EFFECT OF WONDERGRO- A SOIL CONDITIONER FOR ENHANCING DI-AMMONIUM PHOSPHATE (DAP) USE EFFICIENCY IN MAIZE PRODUCTION

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DECLARATION

Declaration by the candidate

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

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DEDICATION

This work is dedicated to everybody who has contributed significantly to the success of the study. Moreso, to the family members, my supervisors, and colleagues.

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ABSTRACT

Despite maize being considered a staple food crop in Kenya, its productivity is low mainly due to inappropriate soil fertility management, especially in smallholder systems. The continuous decline in soil fertility is a consequence of acidic conditions, nutrient imbalances, and sub-optimal fertilizer use, causing depressed maize yield. Use of balanced and adequate fertilizers while improving other soil conditions is a prerequisite for increasing fertilizer use efficiency and maize production. On-farm trials were conducted during the long and short rains seasons of 2023 & 2024 to asses' performance of two formulations of WonderGro (WG3 & WG21)- a soil conditioner- in combination with the commonly applied Di-Ammonium Phosphate (DAP) fertilizer on maize yield and the economic return, under a range of soil pH (sub- optimal (pH<5.5) and optimal (≥5.5)) for maize production. Sixteen (16) study sites located in two agroecological zones (AEZ), of medium potential (western Kenya) and high potential (Rift Valley), with expected maize grain yields of 4.5-5t ha^{-1} and 6-8t ha^{-1}, respectively, were selected for the on-farm trials. Each AEZ had eight (8) sites equally distributed in two (2) counties. The trials involved five treatments: 0 kg DAP ha^{-1} (absolute control), 133 kg DAP ha-^{1} (full rate of recommended DAP application per ha^{-1}), 67 kg DAP ha^{-1} (half rate of recommended DAP application per ha^{-1}), 67 kg DAP+WG3 ha^{-1} and 67 kg DAP+WG21 $ha^{-1,}$ each replicated four (4) times. Maize production in the medium potential AEZ, in the sub-optimal pH category, use of half rate of DAP in combination with WG3, slightly increased yield by 3.5% from the use of the full rate of DAP (133kg DAP ha^{-1}), with 2.8tha^{-1} of maize grain yield in the long rains of 2024. While in high-potential AEZ, suboptimal pH for maize production (<5.5), applying 67 kg DAP + WG21 ha^{-1} slightly increases yield to 5.1t ha^{-1} from 5.0t h^{-1} with application of the full rate of DAP. In high AEZ, there was no variation in maize grain yield in optimal pH, regardless of fertilizer applied, with an average of 7.3 t ha^{-1} and 6.1t ha^{-1} for 2023 and 2024 long rains, respectively. Economically, application of 67kg DAP ha^{-1} +WG21 had the largest Value Cost Ratio (VCR) of 7.54 and 8.24 for long rains 2023 and 2024, respectively, in sub-optimal pH in the high-potential zone. The formulations, therefore, have the potential to boost yield and for better economic returns to the farmers.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA – Analysis of Variance

AG_n- Agronomic Efficiency of Nitrogen

AG_p- Agronomic Efficiency of phosphorus

AP- available phosphorus

DAP - Di ammonium Phosphate

FAO – Food and Agriculture Organization

HI- Harvest index

Kg ha^{-1}- Kilograms per hectare

LSD -Least significant differences

M – meter

$NH4^+$ -ammonium ion

NO_3-nitrate ion

NUE- Nitrogen uptake efficiency

P- phosphorus

N- nitrogen

PFPn-Partial Factor Productivity Nitrogen

PFP_p - Partial Factor Productivity of phosphorus

pH – potential hydrogen

SSA -Sub-Saharan Africa

SHFs- small holder farmers systems

WG – WonderGro

CHAPTER ONE

INTRODUCTION

1.1 Background information

Agriculture has occupied a pivotal role in the lives of humans (Shah & Wu, 2019a). Maize particularly plays a vital role due to its versatility and multi-purpose use as food and feed globally (Erenstein et al., 2022). Maize agro-food systems are important in ensuring global food and nutrition security (Tanumihardjo et al., 2020). Low soil fertility inevitably poses a threat to food security, as it leads to low agricultural productivity (Gomiero, 2016). The fertility of our soils provides the foundation for the productivity of our crops (Mosier et al., 2021; Stewart et al., 2020a). Increasing yield potential through innovative crop/ soil management practices has been regarded as a crucial strategy to overcome the barrier of ensuring higher crop productivity with less environmental impact (Shah & Wu, 2019b). Maize grain yield depends on the availability of fertilizers, its uptake and utilization efficiencies (FUE), which vary across regions, agro-ecological zones, and soil types

Di- ammonium phosphate DAP [$(NH4)_2HPO_4$] is the world's most commonly used phosphorus fertilizer by farmers today and contains 18% N and 46% P_2O_5. According to (Randive et al., 2021), the world phosphate fertilizer demand was around 47.4 million tons in 2020. The use of fertilizers in balanced and adequate amounts is a prerequisite for increasing crop productivity and production (Panhwar et al., 2019). DAP is highly soluble and thus dissolves quickly in soil to release plant-available phosphate and ammonium. A notable feature of DAP is the alkaline pH (7.5–8.0) that develops around the dissolving granule (Weeks Jr & Hettiarachchi, 2020). This is a temporary effect on soil pH, which rises due to ammonium present in the granules, which is later converted to nitrates by soil bacteria, resulting in a subsequent drop in soil pH (Heil et al., 2016). In 2019, the world total DAP consumption in agriculture was approximated at 17.2 mil tons (Maqsood et al., 2022).

Maize grain yield depends on the availability, capture and utilization efficiencies of resources, which vary across regions, sites, agro-ecological zones, and soil types (Gobezie et al., 2025). Use of fertilizers in balanced and adequate amounts is a prerequisite for increasing maize crop productivity and production (Panhwar et al., 2019). However, the reverse can lead to nutrient imbalances, affecting crop health and productivity (Stewart et al., 2020b). Notably, proper use of mineral fertilizers has the potential to counteract soil nutrient degradation in SSA (Dimkpa et al., 2023a).

Soils of sub-Saharan Africa (SSA) are unhealthy, largely due to years of crop nutrient–mining and limited organic and inorganic resupply (Dimkpa et al., 2023b). The soils are therefore unable to provide adequate food and nutrition for the growing population in SSA (Kihara et al., 2020). Although organic inputs are essential soil amendments besides fertilizer, they alone cannot sustain crop production due to their quality and availability limitations (Indoria et al., 2018; Timsina, 2018). Poor soil management and the fragile nature of tropical soils generally account for heavy nutrient losses through soil erosion and nutrient leaching in soils (Sanchez, 2019). Declining soil fertility is a fundamental impediment to agricultural growth and a major reason for slow growth in food production in SSA (Raimi et al., 2017). There is a growing need to develop techniques for improving soil fertility with less harm to the ecosystem (Lal, 2015).

In recent times, there has been an increased use of high-nutrient fertilizers mainly for economic reasons, which farmers often do not realize due to the high cost of fertilizers.

DAP currently costs Ksh. 6000 per ($46.88) 50kg bag in the Kenyan market. Proper fertilizer use leads to higher crop yields and better recovery of the applied nutrients. Therefore, efficient fertilization is crucial to ensure crops reach maturity within the designated growing period. The effectiveness of DAP fertilizer depends on its chemical and physical properties, the rate and method of application, soil and climatic conditions, season, and the maize variety being planted (Mulenga, 2019)

Several drawbacks have been reported in the use of DAP, apart from being expensive and economically unjustifiable, especially by poor smallholder farmers who practice subsistence farming. Other demerits include low availability of soil calcium, magnesium, and potassium ions, which form insoluble compounds (Weeks Jr. & Hettiarachchi, 2019). Phosphorus, known for its immobility, is mainly fixed in soils, with only a small portion rendered readily available for plant uptake, particularly in ferralitic soils (Mahdi et al., 2012). This fixation is pH-dependent and primarily occurs in acidic soils through free oxides and hydroxides of aluminum and iron. After dissolution of ammonium phosphate (DAP), NH_4^-N in the soil solution is converted to nitrate (NO3-N) through nitrification, a biological process. The resulting NO_3^-N can be lost from the soil profile via nitrogen leaching or through emission following denitrification to nitrogen (N2), nitric oxide (NO), and/or nitrous oxide (N2O) gases (Margenot & Lee, 2023).

Despite the unaffordable prices of mineral fertilizers, most farmers in Kenya have embraced their use. The use of organic fertilizer remains a challenge due to the large quantities required and variability in quality (Roba, 2018). To enhance the fertilizer use efficiency and minimize their negative impact on the environment, several soil conditioners have been introduced to be applied solely or in combination with the fertilizers. They are important to improve plant growth, soil health, and reduce chemical fertilizer use.

The study focused on a partial substitution of DAP with a soil conditioner (WonderGro), a multipurpose commercial product addressing the chemical, physical and biological constraints limiting crop production.

1.2 Statement of the problem

The mechanisms of how wonderGro works under different soil environments are not well understood and scientifically proven, though there are claims that it reduces soil acidity, enhances nutrient uptake, microbial activity and root development. The application of WonderGro has been constrained by insufficient information. WonderGro contains negligible N and P and has got very high pH of 8.0 and 8.4 for WonderGro3 and WonderGro21, respectively. The adoption and diffusion of soil fertility management technologies among smallholder farmers in Kenya lags behind scientific and technological advances, thus resulting in persistently low maize production in SHFs, despite the use of fertilizers, mainly due to low use efficiency. Combinations of DAP fertilizers and organic soil conditioners inputs can replenish soil N and P nutrient stocks in Africa and restore service flows to near original levels if put into practice. The effectiveness of adding of partially substituting WonderGro and DAP has captured the interest of the researchers, lack of multiyear observational effects, resulting in an incomplete understanding of the long-term effects of WonderGro.

1.3 Justification of the study

Many efforts to improve soil fertility exist, and some have been adopted by farmers in Kenya, such as using both organic and inorganic fertilizers and practicing crop rotation (Mairura et al., 2022). A detailed survey and summit meeting aimed to understand barriers to improving soil fertility in sub-Saharan Africa and to provide evidence-based recommendations. The focus regions included West Africa, East Africa, the Great Lakes area, and Ethiopia. Overall, recommendations were developed around four main themes: (1) strengthening systems based on inorganic fertilizers, (2) ensuring access to and use of quality organic inputs, (3) building capacity across the entire knowledge-transfer process, and (4) enhancing farming systems research and development across both biological and socio-economic factors.

This evidence drives the prioritization of the obstacles to overcoming barriers to achieving healthy and fertile soils that have persisted over time. Access to inorganic fertilizer, its use, and related implementation issues were prominent considerations; nevertheless, biophysical and socio-economic barriers and solutions were identified as equally important to building soil fertility and natural resources. In addition, in the past, soil fertility improvement efforts have often focused on inorganic fertilizer use as the primary mechanism for improving soil fertility and crop yields. However, under SSA conditions where soils are largely degraded, e.g., limited organic matter (OM) and organic nutrient pools, a focus on inorganic fertilizer use alone has had limited success in improving soil fertility and therefore the introduction of a soil conditioner that enhances nutrient uptake and also boosts the soil pH.

WonderGro is a Soil Conditioner, produced in Kenya by AgRevive Africa Ltd. It consists of naturally occurring, locally available minerals. The product has been designed to improve soil health and improve the efficiency of fertilizer use. WonderGro helps farmers restore the fertility of soils that have been depleted and have become acidic through overuse of inorganic fertilizers. It has been designed to complement, not replace, the use of conventional inorganic fertilizers. WonderGro supplies secondary nutrients (Ca, Mg, S), which are essential for plant growth. It results in improved growth of roots and uptake of plant nutrients, and reduces the incidence of pests in the soil, e.g., plant parasitic nematodes.

Therefore, we believe that applying WonderGro will also reduce the use of inorganic fertilizers, create a better rhizosphere, and boost maize yields, given the importance of maize to Kenya's economy. The specific functions and mechanisms behind WonderGro's use are still are yet to be scientifically proven. Hence, this study aimed to validate WonderGro's impact on soil, maize growth and development and economic benefits to the farmers.

1.4 Objective of the study

1.4.1 Broad objectives

1. To evaluate the effect of the substitution of DAP with WonderGro on increased maize production and fertilizer use efficiency

1.4.2 Specific objectives

1. To determine the influence of the combined use of WonderGro and DAP on maize yield

2. To determine the Nitrogen and phosphorus use efficiency in maize production
3. To assess the effect of WonderGro on soil physicochemical properties
4. To determine the economic benefits of using WonderGro in maize production

1.5 Research Questions

1. Do WonderGro formulations affect maize yield?

2. Under which soil pH does WonderGro perform best?

3. Does application of wonderGro enhance the uptake of N and P?

4. Does WonderGro ameliorate the acidic soils to have better economic returns on maize?

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of soil fertility

Improved agricultural productivity has a great role to play in poverty eradication among millions of people globally (World Bank, 2022). However, any form of land resource degradation can greatly undermine agricultural productivity and reduce the possibility of achieving these noble goals. The land is a finite but also a shrinking resource (Kourmouli & Lesniewska, 2023). The increasing demand for land-based goods and services has resulted in global soil degradation and negative ecosystem impact, adversely affecting humanity (Gupta, 2019).

The level of soil degradation in the SSA region can be linked to several biophysical and socioeconomic factors, coupled with poor adoption of soil fertility management strategies (Mairura et al., 2022). It is acknowledged that soil fertility depletion is an insidious and slow process; hence, farmers' perception of the severity of the problem and associated yield losses are critical in deciding the adoption of soil fertility-enhancing technologies (Midega et al., 2012). Using soil fertility management technologies is necessary to improve farm productivity, reduce poverty, and address challenges due to climate change (Katengeza et al., 2019).

