorption capacity of P into insoluble forms of Al- and Fe-bound ways (Bolan et al., 2023; Bouray et al., 2020). The increased phosphate ion ($H_2PO_4^-$, HPO_4^{2-}) availability produced by this chemical shift enhanced physiological responses, including the root system architecture, increased ATP production, and energy transfer, which is vital in the formation of grains. The obtained P partitioning in grain, especially in Siaya 2 (2018-LR), corresponds with the effects found by Dereje *et al.* (2019), since they noted that lime application enhanced root functional traits and P assimilation efficiency.

Inter-site variation of R^2 denoted the varying genetic and physiological ability of sorghum to mobilize native and applied schemes of P sources, in addition to organic soil mineralogy and redox processes (Kisinyo et al., 2013). Competitive P absorption at micro-doses showed that high P can interfere with the natural balance between roots and shoots and even hormonal interactions, which slows down the growth of the plants overall (Eslamian et al., 2021).

There was also a significant increase in stover P content as a response to liming, equal to 42 percent higher with limed treatments, due to the better root exudation and mycorrhizal activity that increased P scavenging. The insignificance between the lime and fertilizer treatments indicates the lack of synergy, unlike Costa and Crusciol (2016). Altogether, the decreased Al/Fe fixation because of lime and soluble P in the form of fertilizers set the physiologically preferable circumstances of continuous uptake (Da Costa & Crusciol, 2016; Spohn, 2024).

5.2 Objective 2: To determine the influence of lime–fertilizer combinations on sorghum yield components and physiological performance

5.2.3 Influence of liming and inorganic nutrients N and P on biomass yield of sorghum

Observations from this experiment, alluded to by Butchee *et al.* (2012) that biomass sorghum production may be limited when grown on acidic soils. Because liming enhances a conducive environment in the soil to improve plant growth, sorghum productivity probably increased after liming, hence leading to increased biomass yield. The highest SBY change when lime was applied was 81% higher than planting without lime, as was observed in Kakamega during the 2016-LR cropping period, hence, advancing credibility to the effect of liming on SBY in low pH soils. These findings are supported by several authors (Javed et al., 2024; Olego et al., 2021; Tan et al., 1991). The higher sorghum SBY upon liming is attributed to a possible reduction in H^+ ion concentration in the sorghum root zone soil, as evidenced by the elevated soil pH. These observations agree with those of Dereje et al. (2019) and Tan et al. (1993). Further, with 4t Limeha^{-1} application, sorghum biomass accumulation was, therefore, enhanced, possibly due to improved uptake of essential soil nutrients including N and P, as will be discussed shortly. On the contrary, the observation that SBY was lower under limed than unlimed soil suggests an improved nutrient uptake and partitioning, hence improved biomass accumulation. This observation agrees with that of Oberoi & Kaur (2020) and Maw et al. (2020) that the correlation between fertilizer and SBY was significantly ($p <.001$) positive. Although the SBY was significantly influenced by lime and fertilizer treatments, the effects of these treatments varied depending on soil conditions, the doses of fertilizer application, and the local climate at different sites. The interaction of lime with the high dose of fertilizer yielded higher than micro-dose and control treatments, indicating that lime treatment raised the pH to the optimal range, improved nutrient uptake, and potentially increased SBY. Fertilizers provided N and P, essential nutrients that probably increased leaf and stem development, leading to higher biomass production. The interaction of lime with fertilizer micro-dose yielded higher SBY than that of no lime with the higher recommended dose.

5.2.4 Influence of liming and inorganic nutrients N and P on grain yield of sorghum

The increase in sorghum grain yields due to liming of acrisols in the study sites was likely due to increased soil pH attributed to reduced acidity (H^+ and Al^{3+} ions), availability of nutrients, and reduced soil exchangeable acidity. There is similar support from other authors that the increased grain yield of sorghum due to liming of acidic soils may be attributed to the reduction in acidity and improved availability of nutrients Ca and P (Abdi, 2024; Curtin & Syers, 2001; Dereje et al., 2019; Kazungu, 2022). The increased crop grain yield that is likely to come from the above change can be explained by enhanced root growth, leading to increased uptake of water and nutrients. Liming, therefore, likely lowered the toxic effect of the H^+ ions, Mn^{2+} ions, and Al^{3+} saturation or enhanced the availability of basic cations for uptake and, thus, improved SGY. Similar observations were made by Esilaba et al. (2023) and Brignoni et al. (2020). Proper pH levels are crucial for nutrient availability to plants, especially for nutrient uptake by grain crops like sorghum. In the interaction, lime probably enhanced microbial activity, which hastened the rate of organic matter decomposition in the soil. This then led to the release of nutrients necessary for grain development and higher grain yield. While lime treatment helped to raise the pH to the optimal range, fertilizer N and P provided essential nutrients that sorghum plants need for grain production, improving nutrient availability and potentially increasing sorghum grain yield. Like in SBY, the interaction of lime with fertilizer micro-dose yielded higher sorghum SGY than that of no lime with the recommended dose. Nitrogen is particularly important for the development of the reproductive structures in sorghum plants, such as the heads where grains are produced. Proper nitrogen fertilization can result in increased grain development and higher grain yield. Phosphorus is essential for root and overall plant development, consequently increasing the number and size of grain heads. The differential SGY of 2.57, 1.32, and 1.98 t ha^{-1} observed in Kakamega during 2018-LR and in Siaya 1 and site 2 during 2017-LR season was likely due to varying soil characteristics and predominant local climate during the experimental periods.

The significantly higher GYOC of limed than unlimed treatments clearly suggests the impact of lime improvement on sorghum GY. Generally, mean GYOC ranged between 40-70% across study sites over the seasons. In Kakamega Site in 2018-LR, for instance, GYOC rose from 20-60%, indicating the potential of doubling sorghum GY by altering root zone pH through liming. Similar results were reported by Crusciol et al. (2019). The interaction of lime with fertilizer superseded fertilizer without lime in grain yield. In many instances, 4t Lime ha^{-1} lime with a quarter level of the recommended rate yielded higher GYOC than half the rate of fertilizer without lime. The half and quarter rates are the micro-dose application rates in most instances and are superior in GYOC than the recommended rates without lime treatment. This observation indicates the power of liming in the enhancement of nutrient availability for uptake, hence the improvement of sorghum grain yield. When compared to a control group with no treatment, soil pH was raised to the optimal range, making essential nutrients more available to sorghum plants. In the lime-fertilizer interaction, lime likely influenced the rate of OM decomposition in the soil; thus, over-control promoted more efficient nutrient cycling and nutrient release, supporting higher grain yield. This improved nutrient availability resulted in significantly increased grain yield. Nitrogen is crucial for the development of the reproductive structures in sorghum, such as grain heads, and fertilizer N and P applications thus provide an adequate supply of nitrogen and significantly increase grain yield when compared to a control group with no added nitrogen. Additionally, adequate phosphorus supply through fertilizers N and P could have enhanced root and overall plant development, leading to an increased number and size of grain heads when compared to a control group with limited nutrient supply. Further, lime treatment probably improved microbial activity by optimizing soil pH, which led to increased nutrient availability and improved grain yield when compared to a control group with less favorable microbial conditions.

5.2.5 Effect of liming and inorganic nutrients N and P on sorghum harvest index

The harvest index (HI) in sorghum, which is the ratio of grain yield to total above-ground biomass (including stems, leaves, and grain), was influenced by the interaction of lime and fertilizer treatments. Mean HI ranged between 0.16-0.22, showing that fertilizer micro-dose, either with or without lime, recorded higher HI. The observation indicates a lack of justification in the consistent use of previous high recommendation rates with disregard for lime application in acidic soils. Dereje et al. (2022) similarly found that there was a significant interaction of the lime and phosphorus fertilizer, which enhanced the grain yield of sorghum and the stover yield. The use of lime fixed the acidity of the soils, increasing the availability and uptake of phosphorus. This contributed to the increased biomass partitioning and increased yield parts, which supported an HI range of 0.16-0.22 that was observed with microdosing of lime-fertilizer.

In lime-fertilizer N and P interaction, lime treatment corrected soil pH, which otherwise was out of the optimal range for sorghum production in the study sites, easing nutrient availability to sorghum plants. Studies by Guo et al. (2025) in the same way showed that the optimal levels of N and P have a positive effect on grain yield and nutrient use efficiency (NUE) in sorghum. The paper highlighted that equal N and P nutritional status favored grain and nutrient partitioning, resulting in an increased HI. In line with the observation in the current research, Dereje (2022) found that microdosing N and P, particularly with lime, improves the yield of grain compared with biomass. Lime treatment for adjustment of pH to the optimal range, hence improved nutrient uptake and, subsequently, grain yield. A well-balanced nutrient supply contributed to a higher HI. An adequate nutrient supply, particularly nitrogen and phosphorus from N and P fertilizers, is crucial for sorghum grain development, leading to increased grain yield. An optimal supply of nutrients is essential for achieving a high HI. Nitrogen is an important macronutrient for grain production, and the interaction of N and P fertilizers with lime treatments resulted in improved N availability for the sorghum plants, which possibly contributed to higher grain yield. Adequate P supply from N and P fertilizers promoted general plant health and development. Consequently, larger grain heads and better grain filling occurred, thereby positively affecting the HI by increasing the proportion of grain yield relative to total biomass. A higher grain yield, relative to the above-ground biomass, can enhance the HI.

5.2.6 Influence of lime and inorganic nutrients N and P treatments on sorghum nutrient N and P uptake efficiency of sorghum

The current study observed nutrients N and P uptake efficiency in the applied fertilizer at varying levels upon lime application. The findings were in line with those of Fixen *et al.* (2015). The Application of lime in acidic soils, along with improving SOM, contributes to enhanced NUE of cereal crops in global crop production systems. The superiority of sorghum NUE of limed than unlimed soil is primarily attributed to differences in N uptake capacity. According to Bollam *et al.* (2021) NUE variation is driven by changes in N remobilization and utilization efficiency. Under limed conditions, this observation supports the findings in this study that the NUE of 35% in Siaya, which was the highest across study sites, indicates the efficiency in N and P utilization achievable by liming acidic soils. It also became apparent that there was a critical need to raise the soil pH. This observation explains the higher efficiency in sorghum grain increase due to increased utilization of fertilizer N and P applied.