Soil fertility loss is exacerbated by inadequate nutrient management in most smallholder farming systems (Ngome et al., 2011). In the past decades, researchers have developed various soil fertility technologies mainly addressing the most limiting primary nutrients (Nitrogen (N) and phosphorus (P) that are crucial inputs in agriculture to sustain crop life

(Gicheru, 2012a). These nutrients must be used judiciously to maximize crop yields as they bear the nutrients limiting maize production in Kenya. Nitrogen use is an issue of great concern in maize production and therefore, enhanced understanding between maize growth and productivity and the dynamics of maize N recovery is of major significance. There is also an attempt to address holistic, balanced nutrition for maize production in the recent past, which mainly focuses on the most limiting micronutrients (Njoroge et al., 2018). However, the success of these technologies is dependent on nutrient use efficiency and, therefore, the advocacy of integrated soil fertility technology that promotes the combined use of organic and inorganic fertilizers.

Despite global development partners and national efforts and interventions to scale up soil fertility management technologies, their adoption levels have remained low in Kenya (Adimassu et al., 2014). In Kenya, soil fertility technology adoption by small-scale farmers has not been sufficiently explored at the farm level because most studies explore the technologies separately. Small-scale farm households typically adopt multiple technologies and manage them in different plot enterprises simultaneously(Mairura et al., 2022). Soil has dynamics that are driven by genesis, environment and management (Soil Genesis - an Overview | ScienceDirect Topics, n.d.). Therefore, the use of one fertilizer to suit all conditions would be soil mismanagement. Most of the soils in the North Rift and western regions of Kenya have a variable degree of acidity that affects the efficiency of fertilizer use. Therefore, those soils require well-understood and validated amelioration approaches that are site-specific.

2.2 Efforts to manage soil fertility for maize production

Soil fertility provides the foundation for nutritious food production and resilient and sustainable livelihoods (Stewart et al., 2020). Several options exist for soil fertility management, ranging from the use of organic fertilizers to integrated soil fertility management. These options differ from one agricultural system to another, with very degraded soils requiring more innovative and sustainable approaches. The following is a description of the common ways in which soil fertility is managed in the tropics. (I) Conservation agriculture (CA), which is a multidimensional and holistic way of managing soil fertility in sub-Saharan Africa through maintaining a higher infiltration rate and conserving soil moisture and also plays a major role in SOC and subsequent impact on soil physical, chemical and biological properties. (II) The use of soil fertility amendments in this practice enhances the soil's chemical and nutrient indices, which are key indicators of soil health, including soil carbon levels and nitrogen reserves. (III) Along with the nutrient supply from soil organic matter, crop residues, wet and dry deposition, and biological nitrogen fixation, synthetic (inorganic) fertilizer is a primary source of essential nutrients in crop production in the tropics.

2.2.1: Use of inorganic fertilizers

2.2.1.1: Advantages

Inorganic fertilizers are usually immediate and quick-acting, providing all the essential nutrients that plants can access directly. However, continuous use of inorganic fertilizers alone can lead to soil organic matter breakdown, soil acidity, and environmental pollution. Inorganic fertilizers are known to help plants grow quickly because the nutrients are highly water-soluble. As a result, their effects are typically immediate, containing all necessary nutrients that are ready for plant use. Inorganic fertilizers have a high nutrient content, so only small amounts are needed for good productivity. When these fertilizers are applied correctly, they can boost soil organic matter by promoting higher levels of root growth and crop residues.

2.2.1.2: Disadvantages

Over-application of inorganic fertilizers can cause negative effects such as leaching, water pollution, acidification, and reduced availability of trace elements or alkalization of the soil. Chemical fertilizers enhance the decomposition of soil organic matter, which leads to soil structure degradation and decreased soil aggregation. As a result, nutrients are more easily lost from soils through fixation, leaching, gas emission, and this can lead to diminished fertilizer efficiency.

Overuse of chemical fertilizers can tamper with decomposers and other soil organisms, reduce the colonization of plant roots with mycorrhizae, and inhibit symbiotic N-fixation by rhizobia due to high N-fertilization, making it hazardous to the soil environment. This shows that excessive chemical fertilizer application causes problems not only for soil health but also for human health and the physical environment.

2.2.2: Use of organic fertilizers for the management of soil fertility

Organic fertilizers are natural materials of either plant or animal source, including livestock manure, green manures, crop residues, household waste, compost, and works directly as a source of plant nutrients and indirectly influences the physical, chemical and biological properties of soil The use of organic fertilizer remains a challenge due to the large quantities required and variability in quality (Roba, 2018). Organic fertilizer improves the physical and biological activities of soil, but they have comparatively low nutrient content, so a larger quantity is required for plant growth (Bhatt et al., 2019). Organic amendments increase soil carbon and nitrogen content, which results in enhanced soil fertility and crop productivity and it is also eco-friendly and cost-effective (Singh et al., 2020)

2.2.2.1: Advantages

Increasing organic matter content in soil improves the soil structure, creating more air space and water retention within the soil, and enhances soil nitrogen content, nutrient availability, and nutrient mobilization

Organic fertilizers have the following advantages to improve soil fertility: increasing organic matter in soil, which improves the soil structure, creating more air space and water retention within the soil and enhancing soil nitrogen content, enhancing nutrient availability, releasing nutrients at a slower and more consistent rate, improving nutrient mobilization and protecting the soil against rain and wind erosion

Organic fertilizer facilitates soil biological activity and the colonization of mycorrhizae. That enhances the mutual association between fungi and higher plants. Organic fertilizer increases root growth due to enhanced soil structure, promoting soil aggregates, and enhancing cation exchange capacity. Organic fertilizer acts as a buffering agent against undesirable soil pH fluctuations.

2.2.2.2: Disadvantages

Potentially Pathogenic: improperly-processed organic fertilizers may contain pathogens that are harmful to plants because they are derived from substances like animal droppings or plant/animal matter contaminated with pathogens

Limited in Nutrient availability: They are relatively low in nutrient content, so larger volumes are required to supply enough nutrients for plant growth. Hence, large-scale agriculture may experience challenges in the use of these fertilizers.

Accurate application: Due to composition of organic fertilizers highly variable, accurate application of nutrients to match plant production is difficult. Also, Microorganisms that are required to break down and release nutrients into the soil, need warmth and moisture to operate effectively and therefore, the effectiveness of organic fertilizers are limited to seasons.

2.2.3: Integrated soil fertility management (ISFM) and Integrated nutrient management (INM)

The integrated nutrient management system is an alternative system for the sustainable and cost-effective management of soil fertility by combining the application of inorganic with organic materials, resulting in rising soil fertility and productivity without affecting the environment (Titirmare et al., 2023). Soil fertility depletion and the declining agricultural productivity in western Kenya have led to many attempts to develop and popularize integrated nutrient management (INM) technologies that could restore soil fertility and improve productivity (Midega et al., 2012). INM bridges the gap between high external input agriculture and extreme forms of traditional low external input agriculture. The main components of INM are chemical fertilizers, animal manure, improved fallows and green manures. It is, however, not well understood why farmers who rely on agriculture for their livelihoods either do not adopt or adopt it slowly.

2.3 Challenges to Manage Soil Fertility Status

Several factors have affected the adoption of integrated soil fertility management practices in smallholder farming systems, including poor access to improved agricultural inputs, poor understanding of the practices and their benefits, and importantly limited financial capacity (Mutuku, 2017). Most countries have not been able to meet the fertilizer target of 50 kg nutrients ha^{-1} by 2015 in the 2006 Abuja Declaration; over 65% of the smallholder farmers have not used fertilizer and 75% of the agricultural soils have been affected by nutrient depletion (Stewart et al., 2020c). The proliferation of fake agricultural inputs has been reported in over 40-60% of cases because of poor enforcement of quality standards (Masso et al., 2017). In addition to blanket recommendations, fertilization has focused on nitrogen, phosphorus and potassium, with little emphasis on secondary and micronutrients as well as organic amendments or liming materials in acid soils, which has generally resulted in poor crop responses or low yield increments (Masso et al., 2017). Perception of yield risk by farmers can be a major factor that hinders the transfer of technologies, including fertilizer (Udimal et al., 2017). Access to financial resources, knowledge regarding technologies, access to input and output markets, and supporting policy and institutional frameworks are the major factors influencing soil fertility technology adoption patterns in Kenya and the SSA region. (Mucheru-Muna et al., 2021).

2.4 Impact of Soil Fertility Depletion on Maize Production

Soil fertility-related issues are a major concern in Kenya, as attested by numerous policy documents and research projects, e.g., the Strategy to Revitalize Agriculture policy document, which states that '*low and declining fertility of the land'* is one of the factors that continue to limit the growth of agriculture in the country. Tackling soil fertility issues thus requires a long-term perspective and a holistic approach of the kind embodied in the concept of integrated natural resource management (INRM) (Gicheru, 2012b). However, the decline in soil fertility was nominated as the most dominant limitation on the yields of maize (Zea mays L.) and on the sustainability of maize-based cropping systems in southern and eastern Africa (Droppelmann et al., 2017). The conditions under which small-scale farmers grow the maize, and the evidence that even as more farmers turn to improved maize for higher yields, these efforts are frustrated by a persistent decline in soil fertility that reduces productivity (Santpoort, 2020). Similarly, low productivity of the agricultural sector is largely attributed to low and decreasing soil fertility due to many factors such as soil acidity, soil erosion, continuous cropping and inadequate sustainable soil fertility management practices (Aleminew & Alemayehu, 2020)

2.5 Maize production in Kenya

Maize (*Zea mays l.*) is an important annual crop belonging to the family Poaceae (Rouf Shah et al., 2016). It is one of the important cereals grown commercially and for subsistence purposes and ranked first, followed by wheat and rice in Kenya (Gachara et al., 2022). Maize production contributes 3% and 12% to the Kenyan gross domestic product (GDP) and agricultural GDP, respectively (Abodi et al., 2021). In Kenya, maize crop occupies 48.5% of arable land (FAOSTAT 2019). Despite the importance of maize in Kenya, its production remains low and widely variable among the producers (Sileshi et al., 2010).

Maize production entirely depends on soil nutrition and other external factors as climatic conditions, in Kenya especially Rift-valley and western Kenya, Nitrogen (N) and Phosphorous (P) are the major sources of nutrients exploited by farmers for maize production through the application of di-ammonium phosphate found within their reach. However, this has not fully exploited the potential of the regions.

Maize responds well to fertilizer application in these regions except in cases of poorly responsive soils due to other limitations (Njoroge et al., 2018). Causes of declining soil fertility are continuous extraction of nutrients by crops without any renewal measures and this is a major case in Rift Valley, where Maize is grown in the same field yearly. Soils in the regions have a notably variable degree of acidity that affects the efficiency of fertilizer use. Therefore, those soils require well-understood and validated amelioration approaches that are site-specific.

2.6 Agro Ecology and Soil Type for Maize Production

Maize is the most widely cultivated crop and is grown in both tropical and warm temperate latitudes and is well known for its ability to be grown in a wide range of climate conditions and different agro-ecologies. It also grows in a wide range of soil types, ranging from temperate podzol to the leached red soils of the tropics (Edmeades et al., 2017). However, the best suitable soil for maize is deep, rich soils of the sub-tropics where nitrogen is abundant. It performs best in well-drained and well-aerated loam or silty loams or alluvial soils with of pH of 5.5 – 7.

Maize is grown mostly in regions having annual rainfall between 600 mm to 1100 mm. However, it can be grown in areas having rainfall of about 400 mm. It can grow in a wide range of agro-ecological from sea level to 2500 m above Sea Level depending on variety. The rainfall is most critical at flowering and silking stage. Rainfall shortage at flowering time interferes with pollination and drastically reduces yield. Towards harvesting, dry conditions are required to facilitate drying of the grain. Very low or high altitudes results in poor yields. The optimum temperatures for maize are 18°C and 27°C during the day and around 14°C during the night. However, the crop is very susceptible to frost; therefore, its cultivation in temperate latitudes is limited.

2.7 Nutritional Requirements for the growth of maize

2.7.1 Nitrogen

Nitrogen is one of the most limiting nutrients in crop production in most of the agroecological regions and the limitation is due to its low recovery efficiency (<50%) of applied fertilizers (Govindasamy et al., 2023a). The low recovery of N is associated with its losses due to its susceptibility in soil-plant systems mainly by volatilization, leaching, denitrification, and soil erosion (Mahmud et al., 2021). In sub-Saharan Africa its limitation accounts up to 40-100% of the nutrient-limited yield (Kabato et al., 2025). Nitrogen plays a key role in plant metabolism, the element takes part in different metabolic pathways of great importance to plants and participates in protein synthesis and chlorophyll biosynthesis (Amin Fathi, 2022). Plants take up nitrogen from the soil in two forms namely ammonium cation ($NH4^+$ and nitrate anion ($NO3^-$ (Ravazzolo et al., 2020). N is directly related to plant development and productivity; the inadequate management of N is considered a major limiting factor for maize grain yield. Grain quality has been affirmed that is positively affected with nitrogen application (Correndo et al., 2021). Nitrogen fertilization improves grain quality by increasing protein and mineral nutrients content, intervening positively on the number of ears per plant, the weight of ears as the mass of a thousand seeds increases according to N doses. The soil efficiency of maize to utilize soil N depends on its ability to acquire, utilize, and translocate, N which is influenced by root morphology and the biochemical and physiological processes involved in nitrate assimilations(Miflin & Habash, 2002).

Morphological development of the root system affects the process involved in nitrate acquisition (Dechorgnat et al., 2018). Increases in maize grain yield are associated with an increase in aboveground biomass and grain yield improvement is associated with an increased harvest index (Ruiz et al., 2023). The nitrogen harvest index is the proportion of N in grain relative to total aboveground biomass and is an indicator of N translocation efficiency (Fageria, 2014). Nitrogen use efficiency is multifaceted and rests in N availability in the soil and rhizosphere and the utilization ability of the crop.