Sorghum NUE, a determinant of how effectively a crop utilizes applied nutrients to produce grain or biomass, changes with liming-acid soils and increasing fertilizer rates. Means of NUE were observed to range from 21.91- 34.54% across the sites and seasons, where results showed that treatment with $N_{75}P_{26}$ with or without lime consistently yielded the lowest NUE throughout the seasons. In the interaction, lime contributed to the upward adjustment of soil pH to the near-optimal range and enhanced nutrient availability and, consequently, NUE. Fertilizers N and P provide major essential nutrients that sorghum needs for growth and development. Sufficient nutrient supply through fertilizer application is critical for optimizing NUE. The interaction between lime and N and P fertilizers, therefore, affected the availability of specific nutrients, as lime influences nutrient solubility and release. Lime treatment thus created a more favorable environment for root growth and nutrient uptake, potentially enhancing NUE. However, like in HI and AE, a minimum threshold of nutrient supply is required to achieve optimal NUE. Once this threshold is reached, further increases in fertilizer rates may have diminishing returns in terms of NUE. The micro-dose fertilizer application with or without lime recorded the highest NUE against the higher recommendation of $N_{75}P_{26}$. With means of NUE with or without fertilizer application, following the trend $N_{18.8}P_{6.5}$>$N_{37.5}P_{13}$>$N_{75}P_{26}$, it was apparent that higher fertilizer doses potentially reduced NUE. Using balanced fertilization, particularly N and P from mineral and/or organic sources, is an essential practice for improving nutrient efficiency. As reported by Fixen *et al.* (2010), data collected over many years and from many sites in China, India, and North America suggested that balanced fertilization with appropriate N, P, and K increased first-year recoveries by an average of 54%, compared with average recoveries of 21%when only N is applied.

At higher and recommended fertilizer N and P rates, NUE declined, hinting at the relationship between increased fertilizer rates that depresses efficient nutrient utilization in the soil. Compton *et al.* (2011) suggested that overuse of N fertilizer increases nitrate-N accumulation in the soil profile, which may limit yield response to increasing N fertilizer in sorghum. A high level of nitrate-N in the soil can limit yield response to increasing N fertilizer in sorghum, hence reducing crop NUE. The response of NUE to N rate was fitted to an exponential equation, pooling data from both years. Means of nutrient use efficiency (NUE) were observed to differ significantly ($p< 0.001$) under varying doses of fertilizer N and P, as noted by Hao et al. (2014). The application of $N_{18.8}P_{6.5}$ of fertilizer N and P caused higher NUE as compared to the higher doses of $N_{37.5}P_{13}$ and $N_{75}P_{26}$. Lower NUE under higher doses indicated a higher proportion of unaccounted for nutrients N and P that was applied. This observation suggests the need for adjustment for fertilizer recommendation among other factors that govern NUE in sorghum production. Variation of NUE across seasons could be attributed to improved nutrient uptake enhanced by higher soil moisture availability resulting from higher rainfall, such as that experienced in Siaya 2 in the 2018-LR season.

5.2.7 Effect of liming and varying doses of inorganic nutrients N and P on the agronomic efficiency of sorghum

The effect of treatment with and without lime on sorghum performance was isolated by calculating the Agronomic Efficiency (AE). It was observed that this parameter predominantly superseded unlimed experiments across study sites over the seasons. The higher AE of limed soil was probably attributed to the higher supply of protons in the soil solution alongside the high concentration of Ca^{2+}, which resulted in more solubilization of added P than P held tightly in the soil matrix under unlimed treatment. The lime application gave a higher yield than the control treatment, which proved to be more sustainable in sorghum grain productivity. The highest mean AE in Siaya 2 in the 2018-LR season can be explained by the higher P fixation capacity of Ferralsols. Gardner et al. (1994) and Ostmeyer et al. (2023) reported similar observations. As observed, liming with 4t Lime ha^{-1} improved AE between 28% and 121% during the experimental period across the sites. These results indicate an additive effect of lime in increasing grain yield due to fertilization relative to the total amount of fertilizer applied. Results showed the superiority of micro-dose over recommended rates on sorghum agronomic efficiency (AE). This implied that AE increased with a decrease in application rates of N and P fertilizer doses. The higher AE for micro-dose applications of $N_{37.5}P_{13}$ (12.06-25.36) and $N_{18.8}P_{6.5}$ (9.81-15.26) against the recommended rate of $N_{75}P_{26}$ (6.60-11.85) shows the importance of considering micro-dosing for the sustainability of sorghum production. This could be likely due to increased availability of nutrients, but beyond the plants' utilization capacity. Nitrogen could be lost through erosion or volatilization, while phosphorus could be sorbed or leached. Similar findings by Guindo et al. (2022), Kugedera et al. (2022), and Akinseye et al. (2023) found that when applying very large amounts of nutrient inputs, AE is reduced, and conversely, a lower amount of nutrient inputs will lead to an increase in AE.

Sorghum agronomic efficiency (AE), which is a measure of how effectively a crop utilizes applied nutrients, was influenced by the interaction of lime and fertilizer treatments. Lime and fertilizer treatments significantly influenced nutrient availability in the soil. When N and P were supplied from fertilizers, they improved AE differentially depending on the presence or absence of lime. Lime interactively adjusted soil pH to the optimal range and further improved nutrient uptake, potentially leading to increased AE. Higher fertilizer rates led to increased plant growth, as the crop had access to a more abundant supply of nutrients, being higher in limed than in unlimed soils. This positively affected AE as it results in more yield per unit of nutrient applied. As nutrient N and P uptake became more efficient, AE improved as more nutrients N and P were utilized by the crop. However, there is a minimum threshold of nutrient supply required to achieve optimal AE. Below this threshold, yield and nutrient use efficiency may be limited, but once this threshold is reached, further increases in fertilizer rates may have diminishing returns in terms of AE. This observation became apparent considering the recommended higher rates with lower AE and micro-dose rates with higher AE.

Use of the recommended fertilizer dose indicated consistently higher grain yield (1.14-2.57 t ha^{-1}) over microdose (1.08 kg ha^{-1} and 1.39 kg ha^{-1}) or control experiment. This observation, however, may not be the sole determinant of preference for fertilizer dose. Nevertheless, harvest index (HI) and agronomic efficiency (AE) were used to delineate the most appropriate rate to use. Microdose applications ($N_{\mathbf{18.8}}P_{\mathbf{6.5}}$ and $N_{\mathbf{37.5}}P_{\mathbf{13}}$) reported higher HI compared to the higher doses, suggesting the sustainability of

$N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$ over the recommended higher dose. The results are in line with those of Sebnie *et al.* (2020), who found that the use of micro-dose fertilizer N and P would save fertilizer over the recommended rate, making it possible to produce extra sorghum grain in another season or on a different field. The recommended N and P did not produce double the grain yield of the micro-dose applications. High application of N use could have exacerbated the situation on an already low pH soil, making the soil even more acidic. Excessive N likely disrupted the balance of other essential nutrients in the soil, such as P and K. This could have led to nutrient deficiencies or imbalances in plants, affecting their overall health and productivity. Increased solubility of Al, enhanced by low pH due to excess N, likely worsened the situation by increasing Al mobility in the soil, which can harm plant roots and reduce their ability to absorb water and nutrients. On the other hand, in the acidic soils of the study sites, P tends to become fixed or bound to soil particles, making it less available to plants. Excessive P application can aggravate this fixation problem due to the surplus P further binding with soil components, reducing its accessibility to plants. Similar results were reported by Krasilnikov et al. (2022), who observed that inappropriate use of mineral fertilizers, mostly concerning N and P, has ruined the ability of many productive soils to function by chemical as well as by physical and biological indicators.

5.3 Objective 3: To establish relationships among soil chemical properties, sorghum performance metrics, and economic outcomes

5.3.1 Correlation of soil chemical properties and sorghum yield as influenced by lime and varying inorganic N and P doses

Pearson's test between lime, soil available P, N, OC, sorghum GY, and SBY indicated a pairwise positive correlation. Initial soil conditions in the study sites had very low soil pH, and liming was successful in raising the soil pH to a more favorable range, thereby leading to a strong positive correlation between liming and these parameters. As soil pH increased, exchangeable Al indicated an inverse correlation. Consequently, reduced Al toxicity probably increased the availability of nutrients N, P, and OC, leading to a positive correlation. These changes collectively led to higher sorghum grain and biomass yields. The R^2 value close to 1 indicates a strong relationship. The observation also suggests the effectiveness of lime, considering the lime source, initial low pH of the soil in the study sites, and soil predominant in Rhodic Ferralsols and Orthc Acrisols in Siaya 1/Siaya 2 and Kakamega sites, respectively. Fertilizer doses showed a strong positive correlation with GY and SBY, indicating crop response to N and P in the initially N and P-deficient soils. Nitrogen is crucial for plant growth and the development of vegetative biomass, while phosphorus is essential for root development, flowering, and seed formation. However, optimization of N and P is crucial to protect against excess doses that could lead to waste or elicit detrimental effects on soil. If unchecked, increasing N and P fertilizer application may reach a saturation level, and further increases may not result in a proportional rise in these parameters. Conversely, GY and SBY showed a negative correlation with soil exchangeable Al. As exchangeable Al levels increased, the available nutrients, such as N and P, may not have been effectively utilized by the sorghum plants, therefore led to reduced yields. The R^2 value would be -0.5 or close to -1, indicating a strong negative relationship.