Low nitrogen supplying power by the soils call for large additions of nitrogen to soils as fertilizers to meet the N needs of high yielding non-leguminous crops such as maize (Pasley et al., 2019). A good supply of nitrogen for the plant is also important for the uptake of the other nutrients. Generally, the deficiency symptoms of N in plants include stunted plant growth, spindly appearance of plants, reduced growth of leaves, chlorosis, premature senescence of older leaves, and restricted root growth and branching (Yousuf et al., 2023). Therefore, to avoid such problems plants should get nitrogen fertilizer from different sources such as compost, fully rotted manure and commercial fertilizers and ensure sufficient uptake of nitrogen.

2.7.2 Phosphorous

Phosphorus is necessary in plants for activities related to energy transfer and storage. It is an important component of adenosine triphosphate (ATP) (Lu et al., 2023). Phosphorous is an essential nutrient required to increase maize yield and second only to nitrogen in frequency of use as fertilizer nutrient and the second limiting nutrient (Fosu-Mensah & Mensah, 2016). It plays an important part in many physiological processes that occur within a developing and maturing plant. It's important for cell division because it's a constituent element of nucleoproteins which are involved in the cell production process, it is also a component of chemical essential to the reaction of carbohydrate synthesis and degradation; it is important for seed and fruit formation, and crop maturation, it helps to strengthen the skeletal structure of the plant thereby preventing lodging, it also affects the quality of grains and it may increase plant resistance to diseases (Gurmu, 2023)**.** Plants uptake only a small percentage of P applied to soil as fertilizers, while the rest is rapidly converted into insoluble complexes, especially in lower pH soils. The availability of phosphorus to plants is highest when there is a moderate pH of about 5.5 to 7 and becomes decreasingly available at a pH below 5.5 or above 7(Johan et al., 2021).

Plants utilize P in the forms of HPO_4^{2-} and $H2PO_4^-$, soils generally contain 0.02 – 0.2% mean total P (Mwende Muindi, 2019a). Depending on the pH of the growing medium. A portion of absorbed inorganic phosphorus is quickly combined into organic molecules upon entry into the roots or after it is transported into the shoot (Smith, 2002). For most plant species, the total P content of healthy leaf tissue is usually between 0.2 and 0.4% of the dry matter (Osman, 2013). Additions of phosphorus have greatly exceeded the removal of this element by crops. It is only sparingly removed by leaching majorly due to fixation, the utilization of phosphate fertilizers is normally inefficient. Findings have quantified this inefficiency by showing that crops recover only 10 to 30% of phosphorus fertilizers during the first year of application and much of the residual will be available to succeeding crops(Roberts & Johnston, 2015).

The recovery percentage of phosphorous varies widely, depending on Phosphorus source, soil type, crop grown, application method and weather condition (Sun et al., 2018). Soils high in clay content will fix more P than those containing less clay (Simonsson et al., 2009). Soils high in certain types of clay minerals like kaolinite, Al, Fe oxides and hydroxides, and amorphous clay minerals like allophone, imogolite and humus-Al complexes retain or fix more added P than other soils (Koji, 2018). Time of application also affects the availability of phosphorus nutrient. The longer the soil and added P are in contact, the greater the chances for fixation (Augusto et al., 2013).

On high-fixing soils, the crop must use fertilizer P before fixation sets in. Compaction reduces aeration and pore space in the root zone. This reduces P uptake and plant growth. Compaction also decreases the soil volume plants roots penetrate, limiting their total access to soil Phosphorus (Correa et al., 2019). Phosphorus moves such short distances in soils and soil compaction is adversely affects the uptake of this nutrient by restricting root growth(Muhammad Aslam et al., 2021).

2.8 Soil conditioners in the market, how they work and why WonderGro

Fertilizers supply nutrients to plants, whereas soil conditioners generally help improve the soil structure to enable plants to better utilize nutrients. Soil conditioners vary in both their origin and composition. Soil conditioners can be synthetic or naturally occurring; organic or inorganic. There are several soil conditioners in the market e.g., biochar, that are believed to increase porosity, soil water and nutrient retention capacity, soil structure and stability of aggregates (Tsolis & Barouchas, 2023). Similar effects were reported for soil amendments such as humic substances and compost, gypsum, organic waste material, and organic polymers (Leogrande & Vitti, 2019).

In recent years, the hydrogel has been utilized as a soil conditioner to raise soil quality and productivity. Hydrogel is a perfect contender for a soil conditioner because of many of its properties. Hydrogel's high-water concentration and super absorbency can aid in boosting the water-holding capacity of the soil. Studies have shown that iron/biochar composites possess a substantial particular surface area, copious functional groups, and superior mechanical characteristics (Tariq et al., n.d.). It can effectively adsorb organic and inorganic pollutants in the soil, reduce their mobility, and diminish the organism availability and toxic effects of heavy metals (H. Zhu et al., 2023). The introduction of iron may lead to a synergistic effect between iron and biochar. The formation of amorphous iron and iron plaques may have a synergistic effect with biochar, simultaneously reducing the bioavailability of heavy metals (Chen et al., 2024). The high alkalinity of the iron/biochar composite and the water solubility of the carbon also help to immobilize some other elements. WonderGro, which is an organic product, is therefore believed to enhance nutrient uptake by modifying the rhizosphere, enabling an efficient environment for nutrient immobilization. WonderGro is believed to rectify soil pH, reduce soil acidity, suppress soil-borne diseases and also facilitate the uptake of nutrients in the soil.

2.9: Nutrient Use Efficiency and its Measurement

Nutrient use efficiency in maize refers to how effectively the plant utilizes absorbed nutrients, like nitrogen (N) and phosphorus (P), for grain yield and overall growth. A higher nutrient use efficiency means the plant is converting the nutrients it absorbs into more biomass and grain with less input. The comprehensive measure of NUE is the ratio of yield to the amount of applied nutrient, also called the partial factor productivity [PFPN] of applied nutrient, which declines with increasing nutrient application. A fundamental aspect to improve nutrient management in the soil is the utilization efficiency with which plants capture nutrients applied (Selim, 2020). Nutrient use efficiencies measured under practical farming conditions are mostly lower than those reported from research experiments, but information on current levels of fertilizer use and nutrient use efficiency by different crops, cropping systems and world regions remains insufficient; Nutrient use efficiency by crops can be calculated based on differences on yield and total nutrient uptake with the aboveground biomass between fertilized and controlled plots.

CHAPTER THREE

METHODOLOGY

3.1 Study sites

The on-field trials were conducted on a smallholder farmer's (SHF) in Western Kenya (Bungoma & Kakamega) and Rift Valley, Kenya (Nandi &Uasin Gishu) in three subsequent growing seasons: 2023 long rains, 2023 short rains (SR), and 2024 long rains (LR) The regions have expected maize grain yield of 4.5-5t ha^{-1} and 6-8t ha^{-1} respectively for Western and Rift valley, Kenya. Site selection was based on soil pH, specifically optimal (≥5.5) and suboptimal (<5.5) for maize production, as well as areas where WonderGro had not been used in previous seasons, initial soil characterization, and farmers' willingness to host the experiment. The trials consisted of 16 sites, four in each county. Every two sites in each county were characterized by suboptimal soil pH, while the other two had pH levels within or slightly above the optimal (≥5.5) for maize production. However, this was exceptional for Uasin Gishu, where only one site had a pH of <5.5. A detailed description of each site's characteristics is shown in

Table 1.

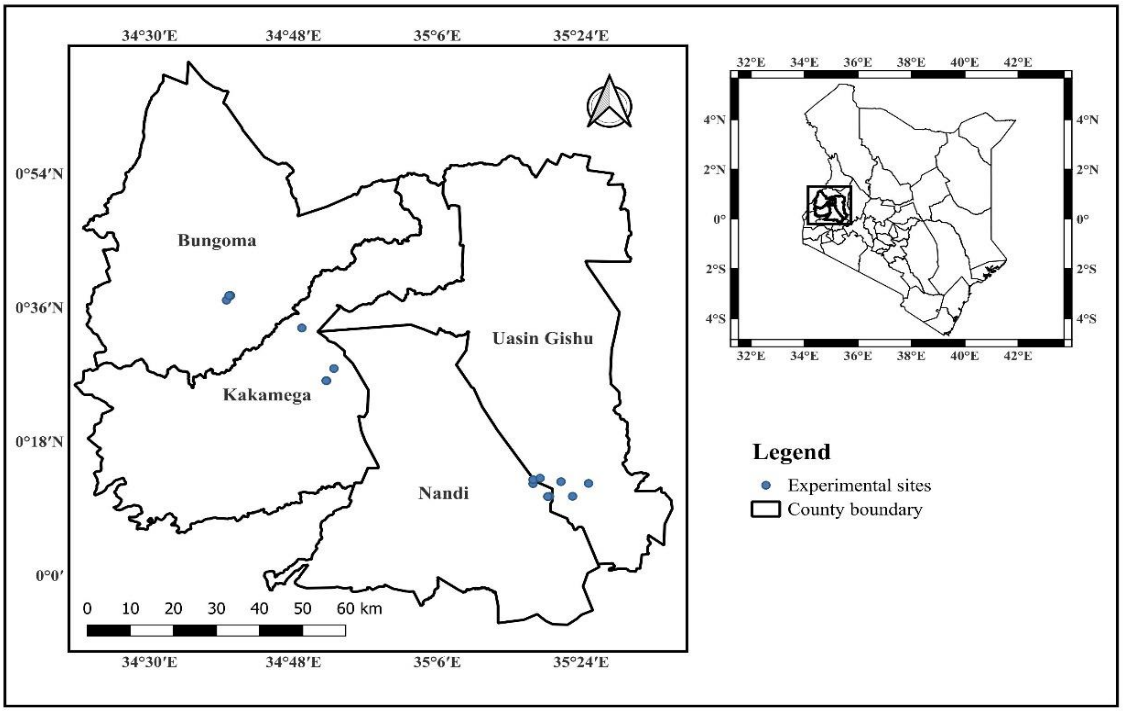

Figure 1: Study map showing areas where the on-farm trials were located

Table 1: Description of sites in the western and the Rift Valley, Kenya

Region	County	Site pH catogry as per maize reguirement	soil pH	Geographical location		Soil type	AEZ
western kenya	Bungoma	(pH <5.5)	5.3	0.616389 N	34.66E	Acrisol	Medium potential
			5.2	0.63	34.66806E	Acrisol	Medium potential
	Kakamega	(pH <5.5)	4.9	0.4361111N	34.8688E	Acrisol	medium potential
			5.2	0.4633333N	34.8841E	Acrisol	medium potential
Western Kenya	Bungoma	(pH ≥ 5.5)	5.8	0.627222N	34.66806E	Acrisols	Medium potential
			5.6	0.626667N	34.66538E	Acrisols	Medium potential
	Kakamega	(pH ≥ 5.5)	5.5	0.55416667N	34.81722E	Acrisols	medium potential
			5.6	0.4361111N	34.86778E	Acrisols	medium potential
Rift Valley	Nandi	(pH <5.5)	4.9	0.21N	35.3577E	Nitisol	High potential
			5.4	0.1772222N	35.3338E	Ferrasols	High potential
	Uasin Gishu	(pH <5.5)	4.2	0.177222N	35.3819E	Ferrasols	High potential
Rift Valley	Nandi	(pH ≥ 5.5)	6.1	0.1766667N	35.33E	Nitisols	High potential
			5.8	0.20555556N	35.29944E	Nitisols	High potential
	Uasin Gishu	(pH ≥ 5.5)	5.8	0.214444N	35.2994E	Ferrasols	High potential
			5.5	0.206111N	35.4152E	Ferrasols	High potential
			6.0	0.217778N	35.3141E	Ferrasols	High potential

In all the sites except in Uasin Gishu, pH 6.0 Phosphorus (P) was insufficient in Bungoma pH 5.6, 5.8, Kakamega pH 4.9, and Uasin Gishu pH 4.2 and 5.5 while the rest of the sites were sufficient, with only excess in Bungoma pH 5.3 and Nandi pH 6.1. All the sites did not have a shortage of potassium(K), sulfur (S), zinc (Zn) and manganese (Mn), while iron was insufficient (Fe). Carbon (C) was adequate in most sites except in Bungoma pH 5.6 and Kakamega pH 4.9 with excess in Uasin Gishu pH 6.0. Calcium (Ca) was in excess in all sites except Bungoma, pH 5.8, and Kakamega, pH 4.9. Copper (Cu) was sufficient in almost all sites except in Kakamega pH 5.2, 5.6, Nandi pH 4.9 and Uasin Gishu pH 5.5.