High levels of exchangeable Al in the soil can be detrimental to plant growth, particularly for crops like sorghum. Aluminum toxicity can negatively affect root development and nutrient uptake. The micro-dosing experiment showed that there was a significantly ($p < 0.001$) high correlation between sorghum grain yield and N and SOC, with high correlation values >0.80. With the application of fertilizer N and P, soil N was increased. SOC levels being moderately present, this likely caused a strong positive correlation (high R^2) between these factors and sorghum SGY. A study conducted in Western Ethiopia demonstrated that combined applications of lime and phosphorus significantly improved sorghum grain yields, with the highest yield reaching 5.65 t ha^{-1} (Dereje et al., 2022). Similarly, the strong positive correlation between fertilizer doses and sorghum yields indicates that increased fertilizer application rates lead to higher sorghum productivity. Fertilizers supply essential nutrients that promote plant growth and development. Research has shown that the combined application of N at 75 kg ha^{-1} and P at 50 kg ha^{-1} gave the highest grain yield of 4859.1 kg ha^{-1} (Mwadalu et al., 2022). The significant positive correlation between soil pH and sorghum yields underscores the importance of maintaining optimal soil pH for nutrient availability and reduced toxicity. Studies have shown that liming acidic soils can effectively increase soil pH, thereby enhancing crop yields (Dereje et al., 2022). The significant positive correlation between soil pH and sorghum yields underscores the importance of maintaining optimal soil pH for nutrient availability and reduced toxicity. Positive correlations between soil available phosphorus (P), nitrogen (N), and organic carbon (OC) with sorghum yields highlight the necessity of these nutrients for optimal crop performance. Adequate levels of these nutrients are crucial for sorghum growth. Conversely, the negative correlation between soil exchangeable Al and sorghum yields suggests that elevated levels of exchangeable aluminum in acidic soils can be toxic to plants, inhibiting root growth and nutrient uptake. Research indicates that soil exchangeable Al levels above 18 mg kg^{-1} can result in yield reductions of 10% or greater in grain sorghum (Baligar et al., 1989). The negative correlation between the soil carbon-to-nitrogen (C: N) ratio and sorghum yields indicates that a high C: N ratio could have led to nitrogen immobilization, hence, reduced its availability to plants and potentially limited growth and yield.

- Though slightly increased, SOC levels contributed to improved nutrient availability among other soil physical and chemical changes. When comparing SGY (t ha^{-1}) to a control group that did not receive N or have lower SOC, the treated group exhibited significantly higher SGY (t ha^{-1}). The $R^2 > 0.70$, as was observed, indicated a strong positive relationship. Sorghum grain yield also significantly ($p<0.01$) correlated with soil P, with a correlation of 0.73. A similar study by Kagwiria (2019) established that nutrient retention and availability improved due to even a small increment of soil organic carbon (SOC), which boosted the performance of the sorghum in the presence of fertilizers. When available soil P levels are in the optimal range for sorghum growth, there is likely to be a strong positive correlation between available soil P and sorghum grain yield. The application of P ensured that sorghum plants had the necessary nutrients to produce healthy grain. When available, P was improved through the application of fertilizer N and P; SGY (t ha^{-1}) yield was increased. The results agree with those of Hailu & Kedir ((2022) who reported that there was a strong positive correlation ($R^2 > 0.70$) between applied nutrients and grain yield, aligning with the present observed trends in SGY. P is essential for various plant processes, including root development, energy transfer, and grain formation. The R^2 value of 0.73 indicated a strong positive relationship. A significant (<0.01) negative correlation existed between sorghum grain yield and both the C: N ratio and AE. An observed low C: N ratio in the soil indicated a higher N content compared to OC, resulting in a positive correlation (high R^2) between the C: N ratio and sorghum grain yield. A lower C: N ratio suggested that N was more readily available to plants, consequently leading to good sorghum growth and grain development. In this scenario, SGY (t ha^{-1}) was significantly increased. The significant R^2 value indicates a strong positive relationship. Agronomic efficiency is a measure of the ratio of grain yield to the amount of fertilizer used in the production processes.

5.3.2 Correlation of soil chemical properties and nutrient N and P uptake as influenced by lime and varying inorganic fertilizer N and P doses

Figure 4.13 suggests that lime and N and P applications strongly affect the way nutrients in sorghum grain and stover are involved in soil chemical properties. They prove that managing soil fertility is very important for making sorghum plants use nutrients more efficiently and produce consistently in the acidic soils of the tropics. There were positive and important connections between grain nitrogen and grain phosphorus, and also between nitrogen in grain and stover, and phosphorus found in stover (each with $p < 0.001$), reflecting how both nutrients interact within the above-ground plant. Enough P in the soil helps nitrogen move into the plant by boosting root development and ATP transport systems (Y. Wang et al., 2021). This means that phosphorus increases the growth of roots and helps them move energy, so nitrate can be absorbed faster and in greater amounts, enhancing nitrogen levels in both grain and stover throughout the plant (Zhang et al., 2023).

A change in the soil's chemicals was shown through the powerful ties between GN, GP, SN, SP, and soil pH. It is in line with the fact that lime helps decrease acidity in soil and helps plants take in P. Because of lime, the soil's chemical composition was transformed, which is clear from the strong ties between GN, GP, SN, SP, and pH of the soil. The role of lime includes removing acidity from the soil, and so it helps decrease the amount of aluminum and improves plants' ability to get needed nutrients like nitrogen and phosphorus. Because of this, the low amount of aluminum ($p < 0.001$) in soil after liming is caused by liming, which transforms the soluble Al^{3+} into the insoluble $Al(OH)_3$ (Haynes & Naidu, 1998). Al is threatening tropical areas as it keeps the root system from growing and prevents any nourishment from the soil. These trends in lime and pH may be why there is still a weak correlation between GN and P, since there can be competition, varied plant absorption, or lime's impact on when nutrients are absorbed, as noticed by Otinga et al. (2012) in the field. The strong and significant link it had with GP, SN, and SP at $p < 0.001$ proves that phosphorus is important for the energy and biomass needs of cereals. Grain production increases when adequate P is available because more carbohydrates are sent to the grains, and Nziguheba *et al.* (2022) confirmed that nitrogen use is also allowed.

Total soil nitrogen and soil organic carbon (SOC) were also strongly and positively associated with GN, GP, SN, and SP, supporting the integral role of organic matter in nutrient cycling and sorghum nutrition. Organic matter, hence, probably contributed both labile N and P pools and enhances soil structure, microbial activity, and moisture retention. This dual function promotes synchronized nutrient availability and uptake across plant tissues. In particular, SOC's influence on soil microbial communities enhances mineralization and availability of otherwise bound nutrients, which aligns with the positive correlations seen here.

It is revealed from this study that exchangeable Al^{3+} can decrease the uptake of nutrients in sorghum, and its levels are shown to reduce grain phosphorus (GP), stover nitrogen (SN), and stover phosphorus (SP) in the crop. A review by Zhao (2018) also indicates that Al^{3+} toxicity affects the growth of roots negatively and interferes with the uptake and assimilation of nitrogen, especially in acid soils. The paper stresses the fact that Al^{3+} disrupts nitrate reductase enzyme activity and root membrane integrity, decreasing nitrogen delivery to shoots. Since the findings were very strong ($p < 0.001$), it emphasizes that using effective soil management is necessary to control aluminum's influence on nutrient availability. Abnormal amounts of Al^{3+} cause the root membrane to lose its strength, which decreases the transport of ions and the uptake of nutrients. Because of aluminum, the amount of calcium and magnesium kept by the roots decreases, weakens their cell walls, and lowers the amount of P and N they can take in. Phosphorus usage in the plant reduces when there is aluminum toxicity because the transport proteins are hindered. According to research, Al^{3+} connects with phosphate ions, and the ensuing bonds render the P less available in soils with a low pH. It is this fact that causes a negative correlation between Al^{3+} and GP, SN, and SP. The presence of aluminum decreases nitrogen binding by stopping the action of nitrate reductase and glutamine synthetases. Due to this suppression, the amount of nitrogen in both grain and stover drops, which lowers sorghum's productivity. The outcomes display the same as before, that applying lime helps remove harmful Al from the soil and so allows better uptake of nutrients from cereals grown in acidic Ferralsols. Treating soil with liming helps by incrementing the pH; Al turns into forms that do not damage plants, while P becomes soluble and available for uptake by crops. When lime and balanced fertilizers are used, the soil's chemical condition is changed to favour basic nutrients such as Ca and Mg for plants to absorb them better. Because of higher pH, less Al toxicity, greater availability of P, and faster breakdown of organic matter, sorghum takes up nutrients more efficiently, leading to higher yields and a sustainable cropping process. The results in this study highlight the value of well-developed soil strategies in preventing the stress caused by Al and maintaining the success of agriculture on degraded tropical lands like those in western Kenya.

5.3.3 Correlation of soil chemical properties with yield assessment indices of grain sorghum under lime and inorganic N and P doses

Sorghum productivity depends highly on soil chemical characteristics, nutrient availability, and environmental conditions. These factors make it important to understand how key yield indices such as harvest index (HI), agronomic efficiency (AE), and nutrient uptake efficiency (NUE) affect sorghum productivity. Similar findings were conducted in semi-arid Kenya by Nguluu et al. (2023), demonstrating that nitrogen fertilizer application influenced nitrogen use efficiency (NUE) and yield across different sorghum genotypes. Further, a study by Guo *et al.* (2025) reported that the best N and P ratios enhanced the yield and nutrient use efficiency (NUE) in saline soils. This highlights the interaction between environmental conditions and nutrient management with regard to influencing the performance of sorghum. It was observed from this study that there were significant correlations between soil properties and these sorghum growth indices. This provided an insight into the underlying physiological and biochemical processes that govern nutrient efficiency and yield formation.

Lime is typically applied to soil to raise its pH, making it less acidic. It does so by providing calcium and magnesium ions that react with soil acidity, increasing soil pH. Although sorghum is relatively more resistant to low pH, the lime rate applied could have led to the desired near-neutral conditions, creating favorable sorghum root zone conditions. Soils with excessively high pH may create several nutrient-related antagonisms. Lime requirement done during site characterization ensured the right quantity of lime was used to correct the initially low pH. High pH due to overliming can reduce the solubility and availability of essential micronutrients, such as iron, manganese, and zinc, which sorghum requires for growth and development, thereby negatively impacting yield. Upon liming, the high pH achieved probably improved the sorghum's ability to take up nutrients, as nutrient ions were rendered soluble and became chemically available for root absorption. The amount of lime required to increase soil pH to the desired level is critical. Imbalanced nutrient ratios due to over-liming may have occurred, consequently becoming detrimental to sorghum growth. If the calcium-magnesium ratio, for instance, becomes skewed, nutrient competition and uptake by the plant may be affected. Sorghum generally thrives in slightly acidic (pH 5.5) to neutral pH (pH 6.5). Lime application at 4t ha^{-1} raised the soil pH to this optimal range, which led to improved sorghum yield.