3.2 Initial soil characterization

Table 2: Initial soil characterization across the study sites

Region	County	Site pH catogry as per maize requirement	soil pH	P $mgkg^{-1}$	%N	K $mgkg^{-1}$	%C	S $mgkg^{-1}$	Ca $mgkg^{-1}$	Cu $mgkg^{-1}$	Fe $mgkg^{-1}$	Zn $mgkg^{-1}$	Mn $mgkg^{-1}$	Textural class
Western Kenya	Bungoma	(pH <5.5)	5.2	12.3	0.1	291.5	1.5	65.7	4863.0	4.7	13.2	2.8	200.8	sandy
			5.3	36.6	0.1	448.5	1.7	159.1	2627.2	4.7	24.7	7.0	224.7	sand clay laom
	Kakamega	(pH <5.5)	4.9	7.3	0.1	179.4	0.6	805.9	1732.8	2.7	7.4	2.0	52.9	sandy loam
			5.2	12.2	0.1	269.1	3.0	297.5	4527.6	0.7	24.7	2.0	214.1	sandy loam
	Bungoma	(pH ≥ 5.5)	5.6	4.5	0.1	179.4	1.3	55.3	8105.0	4.7	24.7	1.4	289.3	sand clay loam
			5.8	7.5	0.1	291.5	2.0	65.7	1844.6	3.5	9.1	1.4	160.1	sandy
	Kakamega	(pH ≥ 5.5)	5.5	11.4	0.1	291.5	2.4	41.5	4304.0	3.0	24.7	2.8	200.8	sandy loam
			5.6	10.3	0.1	403.7	2.1	55.3	2850.8	1.3	19.0	4.2	139.7	sandy clay loam
Rift Valley	Nandi	(pH <5.5)	4.9	13.6	0.1	628.0	2.8	114.1	7993.0	0.4	51.0	2.0	316.0	Sandy Clay Loam
			5.4	15.3	0.1	695.0	3.2	48.4	7546.0	3.5	31.0	5.6	351.0	Silt Loam
	Uasin Gishu	(pH <5.5)	4.2	8.0	0.1	224.0	2.4	211.0	3633.0	3.0	25.0	7.5	425.0	Silt Loam
	Nandi	(pH ≥ 5.5)	5.8	26.2	0.2	1032.0	3.9	86.5	25545.0	5.2	70.0	21.8	569.0	Loam
			6.1	34.0	0.2	1390.0	3.6	51.9	20402.0	3.3	56.0	19.3	569.0	Loam
	Uasin Gishu	(pH ≥ 5.5)	5.5	9.2	0.2	628.0	3.3	62.3	13695.0	1.6	37.0	11.7	551.0	Silt Loam
			5.8	20.3	0.2	875.0	3.0	65.7	16601.0	3.0	44.0	17.9	569.0	Loam
			6.0	20.7	0.3	516.0	10.4	48.4	39407.0	15.1	69.0	15.6	562.0	Silt Loam

in all the sites except in Uasin Gishu, pH 6.0 Phosphorus (P) was insufficient in Bungoma pH 5.6, 5.8, Kakamega pH 4.9, and Uasin Gishu pH 4.2 and 5.5 while the rest of the sites were sufficient, with only excess in Bungoma pH 5.3 and Nandi pH 6.1. All the sites did

not have a shortage of potassium(K), sulfur (S), zinc (Zn) and manganese (Mn), while iron was insufficient (Fe). Carbon (C) was adequate in most sites except in Bungoma pH 5.6 and Kakamega pH 4.9 with excess in Uasin Gishu pH 6.0. Calcium (Ca) was in excess in all sites except Bungoma, pH 5.8, and Kakamega, pH 4.9. Copper (Cu) was sufficient in almost all sites except in Kakamega pH 5.2, 5.6, Nandi pH 4.9 and Uasin Gishu pH 5.5.

Shows initial soil characterization was done for each site before laying the experiment, following procedures outlined in (Okalebo et al., 2002b). Soil samples were randomly collected from a plough layer of 0-20cm using a soil auger for each site. A composite was obtained from the randomly sampled spots of about 1kg and was well labelled. The composite samples (sub-samples) were air-dried in the soil science greenhouse, University of Eldoret. The samples were sieved using a 2mm sieve and a 60 mesh for pH, P, K, Zn, Cu, Fe, Mn, Ca, S, and textural classes, and N and C, respectively. The analysis was done in the soil science laboratory, University of Eldoret, according to procedures described by (Okalebo et al., 2002b). pH ranges from strongly acidic to moderately acidic, total nitrogen was insufficient in all the sites except in Uasin Gishu, pH 6.0 Phosphorus (P) was insufficient in Bungoma pH 5.6, 5.8, Kakamega pH 4.9, and Uasin Gishu pH 4.2 and 5.5 while the rest of the sites were sufficient, with only excess in Bungoma pH 5.3 and Nandi pH 6.1. All the sites did not have a shortage of potassium(K), sulfur (S), zinc (Zn) and manganese (Mn), while iron was insufficient (Fe). Carbon (C) was adequate in most sites except in Bungoma pH 5.6 and Kakamega pH 4.9 with excess in Uasin Gishu pH 6.0. Calcium (Ca) was in excess in all sites except Bungoma, pH 5.8, and Kakamega, pH 4.9. Copper (Cu) was sufficient in almost all sites except in Kakamega pH 5.2, 5.6, Nandi pH 4.9 and Uasin Gishu pH 5.5.

3.3 Treatments and experimental design

The treatments included: (i) an absolute control (0 kg DAP ha^{-1}), (ii) 133 kg DAP ha ^{1}, (iii) 67 kg DAP ha$^{-1,}$ (iv) 67 kg DAP + WonderGro (WG3) ha$^{-1,}$ and (V) 67 kg DAP + WonderGro (WG21) ha^{-1}. The DAP was in granulated form. The treatments were assigned to each plot, replicated four times to increase precision, and arranged in a complete randomized block design (RCBD); the randomization differed in each site. The 20 plots in each site measured 4.5 m × 5 m individually with six (6) planting rows (each line with 20 holes) spaced 75 cm apart and intra-row spacing of 25 cm, resulting in 120 planting hills per plot. During the planting period for both seasons, the various fertilizer treatments were assigned to their respective plots. Two maize seeds (DK 777) were planted per hill.

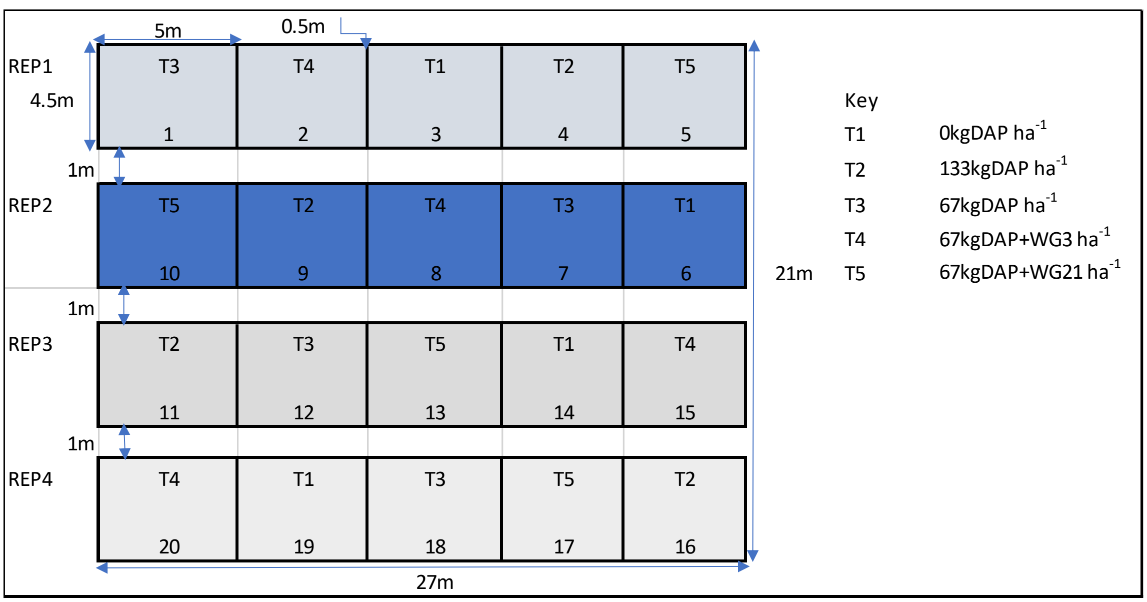

Figure 2: Example of field layout in Site 1, Uasin Gishu County

3.4 Trial management

Two weeks after emergence, seedlings were thinned to one. Three weedings were done using a jembe at the 2^{nd}, 6^{th}, and 10^{th} week after planting to ensure weed-free plots throughout the crop growing seasons. Maize pests and diseases were controlled using appropriate methods depending on their presence, occurrence and density. Harvesting was done at physiological maturity, which varies from one region to another.

3.5 Subsequent soil sampling

After planting maize in the field, soil samples were taken per plot for the four middle lines using the zigzag method using a soil auger at a depth of 20cm, a composite and a sub-sample of about 500g were obtained from it, which enhanced the representativeness of the sample. This helps to monitor the uptake of the fertilizers applied. The soil sampling was done at the silking stage 10-13 weeks after planting (WAP), and later at harvesting to monitor the impact of the formulations.

3.6 Maize plant Tissue sampling

At the onset of the maize silking stage, which is a critical stage of nutrient mobilization, four ear leaf samples were taken from each plot for nutrient uptake analysis. Sampling was done in a zigzag manner, the leaves were washed, rinsed with distilled water, and dried with a kitchen towel to remove the pollen debris and other foreign materials that would otherwise contaminate the sample (Kalra, 2019)The leaves were packed and labeled from each plot in every site and fresh weight was taken before being dried in an oven for 48 hours at 70 °C. This was done to monitor the nutrient mobilization by the maize plant.

3.7 Maize harvesting and Grain yield determination

Harvesting was done at physiological maturity; grain harvesting was confined within a net plot of 3m × 3 m, comprising four inner rows, while leaving 1 m from the row edge. A standing count of all the maize stalks (with or without combs) was recorded from each plot, the number of cobs, total fresh weight of maize ears, and fresh sample weight of randomly picked 10 maize cobs for grain dry weight analysis (**Figure 2).** Additionally, the total fresh weight of stovers was recorded, and a sample was chopped, packed, and transported to the University of Eldoret's Soil Science greenhouse for drying. The dry weight of the sample maize cobs and stovers was then recorded before threshing and grinding, respectively, for analysis of N and P to determine the nutrient concentration. Threshing was done once the cobs attained the correct moisture content (<13%). Grain yield was expressed in tons per hectare (t ha^{-1}). The yield was computed as shown in the following equations

$$Yield\ per\ effective\ area = \frac{total\ weight\ fresh\ cobs\ (kg)}{weight\ of\ fresh\ sample\ cobs\ (kg)} * Grain\ weight\ (kg)$$

Eq. 1

$$Maize\ grain\ yield\ in\ (kg\ ha^{-1}) = \frac{yield\ per\ effective\ area\ (kg) * Area\ of\ hectare(10000m^2)}{size\ of\ effective\ area\ (9m^2)} \quad Eq. 2$$

$$Maize\ grain\ yield\ (t\ ha^{-1}) = \frac{maize\ grain\ yield\ in\ (kg\ ha^{-1})}{1000} \quad Eq. 3$$

3.8. Determination of the profitability of fertilizer use

Economic analysis of the use of WonderGro- DAP treatments was done after getting the market prices of the maize at each harvesting season, this is to identify if it is cost-effective for the farmers. Since all other production costs, such as labor input, remain constant across all fertilizer treatments_Value Cost Ratio (VCR) has often been employed to assess the profitability of fertilizer use (Burke et al., 2017; Njoroge et al, 2018). Economic analysis was conducted to determine the profitability of fertilizer use in both the western and the Rift Valley regions on maize production. The analysis required fertilizer cost and the price of maize dry grains at the local market. VCR analysis was employed as a proxy determinant of the economic benefit of each fertilizer treatment for maize grain production. In this case, to determine if the farmer would be willing to invest in the combined use of DAP and WonderGro, which have shown potential in increasing maize grain yields. The VCR was calculated as a ratio of the value of increased maize crop output to the cost of fertilizer applied:

$$VCR = AE\left[\frac{price\ of\ grain\ kg^{-1}}{price\ of\ fertilizer\ kg^{-1}}\right] \qquad Eq. 4$$

Agronomic efficiency (AE) refers to how effectively a crop utilizes fertilizers. It's calculated as the increase in crop yield (e.g., grain or biomass) per unit of nutrient applied.

A VCR value greater than 1 (>1) means a 100% return on investment, indicating that the cost of fertilizer is recovered (a break-even point). VCR less than 1 (<1) denotes a net loss as long as other production costs are held constant (ceteris paribus). (Shukuru, 2022). While a VCR of or more (≥2) represents a 200% return investment and is acceptable to warrant the investment, for every dollar spent the farmer gets 2 dollars back., one dollar to compensate for the fertilizer cost, while the other dollar is the profit after investment. Therefore, VCR of any value of 2 and above is acceptable as justification to persuade farmers to utilize fertilizer.

3.9. Analysis

3.9.1. Laboratory analysis

The analysis of soil and plant tissues was carried out according to the procedures outlined in (Okalebo et al., 2002a) for pH, N, P, S and Zn. Soil pH (soil/water ratio,1:2.5) was measured using a pH meter. Total nitrogen was determined according to (Bremmer 1960 and Kjeldahl method for plant analysis) using a digestion mixture (hydrogen peroxide + sulphuric acid + selenium and salicylic acid that undergoes three main stages (i) Digestion (Sulphuric acid), (ii) oxidation (hydrogen peroxide) and (iii) cholorometric procedures, selenium act as a catalyst in the process. The absorbency was taken at 650nm. For total phosphorus (in plants), determination was done using the colorimetric method after digestion, while in soil, available P it was determined according to (Olsen 1954) using an extract of 0.5M of Sodium bicarbonate at pH 8.5, and absorbance (blue color) was measured at 880nm wavelength setting. Sulfur in soils is extracted by potassium dihydrogen sulfate extracting solution (SO^{-}_{4}) to get SO^{-}_{4}-S turbidity method was applied, and the absorbance was measured at 420nm on a spectrophotometer. Zinc is measured by atomic absorption as it absorbs radiation from an element-specific hollow cathode lamp at a wavelength of 213.9nm and this is after the digestion for the case of plants. For soils, a chelating agent such as ethylenediaminetetraacetic acid (EDTA) is used in the determination (vitro 1955).