The positive correlation between lime application and AE and NUE indicates improved nutrient availability at a pH above 5.5. A strong positive correlation between lime application and sorghum AE suggests that applying lime leads to more efficient resource use and higher sorghum yields. Essential nutrients like P become more soluble and accessible for plant uptake in well-limed soils. The current findings agree with those of Li et al. (2019) that liming influences both nutrient transformation and uptake, including nutrient use efficiency (NUE). Similar findings by Fageria and Nascente (2014) found that lime application enhances NUE by improving root access to nutrients and reducing aluminum toxicity. This ensures sorghum plants have easier access to vital nutrients. Lime also helps reduce nutrient leaching, which is the loss of nutrients through percolating water in the soil. In the acidic soils of the study sites, nutrients were more likely to leach, and liming probably mitigated this issue. A rate of 4 t Lime ha^{-1} adequately raised soil pH, supporting healthier root development in sorghum. Lime use created a more favorable root environment, contributing to better nutrient uptake and, consequently, higher AE and NUE. In the naturally acidic soils of Siaya and Kakamega, the solubility and toxicity of Al ions could have significantly hindered sorghum productivity. However, adding lime helped reduce Al toxicity by binding it and making it less harmful to sorghum roots. This decrease in Al toxicity likely improved overall plant health and nutrient uptake. These observations corroborate those of Muindi *et al*. (2015) that the interaction of lime with Al and P in the Kenya Highlands, similar to Siaya and Kakamega, has a high solubility of aluminum, which may cause severe inhibition of crop production. The restriction of these soils limits the Al toxicity by precipitating the Al ions so as to protect the root systems and enhance phosphorus availability.

Nitrogen is needed in plants for chlorophyll production for photosynthesis, activating enzymes, and growth. Adequate N levels, even when micro-dose rates were applied, promoted efficient photosynthesis, leading to increased biomass production and improved crop growth. In the current experiment, we showed that application of nitrogen plays a vital role in the growth and yield of sorghum, since the right N levels ensured efficient nutrient use of the sorghum crop, leading to good agronomic performance. These results are in agreement with the current study, in which it is revealed that N availability was linearly related to nutrient uptake and nutrient uptake efficiency.

Phosphorus plays a role in energy transfer processes within the plant. Micro-dose application of P levels was sufficient for the formation of ATP (adenosine triphosphate), which is the energy currency of the cell. This energy is required for various physiological processes in the plant. Even at micro-dose levels, soil N and P provided a readily available source of essential nutrients for sorghum plants. The target application of N and P, at a proper time, greatly enhanced the yield and nutrient restoring efficiency in sorghum, as supported by the findings of Holman *et al.* (2024). The authors emphasize the importance of small doses of chemicals that are targeted at the nutrition of plants and are enough to exclude the ecological risks of excessive fertilization.

When soil N and P levels were sufficient, it ensured that sorghum plants had access to the vital nutrients, supporting overall growth and development. Adequate soil available P supported the formation of new roots and root hairs, which are responsible for nutrient absorption. Well-developed root systems likely explored a larger volume of soil, enhancing sorghum's ability to take up nutrients, including N and P, from the soil. HI is the ratio of grain yield to total biomass. A positive correlation between soil N and P levels and HI can be explained by the fact that these nutrients promote increased biomass production and efficient nutrient utilization. Higher levels of N and P in the soil possibly lead to larger grain yields relative to the total biomass produced, which resulted in an improved HI. Although similar findings have not been explored in western Kenya regarding HI, Kedir et al. (2023) demonstrated that varying rates of N and

P fertilizers directly influenced sorghum yield components. Moderate nutrient levels improved grain yields relative to total biomass, thereby increasing HI.

Adequate soil N and P levels contributed to higher NUE by ensuring that more of the nutrients applied or available in the soil were effectively utilized by the sorghum plants. With sufficient N and P, the sorghum plant could maximize its nutrient uptake and utilize these nutrients efficiently for growth and grain production, reducing nutrient losses through leaching or other forms of wastage. When soil N and P levels were insufficient, sorghum experienced nutrient stress, as observed by the low biomass yield under the control experiment, which limited their growth and development. Inadequate nutrient levels, therefore, led to symptoms of nutrient deficiency, as was seen in the low N and P uptake by grain and stover under control treatments, negatively impacting crop performance.

Our results are in line with the earlier studies, explaining that HI increased with the increase in fertilizer N supply in sorghum and other crops (Shamme et al., 2016). However, these findings contrast with those of Ostmeyer *et al.* (2023) who found that the harvest index did not vary significantly between N treatments in sorghum.

A significant link between SOC and AE, and NUE proved that it is vital for the nutrient and structural content of soil. The function of SOC is to enhance soil pore space, water absorption, and the strengthening of microbial activity. It was demonstrated here that a higher level of organic carbon boosted sorghum's production through greater circulation of nutrients by microorganisms and better soil conditions. Having high SOC levels was associated with getting better soil nutrients and more efficient farming, according to the study.

Phosphorus was highly correlated ($p < 0.01$) with HI, AE, and NUE, indicating that phosphorus plays a significant role in plant development and biochemical processes. Phosphorus plays a pivotal role in root development, energy transfer, and the production of genetic material, and P availability has a major impact on sorghum yield traits. The findings in our study implied that soil P enhanced sorghum root elongation and the absorption of other nutrients in the soil. Soil P function in enhancing yields in sorghum is evidence that it should be included in sorghum nutrition, preferably at planting, to enhance sorghum productivity by improving soil fertility.

Besides, results show that there is a negative relationship between soil Al concentration and AE ($p < 0.001$) and NUE ($p < 0.05$). This suggests that higher Al levels make it harder for crops to absorb nutrients and carry out important biochemical processes. A study by Tan & Keltjens (1990) found that toxicity due to aluminum negatively affects nitrate reductase activity in sorghum, which is the main enzyme in nitrogen metabolism. This biochemical disruption explains the decline in NUE and overall plant productivity. Al accumulation in roots disrupted phosphorus assimilation and reduced biomass, especially in sensitive genotypes. This justifies the biochemical basis that causes a reduction in sorghum AE and NUE under high Al conditions. Too much Al in the soil interferes with sorghum's growth mainly by affecting its roots, the supply of P, and the functioning of some enzymes. It follows that soil saturated with Al affected a plant's ability to absorb nutrients, weakening its productivity and functions. It is evident from the current findings that excess Al is not good for the productivity of sorghum, contrary to the notion that sorghum is tolerant to relatively high Al saturation.

Lime is commonly used on the soil to reduce Al toxicity by lowering soil acidity and improving the availability of nutrients such as Ca and Mg. It follows that the application of lime was quite effective in lessening soil Al toxicity on sorghum, allowing for enhanced root growth and nutrient absorption. The outcome of the current study confirms the importance of lime in reversing growth inhibition caused by high levels of Al, solidifying its role in soil fertility management.

5.3.4 Correlation of yield and nutrients N and P uptake by sorghum grain and stover as influenced by lime and fertilizer doses

These results in the present study showed a strong positive correlation between sorghum yield and nutrients N and P uptake. The observed significant ($p < 0.001$) correlations between lime and fertilizer application, sorghum Liming greatly enhanced both the acquisition of nutrients and yield characteristics, particularly the acquisition of stover phosphorus. Guo *et al.* (2025) examined the effects of nitrogen (N) and phosphorus (P) fertilization on sorghum yield in acidic soils and reported significant increases in biomass yield, grain yield, and nutrient accumulation. The reason is that the effect of lime in increasing soil pH and precipitating Al^{3+} and Fe^{3+} ions, which otherwise fix phosphate and make it unavailable (Enesi et al., 2023). Through the elimination of acidity, liming triggers phosphate desorption and opens the door for improved microbial mineralization of organic P, which in turn triggers improved phosphatase and phosphate transporter gene expression (Enesi et al., 2023; Z. Xu et al., 2025). These processes go hand in hand with the observed strong lime–SP correlation in the current experiment. Fertilizer application had highly significant positive correlations ($p < 0.001$) with all yield and uptake parameters. This validates the function of N and P during chlorophyll formation, energy transfer in the form of ATP, and amino acid development for vegetative growth and grain filling (Nyokabi et al., 2025). Particularly, in the semi-arid agroecology of Kenya, joint use of farmyard manure and inorganic fertilizer has significantly raised total N, biomass, grain yield, and soil pH—similar to our findings on fertilizer–SBY and fertilizer–nutrient uptake relationships (Nyokabi et al., 2025).

The strong correlations of biomass yield and grain and stover phosphorus with stover N but not grain N ($p = 0.67$) indicate phosphorus to be a major driver of yields. This aligns with global meta-analyses indicating that enhanced P-use efficiency promotes higher crop yields compared to mere nitrogen addition (Jin et al., 2023). Besides, the strong correlation of stover N to grain P ($p < 0.001$) justifies an integrated nutrient remobilization approach, as per evidence that cereal harvesting maximizes yield when P and N supply match physiological sink requirement (Jin et al., 2023; Nyokabi et al., 2025). The large correlation ($p = 0.01$) between yield over control (GYOC) and grain N and stover nutrients, but not grain P, indicates that relative yield gains essentially express increased source strength (vegetative storage of nutrients) instead of sink capacity improvement. From a soil chemistry perspective, N and P are among the most limiting macronutrients in acidic or degraded soils due to ionic competition and reduced nutrient solubility. Nitrogen, often supplied as nitrate (NO_3^-) or ammonium (NH_4^+), is essential for chlorophyll synthesis and enzymatic processes, while P, taken up mainly as orthophosphate ions ($H_2PO_4^-$ and HPO_4^{2-}), is critical for ATP formation, nucleic acid synthesis, and root development. An adequate supply of these nutrients improves both root absorption efficiency and internal translocation, thereby enhancing sorghum biomass accumulation and grain filling. The result is in agreement with landscape-specific fertilizer placement research, wherein the efficiency of N and P uptake is more regulated by soil and topographic heterogeneity than by intrinsic direct yield gain (Agegnehu et al., 2023).

5.4 Objective 4: Evaluation of the most sustainable and profitable intervention under lime, microdosing, and intercropping technologies for optimized yield

5.4.1 Gross Marginal analysis of sorghum as influenced by lime and fertilizer doses

The gross margin (GM) profile in Figure 4.22 is enough evidence that the combination of lime with full-rate fertilizer (4t ha^{-1} + $N_{75}P_{26}$) greatly increases the profitability of sorghum production on Western Kenya's acidic soils. The treatment was invariably above 50,000 KES ha^{-1} profitability level for Ferralsols of Siaya and Acrisols of Kakamega, and in Kakamega during the long rains of 2016, maximum returns of as high as 94,983 KES ha^{-1} were realized. These margins are not only statistically significant ($p < .001$) but also economically transformative, especially for poor smallholders who have limited resources.

In Siaya, with relatively lower rainfall and natural fertility, the same treatment under 2017-LR yielded a mean GM of 70,112 KES ha^{-1}—four times that of the control. That is, while total yields vary by site, the proportionate benefit of lime × fertilizer synergy remains the same for each agroecological zone. Interestingly, treatments with full-rate fertilizer + lime were the only ones that always exceeded the 50,000 KES ha^{-1} level, a figure that corresponds with the smallholder breakeven point for profitability estimated for Western Kenya (Kula et al., 2023).

These returns have important ramifications for the poor farmers in the region, who are largely working on less than 2 hectares and earning less than USD 1.25 day^{-1} (Kebeney et al., 2014). To these households, realizing a GM over 50,000 KES ha^{-1} per growing season may signal a threshold from subsistence to surplus agriculture. Uptake of lime is currently low due to cost, access, and knowledge constraints. This highlights the importance of targeted subsidy, decentralized lime depots, and participatory extension methods that simplify the application of lime and illustrate its economic benefit.

Furthermore, the yield and margin reactions documented reveal that microdose fertilizer application—though agronomically rewarding—does not necessarily provide adequate economic gain without pH correction. $N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$ treatments produced intermediate GMs (35,000–45,000 KES ha^{-1}) but were never profitable. This is in agreement with Enesi et al. (2023), whose findings showed that liming increases very significantly the nutrient use efficiency as well as profitability, particularly in highly weathered tropics.

Policy, then, is away from a homogenized fertilizer policy and towards integrated soil fertility management (ISFM) strategies that are responsive to local soil limitations. When the major limiting factor for soils such as Siaya and Kakamega is acidity, lime cannot be a discretionary input but a structural one. The word must be pushed through extension that, in the absence of pH adjustment, even appropriately calibrated use of fertilizer will underachieve—financially and agronomically. In summary, the use of lime blended with full-rate fertilizer not only enhances sorghum production but also has economic benefits that are capable of significantly enhancing the livelihoods of poor smallholder farmers in Western Kenya. Expansion of lime access, in combination with site-specific nutrient management, holds potential to redefine sorghum from a subsistence crop to a commercial entity for poor groups.

5.4.2 Benefit-cost optimality of lime × fertilizer programs for sorghum in acidic Western Kenya soils

Benefit-cost ratio (BCR) analysis showed a strong and uniform benefit of the mixture of lime with full-rate fertilizer (4 t ha^{-1} lime + $N_{75}P_{26}$) in all experimental locations and seasons ($p < .001$). Not only did this treatment perform better than all the other mixtures, but it was the only one to persistently surpass the viability criterion of BCR = 2.0, a value frequently employed to signify economic viability for smallholder adoption. Conversely, the control (0 t ha^{-1} + N_0P_0) yielded the lowest BCR values, and those fertilizers applied at intermediate rates (e.g., $N_{18.8}P_{6.5}$, $N_{37.5}P_{13}$) generated modest gains which were not statistically different from each other but less than the break-even point.

These results are especially pertinent in Western Kenya, where poor farmers struggle with acidity as an omnipresent constraint and sorghum is a key food security crop. For soils with a pH <5.0, which is a frequent characteristic of Ferralsols and Acrisols in the region, Esilaba *et al.* (2023) report that there is higher exchangeable aluminum content, which inhibits root growth and nutrient acquisition. This biochemical constraint greatly impairs fertilizer use efficiency unless mitigated through liming. The greater BCR realized in the lime + $N_{75}P_{26}$ treatment thus suggests not only increased productivity but also a more efficient association of input costs with economic benefit.

Notably, the BCR > 2.0 benchmark is not a statistical outlier but rather an economic feasibility test for small farmers. When the size of farm land is less than 2 hectares and the cost of inputs is a predominant constraint, a BCR of more than 2.0 simply means that two or more shillings are returned for every shilling invested—a minimum return threshold to satisfy risk-averse farmers under extreme cash flow constraints. That only the lime + full-rate fertilizer treatment exceeded this threshold across all site–season combinations is testament to its scalability and potency.

These findings are consistent with later research by Nyokabi *et al.* (2025), which found that the use of inorganic fertilizers with organic supplements like farmyard manure greatly increased sorghum yields and BCR in Kenya's semi-arid environment. Their most profitable treatment (½ NP + ½ FYM) yielded a net return of 56,769 KES ha^{-1} with a BCR highly in excess of 2.0, reinforcing the axiom that soil amendment is essential before profit can be achieved underutilization of nutrients in degraded soils. Further, Esilaba et al. (2023) indicated that at 4 t ha^{-1} of liming, elevated maize BCR from 0.53 (no input control) to 2.84, thus corroborating the economic justification for liming in acid-susceptible areas.

Both policy and development policy recommendations of these findings are to align mainstream into the national programs of soil fertility. Fertilizer subsidies have always been targeted at NPK sources, but the findings indicate that, unless followed by concurrent pH adjustment, such investment may receive low returns. Adoption of lime + fertilizer bundles by Western Kenyan subsistence farmers may be an exit out of the subsistence trap—assuming access, affordability, and awareness barriers are addressed.

CHAPTER SIX

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

- Lime played a central role in the replenishment of fertility in acidic Ferralsols and Acrisols of Western Kenya. It substantially increased the soil pH (by 18–25%), reduced exchangeable Al (by 45–60%), and enhanced the levels of major nutrients, with phosphorus showing the most improvement (available P increased by 40–70%).
- Moderate rates of fertilizer ($N_{18.8}P_{6.5}$ and $N_{37.5}P_{13}$) plus lime as supplements were agronomically and economically efficient. The mixture always equaled or exceeded the maximum-rate fertilizer ($N_{75}P_{26}$) in yield, nutrient value, and profitability, with yield increases of 15–30% and agronomic P use efficiency gains of up to 50%.
- Chemical soil factors, i.e., pH, available phosphorus, SOC, and C: N ratio, had the most effects on sorghum productivity and nutrient utilization efficiency, nutrient uptake, and agronomic efficiency in all the scenarios were better in the treatments where lime application was undertaken.

- Economic analysis confirmed that the lime plus medium dose fertilizer (N37.5P13) can be a future economically viable sustainable approach by reducing micro-dose fertilizer prices at the expense of the lime quantity, which is scalable by smallholders with limited economic resources, yet farming acidic soils in Western Kenya. The 50,000 KES ha^{-1} profitability level and benefit–cost ratios (BCRs) of over 2.0 can always be met or surpassed through application of this treatment, hence making it a viable and revolutionary input package to farmers with low income of less than USD 1.25 per day and who have a land less than 2 hectares. The lime + N37.5P13 option can help shift toward a surplus agriculture (contributed by a combination of local availability of both lime and direct extension activity) by decreasing the cost of all inputs and increasing the substantial amount of both the yield and margin. This synergy points to the fact that ISFM policies should be inclusive by taking into consideration the economic reality of farming systems, which are largely poor-resource.

6.2 Recommendations

- To combat the problem of aluminum toxicity and improve the availability of nutrients N and P, lime application should be included in soil fertility programs where the pH of the soil is less than 5.5. This recommendation will increase soil pH, the availability of soil P, and the increase in sorghum yield, as it did in all study sites.
- Application of lime with medium rates of fertilizer (4 t ha^{-1} lime + $N_{37.5}P_{13}$) can be encouraged as an inexpensive and profitable enterprise compared to the high-

input strategy. The combinations were profitable with high BCRs and gross margins and within the reach of poor-resource farmers.

- The use of fertilizer alone, where soils are acidic dominates should be avoided. Nutrient uptake and profitability without any pH adjustment are low, as evident from the poor performance of fertilizer-alone plots on both profit and yield.

6.3 Recommendations for Future Research

- Subsequent studies need to explore the long-term agronomic and economic viability of lime and moderate fertilizer application rates, residual impacts, compatibility with organic amendments, and response under conservation agriculture management. This would include determining the impact of long-term application of lime on micronutrient availability, soil biological integrity, and productivity of sorghum over several seasons. Assessment of cost-effectiveness and nutrient-use efficiency of lime blending with organic amendments (such as manure or compost) under varied tillage regimes will demonstrate scalability, low-cost fertility rehabilitation possibilities in smallholder agriculture.

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APPENDICES

APPENDIX I: Means of selected soil chemical changes in the experimental sites during the cropping periods as influenced by lime

	2016-LR			2017-LR			2018-LR		
	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2
Soil pH									
L_1	5.98a(18)	5.41a(15)	5.55a(14)	5.52a(11)	5.50a(14)	6.19a(11)	6.08a(6)	5.52a(15)	6.19a(27)
L_0	4.91b (0%)	4.6b (0%)	4.76b (0%)	4.91b (0%)	4.75b (0%)	5.5b (0%)	5.74a (0%)	4.68b (0%)	4.50b
Mean	5.45	5	5.16	5.22	5.13	5.84	5.91	5.1	5.34
Pr(>F)	***	***	***	***	***	***	0.09	***	***
CV%	3.11	5.4	4.59	2.28	3.49	1.59	7.53	8.32	1.74
LSD	0.15	0.23	0.2	0.1	0.15	0.08	0.39	0.37	0.08
Soil available P (mg kg^{-1})									
L_1	4.60a(14)	2.82a(6)	3.24a(21)	7.09a(42)	6.18a(33)	4.11a(21)	5.3a(43)	4.11a(21)	7.68a(58)
L_0	3.95b (0%)	2.64b (0%)	2.57b (0%)	4.1b (0%)	4.14b (0%)	3.24b	3.04b (0%)	3.24b (0%)	3.28b
Mean	4.28	2.73	2.91	5.6	5.16	3.68	4.17	3.68	5.48
Pr(>F)	***	0.003**	***	***	***	0.033*	***	0.034*	***
CV%	3.09	4.48	3.79	3.57	2.12	17.48	18.73	25	10.1
LSD	0.11	0.11	0.1	0.24	0.24	0.17	0.68	0.8	0.48
Soil Exchangeable Al (mg kg^{-1})									
L_0	1.55a(23)	1.61a(22)	1.56a(22)	1.76a(82)	2.2a(86)	1.57a(23)	2.3a(23)	1.61b(22)	1.57b(23)
L_1	1.2b (0%)	1.26b (0%)	1.21b (0%)	0.31b (0%)	0.31b (0%)	1.21b (0%)	1.78b (0%)	1.26a (0%)	1.21a (0%)
Mean	1.37	1.43	1.38	1.03	1.25	1.39	2.04	1.43	1.39
Pr(>F)	***	***	***	***	***	***	***	***	***
CV%%	6.34	9.33	9.67	8.1	4.37	12.48	13.62	6.29	10.91
LSD	0.08	0.12	0.12	0.07	0.05	0.15	0.24	0.08	0.13
Soil N (%)									
L_1	0.21a(14)	0.14a(29)	0.12a(8)	0.24a(13)	0.15a(27)	0.11a(27)	0.24a(25)	0.09a(11)	0.11a(27)
L_0	0.18b (0%)	0.1b (0%)	0.11b (0%)	0.21b (0%)	0.11b (0%)	0.08b (0%)	0.18b (0%)	0.08b (0%)	0.08b (0%)
Mean	0.2	0.12	0.11	0.22	0.13	0.09	0.21	0.09	0.09
Pr(>F)	***	***	0.019*	***	***	***	***	***	***
CV%%	4.66	18.19	6.17	4.89	16.82	6.63	2.25	4.81	6.63
LSD	0.01	0.02	0.01	0.01	0.02	0.01	0	0	0.01
Soil organic carbon (%)									