Figure 3: Laboratory analysis of phosphorus in progress at the University of Eldoret soil science laboratory (Source: Author, 2024)

3.9.2. Detailed soil analysis

3.9.2.1. Soil pH (water) determination

Soil pH was measured in water suspension (1:2.5, soil: water respectively), whereby 50 ml of distilled water was added to 20 g of soil (< 2 mm) before stirring the mixture for 10 minutes using an orbital shaker. The stirred mixtures were then allowed to stand for 30 minutes before stirring again for two minutes. Finally, pH readings of each sample were taken using a calibrated pH meter.

3.9.2.2. Total nitrogen analysis

The percentage total N was determined calorimetrically, whereby 0.3 g of a (0.25 mm) sample was digested with 2.5 ml digestive mixture at 110°C °C for 60 minutes, followed by adding three successive 1 ml portions of hydrogen peroxide to the cooled content. Heating was then continued to raise the temperature to 330 °C until a colorless solution with white sand was obtained. 25 ml of distilled water was then used to dissolve the mixture until no more sediment dissolved and then 50 ml of distilled water was added to top up the solution. The clear solution obtained was used for the colorimetric determination of total N, where absorbency was measured at 650 nm.

3.9.2.3. Available phosphorus (Olsen method) analysis

The available P was extracted using the Olsen method, whereby 2.5 g of air-dried soil samples were mixed with 50 ml of Olsen's extracting solution (0.5 M $NaHCO_3$, pH 8.5) in 250 ml polythene bottles, followed by shaking the mixture for 30 minutes using an orbital shaker. The suspension was filtered through a Whatman No. 42 filter paper. Finally, the filtrate was used for the colorimetric P measurements, where Standards and sample absorbances were measured at 880nm wavelength.

3.9.3. Detailed Plant tissue analysis

The plant tissue was digested using the digestion procedure described in the previous section to obtain plant digest for the determination of total N and P.

3.9.3.1. Determination of total nitrogen and phosphorus in plants

The content of total nitrogen and phosphorus was measured in a digest obtained by treating plant sample with hydrogen peroxide + sulphuric acid + selenium + salicyclic acid + lithium sulphate (Digestion mixture). The principle takes into account the possible omission of nitrates by coupling them with salicyclic acid in ana acid media to form 3-nitrosalicyclic and or 4-nitrosalicyclic. The peroxide oxidizes the organic matter while the selenium compound act as a catalyst for the process and the H_2SO4 completes the digestion at elevated temperatures as well as the inclusion of LiSO4. The main advantage of this method is that a single digestion (for either soil or plant material) is required to bring nearly all nutrients into solution; no volatilization of metals, N, and P takes place and the method is simple and rapid.

3.9.4. Statistical analysis

The data collected from the field trials were managed using Microsoft Excel, and the data were subjected to analysis of variance (ANOVA) using Genstat Statistical Package (14^{th} edition to determine of treatments per pH category per region across the seasons. The standard error of the differences (SED) was used to separate the effects at 5% level of significance. Descriptive analysis was done, and results were presented in box and whiskers, bar charts with error bars, together with the statistical letters showing differences in their means. The means were separated using Fischer's unprotected LSD at $P \leq 0.05$.

The statistical model equation used for data analysis was: -

$Yijkl=\mu+\alpha i+\beta j+\lambda k +ijk$

$Yijkl$=overall plot observation

μ= mean of plot observation

$\alpha i = i^{th}$ effect of the pH categories

$\beta j = j^{th}$ effect of seasons

$\lambda k = k^{th}$ effect of the treatments

ijk= error term

CHAPTER FOUR

RESULTS

4.1 Maize grain yield

In both the season and regions, the maize yield of the control treatment was lower than that of other treatments **(Figure 4).** In western Kenya, sub-optimal pH for maize production (pH<5.5), with application of fertilizer, there was a yield increase, an indicator that these soils need supplementation for higher production. In the long rains of 2023, the use of fertilizer had the largest yield with an average of 4.2t ha^{-1} and this increased yield by 64.3% from absolute control. Short rains had generally low yield, with absolute control having the lowest yield of 0.5t ha^{-1}. With the application of fertilizers, there was no significant difference at ($p<0.05$) with an average yield of 2.0t ha-1. A similar trend was observed during the long rains of 2024, with an absolute control having the lowest yield of 1.1t ha^{-1}. With fertilizer application, there was no significant difference ($p<0.05$) even though application of half rate of DAP in combination of formulation of WG3 (67kgDAP + WG3 ha -1) slightly increased maize grain yield by 9.1%. In optimal pH for maize production (pH≥5.5), application of fertilizer had no differences at ($p<0.05$) with an average yield of 4.2t ha-1, 1.7 t ha^{-1}, and 3.6t ha^{-1} for long rains 2023, short rains 2023, and long rains 2024, respectively.

In the Rift Valley, the application of fertilizers increased maize grain yield in both seasons across the pH categories, with long rains 2023 yielding more than long rains 2024. In suboptimal pH for maize production, applying half the rate of DAP in combination with WG21 (67 kg DAP + WG21 ha^{-1}) slightly increased yield, resulting in an average yield of 5.1t ha^{-1} across. The seasons and season* treatments interaction were not significant (p=

0.746) and (p= 0.387) on maize grain yield, respectively. Use of fertilizer on pH≥ 5.5 had no significant difference (P<0.05) for each season, 2023 and 2024 long rains, with an average of 7.3 t ha-1 and 6.1t ha^{-1}, respectively, which increased yield by 29.7% and 40.0% respectively. Seasons were significant at (p<0.05) while the interaction of treatments was not significant (p=0.418) on maize grain yield. There was a larger yield in optimal pH, as compared to sub-optimal pH, an indicator that correcting pH would improve maize grain yield.

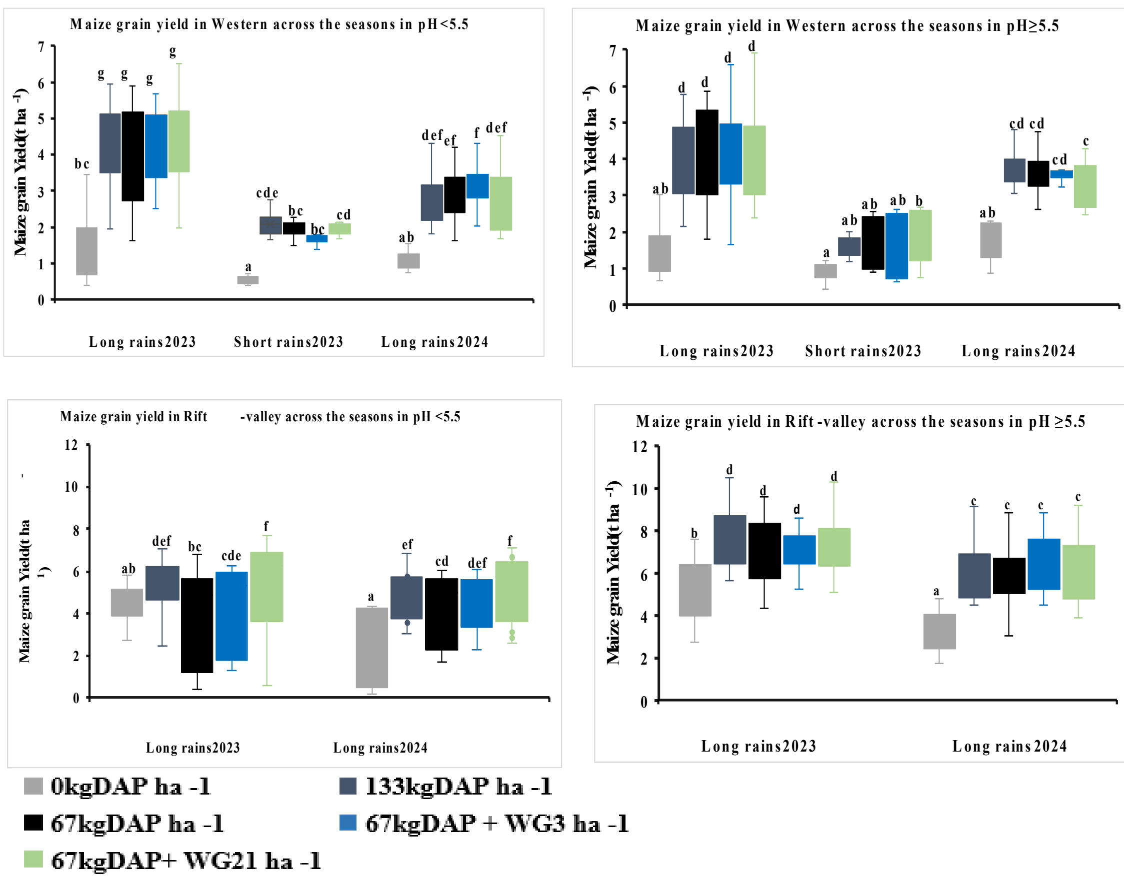

Figure 4: Maize grain (t h^{-1}) yield based on pH category, sub-optimal and optimal for maize production from Western and Rift Valley, Kenya

4.2 Relationship of grain nutrients and relative yield of the maize grain

4.2.1 Relationship of grain N content to the relative yield of maize grain

Under sub-optimal pH for maize production in western Kenya, planting maize without fertilizer contributed to very low relative yield (<40%), with an average of 0.67% grain N content. The fertilizer application did not have any significant differences and increased N content by 9.7%, which boosted the relative yield towards maximum at an average relative yield (RY) of 72.35% (SE± 4.11), thus increasing the Relative yield by 64.21% from the absolute control.

While in the optimal pH of Western Kenya, absolute control contributed to a relative yield above 20%, ranging up to 80 %RY. The application of fertilizers did not have significant differences. It increased N uptake by 8.2% from 0.67% N of the absolute control, and RY quickly nudges towards the plateau (100%), with an average relative yield (RY) of 76.21% (SE± 20.99), thus increasing the Relative yield by 56.49% from the absolute control.

In the Rift Valley, sub-optimal pH for maize production, absolute control had low grain N content, contributing to less than 15% RY. Use of the full rate of DAP (133 kg DAP ha^{-1}), half rate (67 kg DAP ha^{-1}) in combination with either WG3 or WG21 had no significant differences, with an average of 0.69% maize grain N content. For optimal pH, the use of half-rate DAP solely or in combination with either of the formulations had no significant differences with an average maize grain N content of 0.68% N, contributing up to more than 60% relative yield.

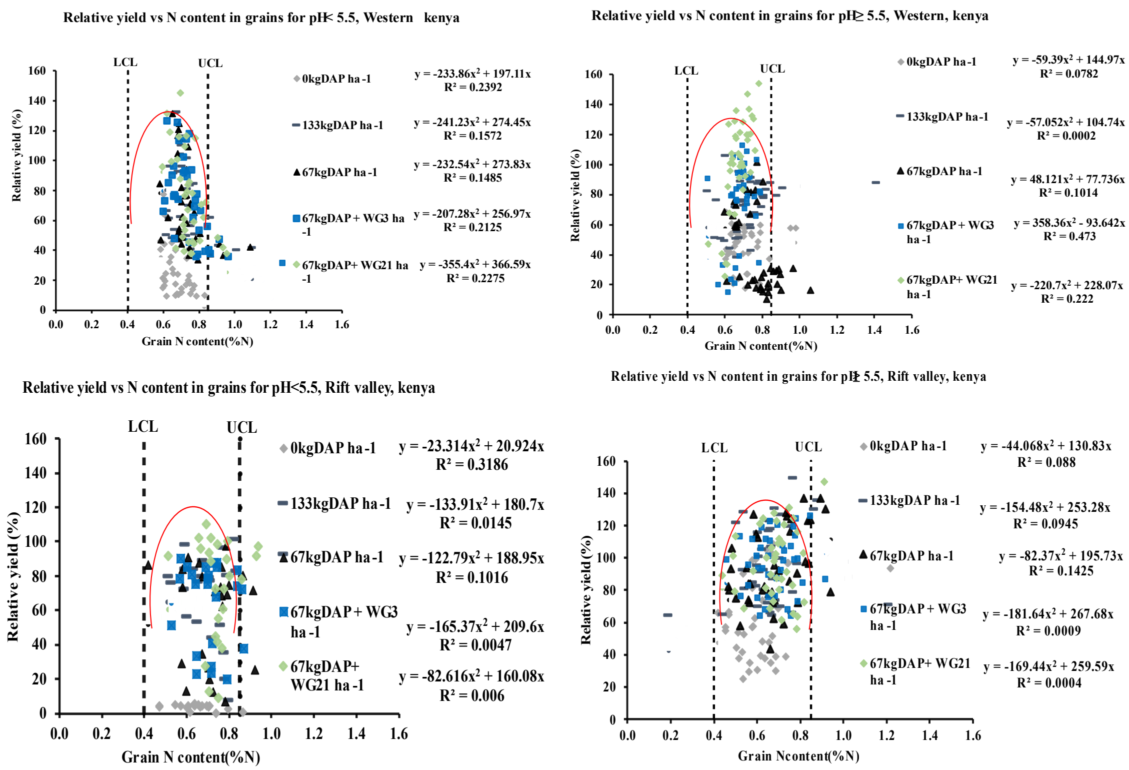

Figure 5: Relationship between relative yield and grain N content based on pH category, sub-optimal and optimal for maize production from Western and Rift Valley, Kenya

4.2.2. Relationship of grain P content to the relative yield of maize grain

Generally, across the regions, pH categories and the seasons, %P grain content was deficient (< 0.25%). **Figure 5 i**n western Kenya, both sub-optimal and optimal pH for maize production, there were no significant differences between the treatments ($p<0.05$) with an average of 0.18%P and 0.17%P, respectively. Similarly, in the Rift Valley, all the treatments had no significant differences ($p<0.05$) with an average of 0.14%P and 0.15%P, respectively, for sub-optimal and optimal pH categories for maize production. The insufficiency of P, therefore, calls for further checks on the uptake efficiency of P by the maize plant.

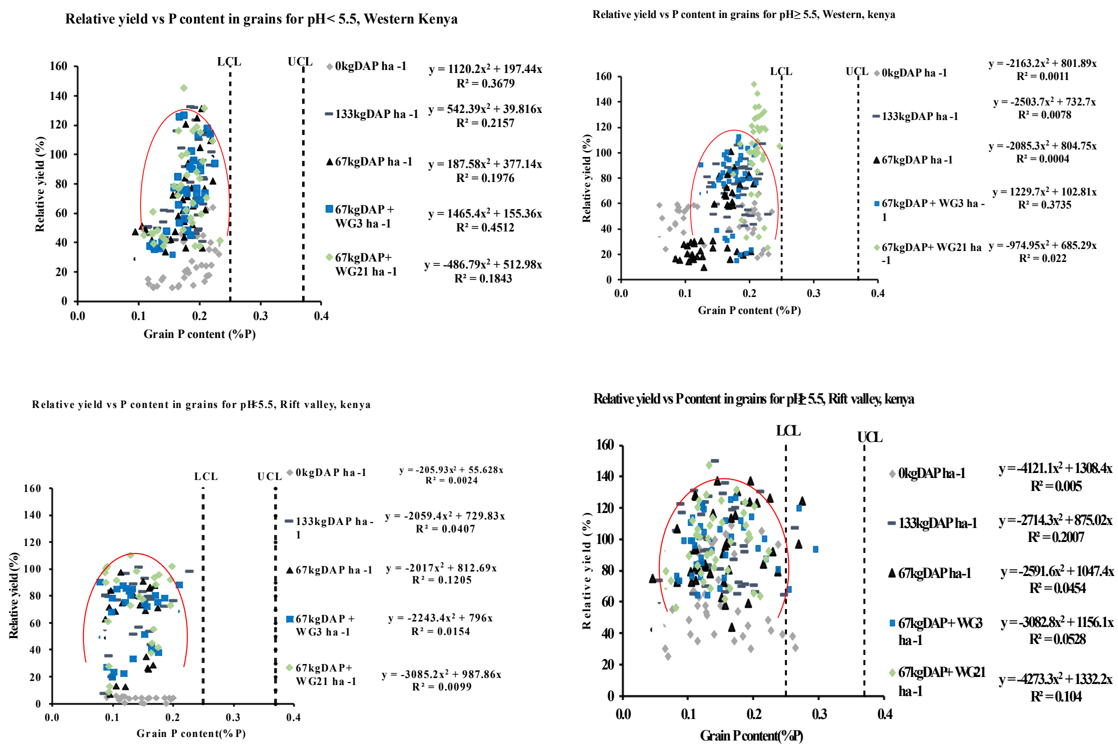

Figure 6: Relationship between relative yield and grain P content based on pH category, sub-optimal and optimal for maize production from Western and Rift Valley, Kenya

4.3. Maize harvest index

In western Kenya (pH < 5.5), planting maize without fertilizer (0 kg DAP ha $^{-1}$) during the short rains had the lowest HI of 0.14, followed by long grains 2023 and 2024, with 0.25 and 028, respectively. Application of half rate of DAP with or without combination with WG21 in 2023 and in 2024, long rains had the largest Harvest index with an average of 0.59. In the optimum pH (≥5.5) of western Kenya, the long rains of 2024 had the largest index (HI) with the application of fertilizers at an average of 0.56. The HI was lower in the 2023 short rains and long rains, at 0.28 and 0.43, respectively. Generally, the application of fertilizers increased HI by 35.82% from 0.29 when no fertilizer was applied.

In the Rift Valley, in sub-optimal pH (<5.5), for maize production, application of half rate of DAP in combination with either WG3 or WG21 in 2024 had the highest harvest index with an average of 0.50, while planting without fertilizers or application of the rest of fertilizers either in 2023 or 2024 long rains had no variation with a HI of 0.39. In the optimum pH (≥5.5), 2023 had the largest harvest index with application of fertilizers having no variation with an average of 0.37, while in 2024, planting without fertilizer (0kgDAP ha^{-1}) and use of sole half rate of DAP (67kgDAP ha^{-1}) had the lowest harvest index (HI) of 0.25 on average. The application of the full rate of DAP, half rate of DAP in combination with the formulations had no differences, with an average of 0.31.

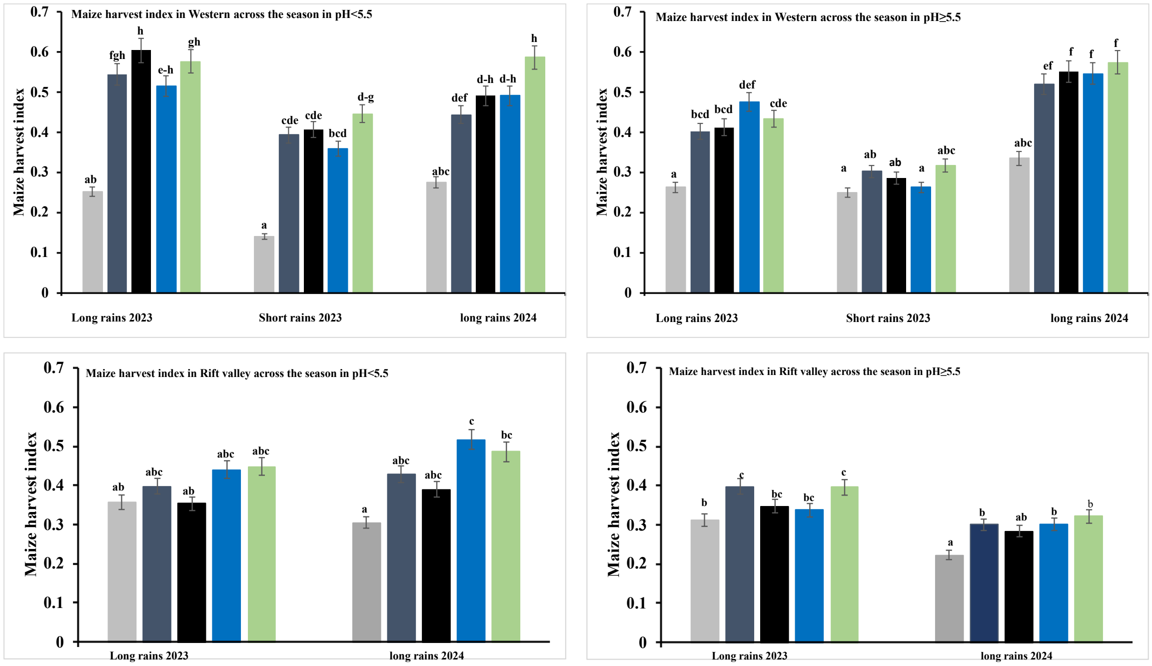

Figure 7: Maize harvest index (HI) as influenced by the seasons based on pH category, sub-optimal and optimal for maize production per region.

4.4. Nutrient uptake efficiency of maize

4.4.1 Nitrogen uptake efficiency

In western Kenya, sub-optimal pH (<5.5), application of the sole half rate of DAP had the lowest N uptake efficiency with 0.21 kg kg^{-1}N, with application of the full rate of DAP or half rate of DAP in combination with either WG3 or WG21, the uptake increased by 21.89%

Table 3. Seasonally, long rains of 2023 had the highest uptake of the above-mentioned with an average of 0.34kg $kg^{-1}N$, preceded by 0.25kg $kg^{-1}N$ uptake in long rains of 2024. While the use of half rate of DAP solely or in combination with WG3 had the lowest uptake efficiency with an average of 0.12kg $kg^{-1}N$ in short rains 2023. In optimal pH (≥5.5), 2023 long rains had the largest Nitrogen uptake efficiency (NUE) under application of full rate DAP (133kg DAP ha^{-1}), the half rate of DAP in combination with either WG3 or WG21, with an average of 0.40kg $ka^{-1}N$. Use 67kg DAP+ WG3 ha^{-1} had slightly higher nitrogen uptake efficiency in short rains 2023 and long rains 2024 with 0.25kg $kg^{-1}N$ and 0.29kg $kg^{-1}N$, respectively.

In Rift Valley, sub-optimal pH (<5.5), for maize production, the use of half the rate of DAP with either of the formulations of WG3 or WG21 had no differences in the long rains of 2024 and had the largest N uptake efficiency with an average of 0.49kg $kg^{-1}N$. Though the formulation of WG21 had the highest N uptake in 2023 long rains, but had no statistically significant differences($p \leq 0.05$) with the full rate of DAP in 2024, with an average of 0.40kg $kg^{-1}N$

Table 3. In optimal pH (>5.55), all the fertilizers applied had no variations in N uptake efficiency with an average of 0.38kg kg^{-1}N in 2023 long rains. On the other hand, application of half rate of DAP in combination with either WG3 or WG21 had the largest uptake with an average of 0.50kg kg^{-1}N in long rains of 2024.

Table 3: Maize nitrogen uptake efficiency (NUE, kg kg-1N) (means±SE) as influenced by seasons per pH category for maize production.

			NUE(kg N uptake kg^{-1} N supply) response for maize production				
Region	**pH Category**	**Seasons**	**133kgDAP ha^{-1}**	**67kgDAP ha^{-1}**	**67kgDAP + WG3 ha^{-1}**	**67kgDAP+ WG21 ha^{-1}**	**mean††**
Western kenya	**pH< 5.5**	Long rains 2023	$0.33(0.03)^{e}$	$0.30(0.03)^{de}$	$0.35(0.02)^{e}$	$0.33(0.02)^{e}$	**0.33**
		Short rains 2023	$0.24(0.06)^{cd}$	$0.11(0.02)^{a}$	$0.14(0.02)^{ab}$	$0.21(0.01)^{bc}$	**0.18**
		Long rains 2024	$0.25(0.01)^{cd}$	$0.18(0.01)^{abc}$	$0.26(0.02)^{cd}$	$0.24(0.04)^{d}$	**0.23**
		mean†	$\mathbf{0.27^{B}}$	$\mathbf{0.20^{A}}$	$\mathbf{0.25^{B}}$	$\mathbf{0.26^{B}}$	**0.25**
Western kenya	**pH≥ 5.5**	Long rains 2023	$0.42(0.04)^{f}$	$0.33(0.04)^{de}$	$0.40(0.04)^{ef}$	$0.38(0.04)^{ef}$	**0.38**
		Short rains 2023	$0.14(0.01)^{ab}$	$0.12(0.01)^{a}$	$0.25(0.03)^{bcd}$	$0.21(0.01)^{abc}$	**0.18**
		Long rains 2024	$0.23(0.04)^{bc}$	$0.21(0.01)^{abc}$	$0.29(0.02)^{cd}$	$0.20(0.02)^{ab}$	**0.23**
		mean†	$\mathbf{0.26^{AB}}$	$\mathbf{0.22^{A}}$	$\mathbf{0.31^{B}}$	$\mathbf{0.26^{AB}}$	**0.26**
Rift valley	**pH< 5.5**	Long rains 2023	$0.33(0.05)^{abc}$	$0.25(0.05)^{a}$	$0.28(0.04)^{ab}$	$0.39(0.04)^{bcd}$	**0.31**
		Long rains 2024	$0.41(0.02)^{bcd}$	$0.43(0.07)^{cd}$	$0.50(0.03)^{d}$	$0.49(0.06)^{d}$	**0.46**
		mean†	$\mathbf{0.37^{AB}}$	$\mathbf{0.34^{A}}$	$\mathbf{0.39^{AB}}$	$\mathbf{0.44^{B}}$	**0.39**
Rift valley	**pH≥ 5.5**	Long rains 2023	$0.29(0.03)^{a}$	$0.38(0.04)^{ab}$	$0.36(0.04)^{ab}$	$0.37(0.02)^{ab}$	**0.35**
		Long rains 2024	$0.41(0.02)^{b}$	$0.39(0.03)^{ab}$	$0.54(0.04)^{c}$	$0.46(0.05)^{bc}$	**0.44**
		mean†	$\mathbf{0.35^{A}}$	$\mathbf{0.39^{AB}}$	$\mathbf{0.45^{B}}$	$\mathbf{0.41^{AB}}$	**0.40**
			western(pH< 5.5)	western(pH≥5.5)	Rift Valley (pH< 5.5)	Rift Valley (pH≥5.5)	
	p-value	Seasons	<.001***	<.001**	<.001***	<.001***	
		Treatments	0.016*	0.02*	ns	0.035*	
		Seasons.Treatments	ns	Ns	ns	ns	
		SE	0.095	0.12	0.166	0.162	
		CV %	36.20	42.80	43.50	40.60	

Abbreviation: PUE is the phosphorus uptake efficiency. Means within a pH category of a region followed by different letters differ significantly at the level of $p < 0.05$. ns means not significant at the level of $p < .05$. CV is the coefficient of variation. SE is the standard error, *, ** and *** indicate the significance at 0.1, 0.01 and <0.001, respectively. †these give the aggregate effects of fertilizer used per pH category, †† these values give averages across the seasons. Lower case letters give differences in the fertilizer used across the seasons, while upper case letters give differences in the fertilizer used.

4.4.2 Phosphorus uptake efficiency

A greater effect of P impact on maize yield was experienced under low rainfall (short rains) because P diffusion from the soil to the root surface is limited due to a deficiency in soil moisture, and the root system is less able to exploit new zones of available soil P and this is evidenced with lower uptake during the short rains in Western Kenya as shown in

Table *4*. Despite the low PUE, the formulations showed larger uptake as compared to other treatments in so many instances in western Kenya under sub-optimal pH for maize production (<5.5) application of Half the rate of DAP (67 kg DAP ha^{-1}) in combination with either WG3 or WG21 had no significant differences with an average of 0.57kg kg^{-1}P during the long rains of 2023, while in optimal pH (≥5.5) application of half rate of DAP with or without the formulation (WG3 or WG21), had the largest P uptake efficiency with no significant difference ($p<0.05$) with an average of 0.69kg kg^{-1}P.