L_1	2.38a(9)	1.84a(13)	1.43a	2.39a(8)	1.85a(13)	1.89(27)	2.34a(7)	1.56a(8)	1.9a(28)
L_0	2.17b	1.6b	1.43a (0%)	2.21b	1.61b	1.38b	2.17b	1.43b	1.37b
Mean	2.28	1.72	1.43a	2.3	1.73	1.63	2.25	1.49	1.63
Pr(>F)	***	***	NS	***	***	***	0.032*	***	***
CV%%	3.13	7.85	0.9	3.2	3.92	3.06	7.5	1.67	3.52
LSD	0.06	0.12	0.01	0.06	0.06	0.04	0.15	0.02	0.05
	C: N Ratio								
L_1	12.54a(6)	36.12a(10)	12.93a(3)	10.78a(6)	25a(10)	12.58(8)	11.72a(18)	18.54a(7)	18.19a(1)
L_0	11.79b	32.38b	12.54a	10.16b	22.56a	11.54b	9.63b	17.27b	18.19a
Mean	12.17	34.25	12.74	10.47	23.78	12.06	10.67	17.91	18.15
Pr(>F)	*	***	NS	**	NS	*	***	*	NS
CV%%	6.73	5.91	7.24	4.81	15.16	7.25	7.86	6.32	3.78
LSD	0.71	1.75	0.8	0.44	3.12	0.76	0.73	0.98	0.59

APPENDIX II: Means of some soil chemical changes in the experimental sites during the cropping periods as influenced by fertilizer doses

	Soil pH								
	2016-LR			**2017-LR**			**2018-LR**		
	Kakamega	**Siaya 1**	**Siaya 2**	**Kakamega**	**Siaya 1**	**Siaya 2**	**Kakamega**	**Siaya 1**	**Siaya 2**
$N_{75}P_{26}$	5.49a (4)	5.01a (1)	5.25a (5)	5.14b (1)	5.13ab (1)	6.11a (3)	6.13a (10)	5.1ab (2)	6.11a (9)
$N_{37.5}P_{13}$	5.52a (5)	4.97a (0)	5.19a (4)	5.11b (0)	5.08ab (1)	5.91b (3)	6.04ab (9)	5.02b (0)	5.91ab (5)
$N_{18.8}P_{6.5}$	5.5a (4)	5a (1)	4.99a (0)	5.23b (2)	5.28a (3)	5.75c (2)	5.92ab (7)	5.2a (4)	5.75ab (2)
N_0P_0	5.28b (0)	5.04a (1)	5.18a (4)	5.39a (3)	5.01b (0)	5.61d (0)	5.56b (0)	5.09ab (1)	5.61b (0)
Mean	5.45	5.00	5.15	5.22	5.13	5.84	5.91	5.10	5.84
Pr(>F)	NS	NS	NS	**	NS	***	NS	NS	***
CV	3.11	5.40	4.59	2.28	3.49	1.59	7.53	8.32	1.59
LSD	0.21	0.33	0.29	0.15	0.22	0.11	0.54	0.52	0.11
	Soil Available P (mg kg^{-1})								
$N_{75}P_{26}$	4.41ab (11)	2.78a (3)	3.13a (21)	6.37a (31)	5.72a (23)	7.67a (49)	6.92a (70)	5.44a (63)	7.67a (49)
$N_{37.5}P_{13}$	4.48a (12)	2.69a (0)	3.13a (21)	6.20a (21)	5.59a (21)	5.57b (30)	4.67b (56)	4.34b (53)	5.57b (31)
$N_{18.8}P_{6.5}$	4.28b (8)	2.70a (0)	2.90b (5)	5.44b (19)	4.9b (10)	4.80c (18)	3.01c (31)	2.89c (29)	4.80c (19)
N_0P_0	3.94c (0)	2.74a (2)	2.47c (0)	4.38c (0)	4.43c (0)	3.89d (0)	2.08c (0)	2.04c (0)	3.89c (0)

Mean	4.28	2.73	2.91	5.60	5.16	5.48	4.17	3.68	5.48
Pr(>F)	***	NS	***	***	***	***	***	***	***
CV	3.09	4.48	3.79	3.57	3.73	10.16	18.73	25.00	10.16
LSD	0.16	0.15	0.13	0.24	0.24	0.68	0.96	1.13	0.68
Soil Exchangeable Al (mg kg^{-1})									
$N_{75}P_{26}$	1.38a (4)	1.36b(4)	1.31b(3)	1.05a(0)	1.25a(5)	1.32a(0)	1.32a(0)	1.29c(0)	1.32c(0)
$N_{37.5}P_{13}$	1.32a (0)	1.38b(0)	1.33b(4)	1.00a(2)	1.25a(0)	1.33a(1)	1.33a(1)	1.37b(6)	1.78b(26)
$N_{18.8}P_{6.5}$	1.42a (7)	1.43ab (7)	1.38ab (8)	1.08a(5)	1.27a(7)	1.38a(4)	1.38a(4)	1.43a(10)	2.38a(45)
N_0P_0	1.36a (3)	1.56a(3)	1.51a(15)	1.00a(13)	1.25a(0)	1.52a(13)	1.52a(13)	1.62a(20)	2.67a(51)
Mean	1.37	1.43	1.38	1.03	1.25	1.39	2.04	1.43	1.39
Pr(>F)	NS	*	*	NS	NS	NS	***	***	NS
CV	6.34	9.33	9.67	8.10	4.37	12.48	13.62	6.29	10.91
LSD	0.11	0.16	0.16	0.10	0.07	0.21	0.34	0.11	0.19
Soil N (%)									
$N_{75}P_{26}$	0.22a(41)	0.22a(68)	0.13a(23)	0.23a(13)	0.11a(27)	0.23a(17)	0.23a(65)	0.11a(27)	0.11a(27)
$N_{37.5}P_{13}$	0.22a(41)	0.16a(56)	0.12b(17)	0.23a(13)	0.09a(11)	0.22b(14)	0.22a(64)	0.09a(11)	0.09a(11)
$N_{18.8}P_{6.5}$	0.21b(38)	0.12b(42)	0.11b(9)	0.22b(9)	0.08b(0)	0.21b(10)	0.21b(62)	0.08b(0)	0.08b(0)
N_0P_0	0.13c(0)	0.07c(0)	0.10c(0)	0.20c(0)	0.08c(0)	0.19c(0)	0.08c(0)	0.08c(0)	0.08c(0)
Mean	0.20	0.14	0.11	0.22	0.13	0.09	0.21	0.09	0.09
Pr(>F)	***	***	***	***	***	***	***	***	***
CV	4.66	18.19	6.17	4.89	16.82	6.63	2.25	4.81	6.63
LSD	0.01	0.03	0.01	0.01	0.03	0.01	0.01	0.01	0.01
Soil Organic carbon (%)									
$N_{75}P_{26}$	2.38a (12)	1.84a (16)	1.45a (3)	2.38a (1)	1.95a (10)	1.87a (11)	2.55a (43)	1.73a (36)	1.86a (31)
$N_{37.5}P_{13}$	2.35a (11)	1.8ab (14)	1.44ab (2)	2.35ab (4)	1.77b (5)	1.69b (8)	2.39ab (34)	1.55ab (22)	1.7ab (20)
$N_{18.8}P_{6.5}$	2.25b (6)	1.65bc (4)	1.43b (1)	2.27bc (3)	1.68c (11)	1.56c (10)	2.29b (29)	1.43b (13)	1.56b (10)
N_0P_0	2.13c (0)	1.58c (0)	1.41c (0)	2.2c (0)	1.52d (0)	1.42d (0)	1.78c (0)	1.27c (0)	1.42c (0)
Mean	2.28	1.72	1.43	2.30	1.73	1.63	2.25	1.49	1.63
Pr(>F)	***	*	***	**	***	***	***	***	***
CV	3.13	7.85	0.90	3.20	3.92	3.06	7.50	1.67	3.52
LSD	0.09	0.16	0.02	0.09	0.08	0.06	0.21	0.03	0.07
C: N Ratio									
$N_{75}P_{26}$	10.71b (1)	9.63c (0)	10.98c (0)	10.27b (1)	9.12b (0)	10.44c (0)	11.07a (18)	16.11b (0)	17.63b (0)
$N_{37.5}P_{13}$	10.58b (0)	11.75bc (22)	12.27b (12)	10.12b (0)	10.87b (19)	11.23bc (8)	11.23a (20)	16.84a (5)	18.08a (3)
$N_{18.8}P_{6.5}$	10.94b (3)	14.02b (46)	13b (18)	10.52ab (2)	12.98b (19)	11.67b (4)	11.05a (18)	18.07a (12)	18.48a (5)
N_0P_0	16.44a (55)	101.58a (954)	14.7a (34)	10.97a (4)	62.15a (379)	14.89a (28)	9.36b (0)	20.6a (28)	18.38a (4)
Mean	12.17	34.25	12.74	10.47	23.78	12.06	10.67	17.91	18.15
Pr(>F)	***	***	***	*	***	***	**	***	NS