Similarly, in Rift Valley, sub-optimal pH (<5.5), application of Half the rate of DAP (67 kg DAP ha^{-1}) in combination with either WG3 or WG21 had the largest PUE with no differences with an average of 0.73kg kg^{-1}P during the long rains of 2024, while in optimal pH application of half rate of DAP with or without the formulation (WG3 or WG21), had the largest P uptake efficiency with no difference ($p<0.05$) with an average of 1.05kg kg^{-1}P during long rains of 2024. It's therefore evident that PUE increased with the application of the formulations.

Table 4: Maize phosphorus uptake efficiency (PUE, kg kg^{-1}P) (means±SE) as influenced by seasons per pH category for maize production.

			PUE response for maize production in 3 consuctive seasons for western and Rift valley, kenya				
Region	**pH Category**	**Seasons**	**133kgDAP ha $^{-1}$**	**67kgDAP ha $^{-1}$**	**67kgDAP + WG3 ha $^{-1}$**	**67kgDAP+ WG21 ha $^{-1}$**	**mean**
Western kenya	**pH< 5.5**	Long rains 2023	0.24(0.02)^{abc}	0.46(0.04)^{de}	0.610.08)^{f}	0.54(0.06)^{ef}	**0.46**
		Short rains 2023	0.15(0.01)^{a}	0.12(0.00)^{a}	0.19(0.04)^{ab}	0.14(0.02)^{a}	**0.15**
		Long rains 2024	0.17(0.02)^{a}	0.22(0.04)^{abc}	0.35(0.08)^{cd}	0.31(0.06)^{bc}	**0.26**
		mean†	**0.19^{A}**	**0.27^{B}**	**0.38^{C}**	**0.33^{BC}**	**0.29**
Western kenya	**pH≥ 5.5**	Long rains 2023	0.41(0.03)^{de}	0.72(0.07)^{f}	0.66(0.04)^{f}	0.70(0.05)^{f}	**0.62**
		Short rains 2023	0.07(0.01)^{a}	0.08(0.02)^{a}	0.13(0.02)^{ab}	0.11(0.02)^{ab}	**0.10**
		Long rains 2024	0.22(0.01)^{bc}	0.41(0.05)^{de}	0.44(0.04)^{e}	0.30(0.03)^{cd}	**0.34**
		mean†	**0.23^{A}**	**0.40^{B}**	**0.41^{B}**	**0.37^{B}**	**0.35**
Rift valley	**pH< 5.5**	Long rains 2023	0.11(0.03)^{a}	0.13(0.02)^{a}	0.29(0.08)^{ab}	0.19(0.03)^{a}	**0.18**
		Long rains 2024	0.46(0.07)^{bc}	0.57(0.08)^{cd}	0.68(0.12)^{de}	0.78(0.09)^{e}	**0.62**
		mean†	**0.29^{A}**	**0.35^{AB}**	**0.49^{B}**	**0.49^{B}**	**0.40**
Rift valley	**pH≥ 5.5**	Long rains 2023	0.19(0.02)^{a}	0.34(0.02)^{abc}	0.49(0.06)^{bc}	0.26(0.03)^{ab}	**0.32**
		Long rains 2024	0.51(0.06)^{c}	1.08(0.10)^{d}	1.34(0.12)^{e}	1.24(0.16)^{de}	**0.91**
		mean†	**0.35^{A}**	**0.71^{B}**	**0.92^{C}**	**0.75^{B}**	**0.68**
			western(pH< 5.5)	western(pH≥5.5)	Rift Valley (pH< 5.5)	Rift Valley (pH≥5.5)	
	p-value	Seasons	<.001***	<.001***	<.001***	<.001***	
		Treatments	<.001***	<.001***	0.018*	<.001***	
		Seasons.Treatmen	0.05*	0.013*	ns	0.01**	
		SE	0.17	0.16	0.26	0.415	
		CV %	35.20	38.70	36.70	26.90	

Abbreviation: PUE is the phosphorus uptake efficiency. Means within a pH category of a region followed by different letters differ significantly at the level of $p < 0.05$. ns means not significant at the level of $p < .05$. CV is the coefficient of variation. SE is the standard error, *, ** and *** indicate the significance at 0.1, 0.01 and <0.001, respectively. †these give the aggregate effects of fertilizer used per pH category, †† these values give averages across the seasons. Lower case letters give differences in the fertilizer used across the seasons, while upper case letters give differences in the fertilizer used.

4.5. Agronomic efficiency and partial factor productivity of maize

4.5.1 Agronomic efficiency of N (AGn) and partial factor productivity of N (PFPn)

Agronomic efficiency of N is the product of the efficiency of N recovery from applied N and the efficiency with which the plant uses each additional N acquired. Generally, short rains had the lowest AGn of 14.24kg grain kg^{-1}N on average across the treatments in a sub-optimal pH (<5.5) of western Kenya. While in 2024, long rains application of the half rate of DAP in combination with WG3 (67kg DAP+ WG3 ha^{-1}) slightly increased the AGn efficiency by 2.02% from 17.95kg grain kg^{-1}N when other fertilizers were applied. Use of full rate of DAP (133kg DAP ha-1), application of half rate of DAP in combination of either of the formulations in (WG3 or WG21) had the largest AGn efficiency with an average of 28.92kg grain kg-1N. In optimal pH (≥5.5), short rains had the lowest AGn efficiency with an average of 8.16kg grain kg^{-1}N among the fertilizers applied, there was no variation of the fertilizer applied at ($p<0.05$) in 2023 and 2024 long rains, with an average of 25.66kg grain kg^{-1}N and 18.93kg grain kg^{-1}N, respectively.

In rift valley under sub-optimal pH (<5.5.) for maize production, application of full rate of DAP (133kg DAP ha^{-1}), the half rate of DAP in combination with WG21 (67kg DAP+ WG21 ha^{-1}), in long rains 2023 and 2024 long rains and also the use of 67kg DAP+ WG21 ha-1 in 2024, had no variation with ana average of 20.26kg grain kg^{-1}N. In optimal pH (>5.5), use of full rate of DAP in 2023 long rains and half rate of DAP in combination with WG3 in 2024 long rains had no differences with the largest AGn efficiency of 27.89kg grain kg^{-1}N, which increased the efficiency from other fertilizers across the season by 15.69%.

In sub-optimal pH (<5.5) of western Kenya, short rains had the lowest PFPn, followed by long rains of 2024, and the largest was long rains 2023, with application of fertilizers having no difference with the seasons at an average of 19.52kg kg^{-1}, 29.05kg kg^{-1}, and 41.7052kg kg$^{-1,}$ respectively. Similarly, in optimum pH in western Kenya, the treatments had no significant differences in the PFPn within the seasons, with short rains having the lowest, followed by 2024 long rains, and the largest was 2023 long rains, with an average of 16.92kg kg^{-1}, 35.74kg kg^{-1}, and 41.53kg kg^{-1}, respectively

In Rift valley in the sub-optimal pH for maize production regardless of the season or fertilizer applied there no variation in the PFPn with an average of 48.47kg kg^{-1} while in the optimum pH (≥5.5), application of fertilizers had no variations within the seasons and was lower in 2024 compared to 2023, with an average of 61.40kg kg^{-1}, and 73.00kg kg^{-1}, respectively.

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Table 5: Maize Agronomic efficiency of nitrogen (AGn, kg grain kg-1N), Partial factor productivity of nitrogen (PFPn, kg kg-1N) (means±SE) as influenced by seasons per pH category for maize production

			AE_N (kg grain kg^{-1}N) response for maize production					PFP_N (kg kg^{-1} N) response for maize production				
Region	**pH Category**	**Seasons**	**133kgDAP ha^{-1}**	**67kgDAP ha^{-1}**	**67kgDAP + WG3 ha^{-1}**	**67kgDAP+ WG21 ha^{-1}**	**mean††**	**133kgDAP ha^{-1}**	**67kgDAP ha^{-1}**	**67kgDAP + WG3 ha^{-1}**	**67kgDAP+ WG21 ha^{-1}**	**mean††**
Western kenya	**pH< 5.5**	Long rains 2023	28.35(2.47)^{e}	24.02(2.02)^{d}	27.97(1.23)^{de}	30.45(1.06)^{e}	**27.70**	42.68(3.02)^{f}	38.50(3.57)^{f}	42.12((2.45)^{f}	43.50(3.07)^{f}	**41.70**
		Short rains 2023	15.67(1.16)^{ab}	14.79(0.57)^{ab}	11.67(0.66)^{a}	15.05(1.17)^{ab}	**14.30**	21.10(1.26)^{abcd}	19.41(0.92)^{ab}	17.10(0.74)^{a}	20.48(1.14)^{abc}	**19.52**
		Long rains 2024	17.71(1.88)^{b}	18.32(1.07)^{b}	19.70(1.53)^{bc}	17.82(2.31)^{b}	**18.39**	28.05(2.52)^{cde}	29.24(2.12)^{de}	31.18(1.94)^{e}	27.74(2.55)^{bcde}	**29.05**
		mean†	**20.58^{A}**	**19.04^{A}**	**19.78^{A}**	**21.11^{A}**	**20.13**	**30.61^{A}**	**29.05^{A}**	**30.13^{A}**	**30.57^{A}**	**30.09**
Western kenya	**pH≥ 5.5**	Long rains 2023	25.90(2.20)^{e}	24.54(2.76)^{de}	27.78(2.33)^{e}	24.41(1.61)^{de}	**25.66**	41.69(3.07)^{c}	40.32(3.67)^{c}	42.16(3.64)^{c}	41.96(3.41)^{c}	**41.53**
		Short rains 2023	7.00(0.47)^{a}	8.28(1.89)^{a}	7.18(2.51)^{a}	10.17(1.78)^{ab}	**8.16**	15.95(1.10)^{a}	17.22(2.65)^{a}	16.00(3.33)^{a}	18.51(2.84)^{a}	**16.92**
		Long rains 2024	20.26(1.50)^{cd}	19.88(1.30)^{cd}	19.49(1.78)^{cd}	16.09(1.51)^{bc}	**18.93**	37.31(2.63)^{bc}	36.50(1.49)^{bc}	36.33(0.86)^{bc}	32.82(1.62)^{b}	**35.74**
		mean†	**17.72^{A}**	**17.58^{A}**	**18.15^{A}**	**16.89^{A}**	**17.59**	**31.65^{A}**	**31.35^{A}**	**31.50^{A}**	**31.10^{A}**	**31.40**
Rift valley	**pH< 5.5**	Long rains 2023	18.86(2.92)^{abc}	14.02(2.38)^{a}	14.70(1.54)^{a}	21.64(2.23)^{bc}	**18.01**	53.43(4.19)^{a}	46.40(4.48)^{a}	43.5(5.94)^{a}	54.86(5.58)$^{)a}$	**49.55**
		Long rains 2024	20.93(2.53)^{bc}	15.88(1.59)^{ab}	17.20(1.46)^{abc}	22.69(1.90)^{c}	**19.18**	49.99(3.28)^{a}	43.25(5.09)^{a}	45.67(4.28)^{a}	50.62(4.90)^{a}	**47.38**
		mean†	**19.89^{BC}**	**14.95^{A}**	**15.95^{AB}**	**22.17^{C}**	**18.24**	**51.71^{A}**	**44.82^{A}**	**44.58^{A}**	**52.74^{A}**	**48.46**
Rift valley	**pH≥ 5.5**	Long rains 2023	27.69(1.82)^{b}	22.31(1.32)^{ab}	20.88(2.28)^{a}	25.92(1.56)^{ab}	**24.20**	75.79(3.23)^{c}	71.15(3.55)^{bc}	71.1(2.06)^{bc}	73.94(2.83)^{c}	**73.00**
		Long rains 2024	22.98(2.33)^{ab}	23.89(2.11)^{ab}	28.09(2.96)^{b}	25.11(2.64)^{ab}	**25.02**	59.84(3.52)^{a}	60.03(3.67)^{a}	63.96(3.25)^{ab}	61.75(3.58)^{a}	**61.40**
		mean†	**25.34^{A}**	**23.1^{A}**	**24.49^{A}**	**25.51^{A}**	**24.61**	**67.82^{A}**	**65.59^{A}**	**67.53^{A}**	**67.84^{A}**	**67.20**
			western(pH< 5.5)	western(pH≥5.5)	Rift Valley (pH< 5.5)	Rift Valley (pH≥5.5)		western(pH< 5.5)	western(pH≥5.5)	Rift Valley (pH< 5.5)	Rift Valley (pH≥5.5)	
	p-value	Seasons	<.001***	<.001***	ns	ns		<.001***	<.001***	ns	<.001***	
		Treatments	ns	ns	0.003**	ns		ns	ns	ns	ns	
		Seasons.Treatments	ns	ns	ns	0.055*		ns	ns	ns	ns	
		SE	6.09	7.307	7.371	9.783		9.52	9.968	16.57	14.534	
		CV %	28.2	37.50	40.40	39.8		29.3	29.1	34.2	21.6	

Abbreviation: AGn is the agronomic efficiency of nitrogen, and PFPn partial productivity of nitrogen. Means within a pH category of a region followed by different letters differ significantly at the level of *p* < 0.05. ns means not significant at the level of *p* < .05. CV is the coefficient of variation. SE is the standard error, *, ** and * indicate the significance at 0.1, 0.01 and <0.001, respectively. †these give the aggregate effects of fertilizer used per pH category, †† these values give averages across the seasons. Lower case letters give differences in the fertilizer used across the seasons, while upper case letters**

4.5.2. Agronomic efficiency of P (AG_P) and partial factor productivity of P (PFP_P)

In sub-optimal pH(<5.5) for maize production, application of full rate of DAP(133kg DAP ha-1) in short rains and long rains 2024 had the lowest AGp efficiency with an average of 59.65kg grain kg^{-1}P, while application of half rate of DAP in combination with either of the formulation of WG3 or WG21 had no differences with the highest AGp efficiency of 206.80kg grain kg^{-1}P, and this increased the AGp efficiency by 50.24% **Table *6***. In optimal pH (≥5.5), during short rains, the application of the full rate of DAP, half rate with or without combination with WG3 had the lowest AGp efficiency with an average of 47.37kg grain kg^{-1}. The largest efficiency was recorded in 2023 long rains when a half rate of DAP was applied solely or in combination with WG3 or WG21, with an average of 191.60kg grain kg^{-1}P.