CV	6.73	5.91	7.24	4.81	15.16	7.25	7.86	6.32	3.78
LSD	1.00	2.48	1.13	0.62	4.41	1.07	1.45	1.39	0.84

† Significant codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1, NS-Not Significant. Means sharing the same letters are not significantly different. Values in brackets are the percent changes from the control experiment

APPENDIX III: Means of soil yield and yield components in the experimental sites during cropping periods as influenced by lime

	---------- Sorghum Biomass Yield ($t\ ha^{-1}$) ----------								
	------2016-LR------			------2017-LR------			------2018-LR------		
	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2
L_1	10.22a (81%)	8.72a (23%)	7.57a (30%)	7.77a (62%)	8.19a (22%)	8.14a (46%)	10.2a (81%)	8.72a (23%)	12.27a (45%)
L_0	5.63b (0%)	7.09b (0%)	5.82b (0%)	4.79b (0%)	6.7b (0%)	5.58b (0%)	5.63b (0%)	7.09b (0%)	8.44b (0%)
Mean	7.93	7.90	5.82b (%)	6.28	7.44	6.86	7.93	7.90	10.35
Pr(>F)	***	***	***	***	***	***	***	***	***
CV%	10.42	5.87	10.68	8.71	4.46	5.05	10.4	5.93	4.63
LSD	0.71	0.40	0.62	0.47	0.29	0.30	0.71	0.41	0.42
	---------- Sorghum Grain Yield ($t\ ha^{-1}$) ----------								
L_1	2.03a (52%)	1.38a (28%)	1.44a (73%)	1.51a (32%)	1.38a (10%)	1.65a(42%)	3.2a (65%)	1.38a (28%)	1.61a (31%)
L_0	1.34b (0%)	1.08b (0%)	0.83b (0%)	1.14b (0%)	1.26b (0%)	1.16b	1.94b (0%)	1.08b	1.23b (0%)
Mean	1.69	1.23	1.14	1.33	1.32	1.40	2.57	1.23	1.42
Pr(>F)	***	***	***	***	***	***	***	***	***
CV%						5.70		5.24	
%	3.97	4.17	3.54	4.12	5.20		18.66		5.22
LSD	0.06	0.04	0.04	0.05	0.06	0.07	0.42	0.54	0.06
	---------- Grain yield Over Control (%) ----------								
L_1	61.99a (9%)	56.76a (15%)	70.88a (23%)	77.35a (26%)	58.89a (23%)	56.66a (1%)	60.3a (207%)	66.94b (10%)	69.8a (84%)
L_0	56.74b	49.34b	57.61b	61.38b	47.76b	55.92a	19.64b	73.66a (0%)	37.87b
Mean	59.37	53.05	64.25	69.37	53.32	56.29	40.0	70.3	53.8
Pr(>F)	*	***	***	***	*	NS	***	*	***
CV%									
%	6.63	4.92	4.68	8.78	14.91	6.58	19.1	7.0	8.7

LSD	4.05	2.68	3.09	6.26	8.17	3.80	7.8	5.0	4.8
	---Harvest Index (%)---								
L_1	0.17b	0.16a	0.19a (27%)	0.25a (25%)	0.23a (21%)	0.21a	0.16b	0.15a	0.21a
L_0	0.22a (25%)	0.16a (2%)	0.15b	0.20b	0.19b	0.21a	0.23a (42%)	0.16a (5%)	0.21a (3%)
Mean	0.19	0.16	0.17	0.22	0.21	0.21	0.20	0.16	0.21
Pr(>F)	***	NS	***	***	***	NS	0.***	NS	NS
CV% %	11.66	7.76	9.78	11.98	3.09	9.05	18.39	7.48	9.05
LSD	0.02	0.01	0.01	0.02	0.01	0.02	0.03	0.01	0.02
	---Agronomic efficiency (%)---								
L_1	17.9a (66%)	13.06a (46%)	13.7a (121%)	15.84a (63%)	11.33a (28%)	13.99a (46%)	13.73a (44%)	12.18a (40%)	20.55a (68%)
L_0	10.78b	8.94b	6.21b	9.74b	8.82b	9.57b	9.55b	8.72b	12.26b
Mean	14.34	11.00	9.95	12.79	10.08	11.78	11.64	10.45	16.40
Pr(>F)	***	***	***	***	**	***	***	***	***
CV% %	4.94	4.97	6.47	11.86	17.07	9.10	16.63	10.08	8.40
LSD	0.73	0.56	0.66	1.52	1.77	1.10	1.99	1.08	1.42
	---Nutrient Uptake Efficiency (%)---								
L_1	41.72a (53%)	32.16a (28%)	23.73a (18%)	37.88a (36%)	33.43a (11%)	40.78a (44%)	38.38a (32%)	31.72a (27%)	38.68a (27%)
L_0	27.23b (0%)	25.19b (0%)	20.09b (0%)	27.84b (0%)	30.21b (0%)	28.34b (0%)	28.99b (0%)	24.97b (0%)	30.39b (0%)
Mean	34.48	28.67	21.91	32.86	31.82	34.56	33.69	28.34	34.54
Pr(>F)	***	***	**	***	*	***	***	***	***
CV% %	4.83	4.59	8.76	5.18	7.50	6.97	5.79	3.70	3.99
LSD	1.71	1.35	1.97	1.75	2.45	2.47	2.00	1.08	1.42

Means sharing the same letter are not significantly different. The values in parentheses indicate percent mean change from control. Significant mean difference in cropping systems is represented by: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, ns= not significant.

APPENDIX IV: Means of sorghum yield and yield indices in the experimental sites during cropping periods as influenced by fertilizer doses

	Sorghum Biomass Yield (tha^{-1})								
	2016-LR			2017-LR			2018-LR		
	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2
$N_{75}P_{26}$	11a (54)	11a (58)	9a (49)	9a (54)	11a (67)	9a (46)	12a (57)	10a (57)	13a (46)
$N_{37.5}P_{13}$	9b (43)	9b (50)	7b (36)	7b (44)	9b (62)	8b (41)	10ab (50)	9b (55)	12b (40)
$N_{18.8}P_{6.5}$	7c (32)	7c (35)	6c (23)	6c (32)	6c (39)	6c (29)	8bc (34)	8c (47)	10c (28)
N_0P_0	5d (0)	5d (0)	5d (0)	4d (0)	4d (0)	5d (0)	5c (0)	4d (0)	7d (0)
Mean	7.93	7.90	6.69	6.28	7.44	6.86	8.54	7.96	10.35
Pr(>F)	***	***	***	***	*	***	***	***	***
CV%	10.42	5.87	10.68	8.71	4.46	5.05	21.2	5.93	4.63
LSD	1.01	0.57	0.88	0.67	0.57	0.42	3.08	1.27	0.59
	Grain Yield (tha^{-1})								
$N_{75}P_{26}$	2.38a(58)	1.67a(53)	1.43a(47)	1.60a(46)	1.60a(41)	1.65a(40)	3.54a(58)	1.57a(52)	1.71a(40)
$N_{37.5}P_{13}$	1.89b(47)	1.39b(44)	1.26b(40)	1.50b(42)	1.45b(35)	1.54b(36)	2.78b(46)	1.31b(43)	1.53b(33)
$N_{18.8}P_{6.5}$	1.47c(32)	1.08c(28)	1.10c(31)	1.34c(35)	1.29c(27)	1.44c(31)	2.47b(39)	1.18b(36)	1.43b(29)
N_0P_0	1.00d(0)	0.78d(0)	0.76d(0)	0.87d(0)	0.94d(0)	0.99d(0)	1.50c(0)	0.75c(0)	1.02c(0)
Mean	1.69	1.23	1.14	1.33	1.32	1.40	2.57	1.20	1.42
Pr(>F)	***	***	***	***	***	***	***	***	***
CV%	3.97	4.17	3.54	4.12	5.20	5.70	18.66	4.15	5.22
LSD	0.08	0.06	0.05	0.07	0.08	0.10	0.59	0.06	0.09
	Grain yield over control								
$N_{75}P_{26}$	72.52a(37)	63.9a(39)	87.49a(51)	83.12a(36)	69.5a(47)	67.13a(32)	55.15a(58)	93.72a(59)	64.7a(33)

$N_{37.5}P_{13}$	60.27b(25)	56.37b(31)	62.87b(32)	71.57b(25)	53.57b(31)	56.47b(20)	41.37b(43)	78.37b(50)	53.37b(18)
$N_{18.8}P_{6.5}$	45.34c(0)	38.92c(0)	42.45c(0)	53.46c(0)	36.89c(0)	45.32c(0)	23.38c(0)	38.89c(0)	43.5c(0)
Mean	59.37	53.05	64.25	69.37	53.32	56.29	39.97	70.30	53.84
Pr(>F)	***	***	***	***	***	***	***	***	***
CV%	6.63	4.92	4.68	8.78	14.91	6.58	19.05	6.97	8.71
LSD	4.95	3.29	3.78	7.66	10.00	4.66	9.58	6.16	5.90
Harvest index									
$N_{75}P_{26}$	0.19a(5)	0.16b(6)	0.16b(0)	0.19b(0)	0.15d(0)	0.19b(0)	0.17b(0)	0.14b(0)	0.19b(0)
$N_{37.5}P_{13}$	0.20a(10)	0.16b(6)	0.17ab (6)	0.23a(17)	0.16c(6)	0.20ab (5)	0.20b(15)	0.16b(13)	0.20b(5)
$N_{18.8}P_{6.5}$	0.18a(0)	0.15b(0)	0.18a(11)	0.24a(21)	0.24b(38)	0.22a(14)	0.19b(11)	0.15b(7)	0.22a(14)
N_0P_0	0.20a(10)	0.18a(17)	0.16ab (0)	0.24a(21)	0.30a(50)	0.22a(14)	0.24a(29)	0.18a(22)	0.22b(14)
Mean	0.19	0.16	0.17	0.22	0.21	0.21	0.20	0.16	0.21
Pr(>F)	NS	**	NS	*	***	NS	*	***	NS
CV%	11.66	7.76	9.78	11.98	3.09	9.05	18.39	7.48	9.05
LSD	0.03	0.02	0.02	0.03	0.01	0.02	0.04	0.01	0.02
Agronomic efficiency									
$N_{75}P_{26}$	12b (0)	9b (0)	7c (0)	7c (0)	6c (0)	7c (0)	8b (0)	7b (0)	9b (0)
$N_{37.5}P_{13}$	15a (22)	12a (27)	10b (33)	12b (42)	10b (35)	11b (40)	12a (39)	12a (40)	15a (38)
$N_{18.8}P_{6.5}$	16a (26)	12a (27)	13a (51)	19a (62)	14a (53)	18a (63)	15a (49)	12a (40)	25a (64)
Mean	14.34	11.00	9.95	12.79	10.08	11.78	11.64	10.45	16.40
Pr (>F)	***	***	***	***	***	***	***	***	***
CV%	2.18	4.97	6.47	11.86	17.07	9.10	16.63	10.08	8.40
LSD	0.89	0.69	0.81	1.86	2.16	1.35	2.44	1.33	1.73
Nutrient use efficiency									
$N_{75}P_{26}$	20c (0)	16c (0)	12c (0)	16c (0)	16c (0)	16c (0)	17c (0)	15c (0)	17c (0)
$N_{37.5}P_{13}$	33b (37)	27b (42)	20b (42)	30b (47)	29b (45)	30b (47)	31b (46)	27b (46)	30b (44)

$N_{18.8}P_{6.5}$	50a (59)	43a (63)	34a (66)	53a (70)	51a (69)	57a (71)	53a (68)	43a (65)	56a (70)
Mean	34.48	28.67	21.91	32.86	31.82	34.56	33.68	28.34	34.53
Pr (>F)	***	***	***	***	***	***	***	***	***
CV%	4.83	4.59	8.76	5.18	7.50	6.97	5.79	3.70	3.99
LSD	2.09	1.65	2.41	2.14	3.00	3.03	2.45	1.32	1.73

Means sharing the same letter are not significantly different. The values in parentheses indicate the percent mean change from control. Significant mean difference in cropping systems is represented by: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, ns = not significant.

APPENDIX V: Means of sorghum grain and stover N and P uptake in the experimental sites during the cropping periods as influenced by lime

	Grain N (%)								
	2016-LR			2017-LR			2018-LR		
	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2
L_1	2.05a (12)	2.11a (11)	1.67a (14)	1.77a (14)	1.97a (10)	0.68a (33)	1.4a (2)	2.08a (2)	1.94a (14)
L_0	1.84b (0)	1.91b (0)	1.46b (0)	1.55b (0)	1.79b (0)	0.51b (0)	1.38b (0)	2.03b (0)	1.7b (0)
Mean	1.95	2.01	1.56	1.66	1.88	0.60	1.39	2.05	1.82
Pr(>F)	***	***	***	***	***	***	**	**	***
CV% %	2.18	0.88	4.18	1.78	0.86	3.00	1.00	1.78	0.95
LSD	0.04	0.02	0.06	0.03	0.01	0.02	0.01	0.03	0.01
	Grain P (%)								
L_1	0.38a (26)	0.37a (20)	0.35a (30)	0.32a (33)	0.24a (20)	0.23a (35)	0.32a (40)	0.24a (23)	0.39a (16)
L_0	0.30b	0.30b	0.27b	0.24b	0.20b	0.17b	0.23b	0.19b	0.34b
Mean	0.34	0.33	0.31	0.28	0.22	0.20	0.28	0.22	0.37
Pr(>F)	***	***	***	***	***	***	***	***	***
CV% %	6.49	5.19	2.23	3.85	8.93	4.73	14.15	6.69	2.58
LSD	0.02	0.02	0.01	0.01	0.02	0.01	0.034	0.01	0.01
	Stover N (%)								

L_1	1.04a (14)	0.75a (12)	0.74a (4)	0.89a (17)	0.63a (11)	0.64a (7)	0.84a (6)	0.79a (17)	0.73a (11)
L_0	0.91b (0)	0.67a (0)	0.71b (0)	0.76b (0)	0.57a (0)	0.6b (0)	0.79b (0)	0.68b (0)	0.66b (0)
Mean	0.98	0.71	0.73	0.82	0.60	0.62	0.82	0.73	0.69
Pr(>F)	**	NS	*	***	NS	*	**	***	***
CV%									
%	8.53	19.34	5.29	3.96	22.37	6.22	3.95	3.88	2.58
LSD	0.07	0.12	0.03	0.03	0.12	0.03	0.03	0.02	0.02
	Stover P (%)								
L_1	0.11a (32)	0.07a (27)	0.08a (33)	0.09a (29)	0.05a (0)	0.07a (40)	0.08a (31)	0.08a (23)	0.07a (42)
L_0	0.08b	0.06b	0.06b	0.07b	0.05a	0.05b	0.06b	0.07b	0.05b
Mean	0.10	0.06	0.07	0.08	0.05	0.06	0.07	0.07	0.06
Pr(>F)	**	**	***	***	NS	***	***	***	***
CV%									
%	22.02	19.12	6.59	3.70	18.31	7.52	3.09	7.673	7.64
LSD	0.02	0.01	0.00	0.00	0.01	0.00	0.00	0.005	0.00

Means sharing the same letters are not significantly different. Means sharing the same letter are not significantly different. The values in parenthesis indicate the percent mean change from control. Significant mean difference in cropping systems is represented by: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, ns= not significant.

APPENDIX VI: Means of sorghum grain and stover N and P uptake in the experimental sites during the cropping periods as influenced by fertilizer doses

	Grain N uptake (%)								
	2016-LR			2017-LR			2018-LR		
	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2	Kakamega	Siaya 1	Siaya 2
$N_{75}P_{26}$	2.11a (17)	2.13a (14)	1.68a (16)	1.79a (7)	2.00a (3)	0.67a (5)	1.45a (8)	2.21a (15)	1.91a (13)
$N_{37.5}P_{13}$	1.97b (10)	2.07b (11)	1.6ab (10)	1.67b (4)	1.94b (5)	0.64b (12)	1.40b (5)	2.09b (9)	1.88b (11)
$N_{18.8}P_{6.5}$	1.90c (5)	1.98c (6)	1.53bc (6)	1.61c (3)	1.85c (7)	0.57c (12)	1.36c (2)	1.99c (4)	1.8c (7)
N_0P_0	1.80d (0)	1.86d (0)	1.45c (0)	1.56d (0)	1.73d (0)	0.51d (0)	1.34d (0)	1.92d (0)	1.69d (0)
Mean	1.95	2.01	1.56	1.66	1.88	0.60	1.39	2.05	1.82
Pr (>F)	***	***	***	***	***	***	***	***	***
CV%	2.18	0.88	4.18	1.78	0.86	3.00	1.00	1.78	0.95
LSD	0.05	0.02	0.08	0.04	0.02	0.02	0.02	0.04	0.02
	Grain P Uptake (%)								
$N_{75}P_{26}$	0.37a (21)	0.36a (19)	0.35a (30)	0.33a (38)	0.25a (32)	0.23a (35)	0.41a (173)	0.29a (93)	0.40a (25)
$N_{37.5}P_{13}$	0.35a (14)	0.35a (14)	0.31b (15)	0.30b (15)	0.24a (14)	0.21b (11)	0.33b (120)	0.23b (53)	0.38b (19)
$N_{18.8}P_{6.5}$	0.32b (5)	0.32b (5)	0.30c (11)	0.26c (8)	0.21b (11)	0.19c (12)	0.22c (46.67)	0.20c (33)	0.36c (13)
N_0P_0	0.31b (0)	0.31b (0)	0.27d (0)	0.24d (0)	0.19b (0)	0.17d (0)	0.15d (0)	0.15d (0)	0.32d (0)
Mean	0.34	0.33	0.31	0.28	0.22	0.20	0.28	0.22	0.37
Pr(>F)	***	***	***	***	***	***	***	***	***
CV%	6.49	5.19	2.23	3.85	8.93	4.73	14.15	6.69	2.58
LSD	0.03	0.02	0.01	0.01	0.02	0.01	0.05	0.02	0.01
	Stover N Uptake (%)								
$N_{75}P_{26}$	1.03a (12)	0.73a (6)	0.79a (22)	0.89a (22)	0.61a (5)	0.68a (25)	0.88a (22)	0.85a (37)	0.82a (52)

$N_{37.5}P_{13}$	0.99ab (8)	0.73a (6)	0.76ab (17)	0.86a (18)	0.62a (7)	0.65ab (20)	0.85a (18)	0.78b (26)	0.74a (37)
$N_{18.8}P_{6.5}$	0.97ab (6)	0.69a (0)	0.71b (9)	0.81b (11)	0.58a (0)	0.60b (11)	0.81b (12)	0.69c (11)	0.67b (24)
N_0P_0	0.92b (0)	0.70a (2)	0.65c (0)	0.73c (0)	0.59a (2)	0.54c (0)	0.72c (0)	0.62d (0)	0.54c (0)
Mean	0.98	0.71	0.73	0.82	0.60	0.62	0.82	0.73	0.69
Pr(>F)	NS	NS	***	***	NS	***	***	***	***
CV%	8.53	19.34	5.29	3.96	22.37	6.22	3.95	3.88	2.58
LSD	0.10	0.17	0.05	0.04	0.16	0.05	0.04	0.03	0.02
	-- Stover P Uptake (%) ---								
$N_{75}P_{26}$	0.10a (25)	0.07a (15)	0.08a (33)	0.09a (29)	0.06a (100)	0.08a (60)	0.08a (60)	0.09a (50)	0.07a (40)
$N_{37.5}P_{13}$	0.11a (37)	0.07a (15)	0.08a (33)	0.08b (14)	0.05ab (67)	0.07b (40)	0.08a (60)	0.08b (33)	0.07a (40)
$N_{18.8}P_{6.5}$	0.10a (25)	0.06a (0)	0.07b (17)	0.08b (14)	0.05b (67)	0.06c (20)	0.07b (40)	0.07c (17)	0.06b (20)
N_0P_0	0.08a (0)	0.06a (0)	0.06c (0)	0.07c (0)	0.03c (0)	0.05d (0)	0.05c (0)	0.06d (0)	0.05c (0)
Mean	0.10	0.06	0.07	0.08	0.05	0.06	0.07	0.07	0.06
Pr(>F)	NS	NS	***	***	**	***	***	***	***
CV%	22.02	19.12	6.59	3.70	18.31	7.52	3.09	7.67	7.64
LSD	0.03	0.02	0.01	0.00	0.01	0.01	0.00	0.01	0.01

Means sharing the same letter are not significantly different. The values in parenthesis indicate percent mean change from control. Significant mean difference in cropping systems is represented by: * $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$, ns= not significant.

APPENDIX VII: Similarity Report

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