In the Rift Valley, sub-optimal pH (<5.5) for maize production, application of the full rate of DAP in 2023 and 2024, and use sole half rate of DAP (67kg DAP ha^{-1}) had no variation statistically, with the lowest AGp efficiency of 74.77kg grain kg^{-1}P on average. Application of 67kg DAP+WG21 ha^{-1} on both seasons had the largest AGp efficiency with an average of 182.95kg grain kg^{-1}P. In optimal pH (≥5.5), application of full rate of DAP for both the seasons had the lowest AGp efficiency with an average of 91.90kg grain kg^{-1}P, while use of half rate of DAP in combination with WG3 had the highest AGp of 200.90kg grain kg^{-1}P and this increase the efficiency by 57.64% from application of full rate of DAP in 2024, long rains.

For the PFPp in sub-optimal pH (<5.5) in western Kenya, for maize production, the results indicate that both season and fertilizer applied significantly influenced maize partial factor productivity of P (PFPp), application of the half rate of DAP with or without combination of WG3 or WG21 had the largest PFPp with an average of 306.47kg kg^{-1}P, in contrast to the short rains 2023 and long rains 2024, that resulted into the lowest PFPp particularly with application of full rate of DAP (133kg DAP ha^{-1}) with an average of 91.05kg kg^{-1}P. In the optimal pH (≥5.5), the lowest PFPp was recorded with application of 133kgDAP ha^{-1}, during the short rains with 59.10kg kg^{-1}P, indicating minimal response under this condition. During the long rains of 2023, use of half-rate of DAP with or without combination with formulations of WG3 or WG21 did not vary and had the largest PFPp of 302.40kg kg^{-1}P, while in long rains of 2024, use of half-rate DAP with or without a combination of WG3 had an average of 264.95kg kg^{-1}P suggesting application of the formulations during the long rains significantly enhances PFPp

In Rift valley, sub-optimal pH (<5.5), application of full rate of DAP (133kg DAP ha^{-1}) in both the seasons had the lowest PFPp with an average of 179.7kg kg^{-1}P, while application of half rate of DAP solely or with either WG3 or WG21 had no diffrences with an average PFPp of 336.28kg kg^{-1}P across the seasons. In optimal pH (≥5.5), generally, full rate of DAP in 2024 long rains had the lowest PFPp with 221.6kg kg^{-1}P. The application half rate of DAP in combination with WG3 or WG21 had the largest PFPp in 2023, with an average of 536.80kg kg^{-1}P. The DAP combined with the formulations tends to be higher in PFPp in every season

Table 6: Maize Agronomic efficiency of phosphorous (AGp, kg grain kg-1p), Partial factor productivity of phosphorous (PFPp, kg kg-1p) (means±SE) as influenced by seasons per pH category for maize production.

			AEp (kg grain kg^{-1}P) response for maize production					PFPp (kg kg^{-1} P) response for maize production				
Region	pH Category	Seasons	133kgDAP ha^{-1}	67kgDAP ha^{-1}	67kgDAP + WG3 ha^{-1}	67kgDAP+ WG21 ha^{-1}	mean††	133kgDAP ha^{-1}	67kgDAP ha^{-1}	67kgDAP + WG3 ha^{-1}	67kgDAP+ WG21 ha^{-1}	mean††
Western kenya	pH< 5.5	Long rains 2023	102.90(9.62)^{bc}	174.90(16.25)^{ef}	201.70(10.85)^{fg}	211.90(12.07)^{g}	172.85	158.10(11.17)^{cd}	285.20(26.44)^{f}	312.00(18.18)^{f}	322.20(22.72)^{f}	269.38
		Short rains 2023	58.00(4.30)^{a}	103.60(6.71)^{bc}	86.50(4.89)^{ab}	111.50(8.64)^{bcd}	89.90	78.20(4.67)^{a}	143.80(6.83)^{bc}	126.70(5.51)^{abc}	151.70(8.41)^{bcd}	125.10
		Long rains 2024	61.30(6.57)^{a}	131.50(9.95)^{cd}	145.90(11.34)^{de}	120.40(16.93)^{bcd}	114.78	103.90(9.33)^{ab}	216.60(15.72)^{e}	231.00(14.35)^{e}	205.50(18.90)^{de}	189.25
		mean†	**74.07^{A}**	**136.67^{B}**	**144.70^{B}**	**147.93^{B}**	125.84	**113.40^{A}**	**215.20^{B}**	**223.23^{B}**	**226.47^{B}**	**194.58**
Western kenya	pH≥ 5.5	Long rains 2023	99.30(7.76)^{cd}	191.30(20.74)^{f}	205.40(18.71)^{f}	178.10(10.86)^{f}	168.53	156.60(11.53)^{b}	297.40(26.40)^{de}	311.00(25.39)^{e}	298.80(22.40)^{de}	265.95
		Short rains 2023	25.90(1.76)^{a}	61.30(13.97)^{abc}	54.90(17.92)^{ab}	75.30(13.22)^{bc}	54.35	59.10(4.09)^{a}	127.60(19.61)^{b}	118.50(24.68)^{ab}	137.10(21.07)^{b}	110.58
		Long rains 2024	75.00(5.54)^{bc}	137.90(10.94)^{e}	141.00(13.37)^{e}	119.50(11.24)^{de}	118.35	142.10(3.89)^{b}	264.20(9.58)^{cd}	265.70(6.25)^{cd}	239.30(10.77)^{c}	227.83
		mean†	**74.90^{A}**	**143.90^{B}**	**149.50^{B}**	**134.10^{B}**	125.60	**131.30^{A}**	**250.20^{B}**	**254.40^{B}**	**242.60^{B}**	**219.63**
Rift valley	pH< 5.5	Long rains 2023	68.30(10.38)^{a}	78.50(15.33)^{ab}	104.80(13.12)^{abc}	165.10(19.08)^{d}	104.18	174.30(23.42)^{a}	294.30(50.72)^{b}	322.20(44.02)^{b}	367.50(52.66)^{b}	289.58
		Long rains 2024	77.50(9.36)^{ab}	109.50(12.38)^{bc}	124.60(9.64)^{c}	200.80(19.28)^{d}	128.10	185.10(12.15)^{b}	320.40(37.67)^{b}	338.30(31.71)^{b}	375.00(36.33)^{b}	304.70
		mean†	**72.90^{A}**	**94.00^{AB}**	**114.70^{B}**	**182.90^{C}**	116.13	**179.70^{A}**	**307.40^{B}**	**330.20^{B}**	**371.30^{B}**	**297.15**
Rift valley	pH≥ 5.5	Long rains 2023	98.70(6.13)^{a}	155.40(10.23)^{b}	154.50(17.11)^{b}	168.70(12.50)^{bc}	144.33	280.70(11.95)^{b}	514.90(23.96)^{def}	526.60(15.23)^{ef}	547.00(15.78)^{f}	467.30
		Long rains 2024	85.10(8.64)^{a}	177.00(15.62)^{bc}	200.90(23.97)^{c}	185.90(18.11)^{bc}	155.48	221.60(13.04)^{a}	444.70(27.20)^{c}	473.80(24.08)^{cde}	457.40(26.49)^{cd}	399.38
		mean†	**91.90^{A}**	**166.20^{B}**	**177.70^{B}**	**177.30^{B}**	204.37	**251.20^{A}**	**479.80^{B}**	**500.20^{B}**	**502.20^{B}**	**438.30**
			western(pH< 5.5)	western(pH≥5.5)	Rift Valley (pH< 5.5)	Rift Valley (pH≥5.5)		western(pH< 5.5)	western(pH≥5.5)	Rift Valley (pH< 5.5)	Rift Valley (pH≥5.5)	
	p-value	Seasons	<.001***	<.001***	ns	0.095*		<.001***	<.001***	ns	<.001***	
		Treatments	<.001***	<.001***	<.001***	<.001***		<.001***	<.001***	<.001***	<.001***	
		Seasons.Treatments	0.039*	ns	0.099*	ns		ns	ns	ns	ns	
		SE	41.87	50.55	48.752	67.308		63.296	64.658	132.61	92.049	
		CV %	31	40.20	42	43.9		30.1	29.4	44.6	21.2	

Abbreviation: AGp is the agronomic efficiency of phosphorus, PFPp partial productivity of phosphorus. Means within a pH category of a region followed by different letters differ significantly at the level of *p* < 0.05. ns means not significant at the level of *p* < .05. CV is the coefficient of variation. SE is the standard error, *, ** and * indicate the significance at 0.1, 0.01 and <0.001, respectively. †these give the aggregate effects of fertilizer used per pH category, †† these the seasons, while upper case letters give differences in the fertilizer used.**

4.6. Effect of partially substituting DAP with WonderGro on Soil parameters

4.6.1. Effect of partially substituting DAP with WonderGRO on soil pH

In western Kenya, sub-optimal pH ($pH < 5.5$) for maize production, the soil pH was observed to be higher during leaf sampling in 2023 and 2024, with an average soil pH of 5.0, but slightly less than the initial with pH of 5.15. Generally, the pH reduced from 2023 to the 2024 seasons regardless of the application of full rate of DAP, sole half rate of DAP in combination of either of the formulation of WG3 and WG21. There were no variations in soil pH in long rains and short rains in 2023, with an average soil pH4.7 except with absolute control (0 kg DAP ha^{-1}) during the short rains, which had a slight increase in soil pH of 0.3. In the optimal pH during long rains of 2023, regardless of the sampling time, the pH of the soil had no variation at ($p<0.05$), with an average soil pH of 5.5. The pH trend declines in the subsequent season despite the addition of the DAP solely or in combination with the formulations, as shown in **(.**

). The use of half the rate of DAP in combination with either WG3 or WG21 resulted in the lowest pH by the end of the 2024 sampling period, which contrasted with the situation in the rift valley region.

In sub-optimal pH of the rift valley, soil pH increased from 2023 to 2024 during the long rains, even though no variations were observed between the treatments in 2023 for both at leaf sampling and harvesting, as well as in leaf sampling in 2024, with an average soil pH of 4.8. However, in 2024 at harvesting, the soil pH slightly rose regardless of the fertilizer application, averaging at pH of 5.2. In optimal soil pH, there were no variation in soil pH throughout the season, sampling times, and fertilizer applied, with an average soil pH of

6.0. This was exceptional for the application of half the rate of DAP in combination with wonderGro21 (67kgDAP ha^{-1} +WG21) and absolute control (0 kg DAP ha^{-1}), during the long rains of 2024, particularly for soils sampled at harvesting which had an average soil pH of 6.2.

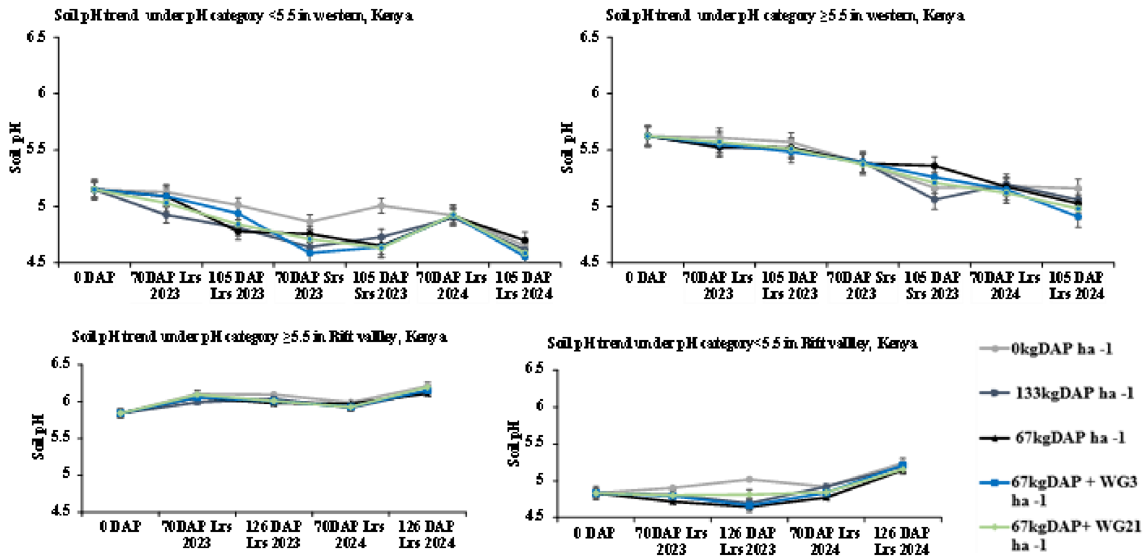

Figure 8: Effect of substituting DAP with wonderGro on soil pH based on pH category, sub-optimal and optimal for maize production per region.

4.6.2. Effect of partially substituting DAP with WonderGRO on soil N

In western, sub-optimal pH (pH<5.5, for maize production, soil total N had no significant differences across the season during the sampling periods ($p<0.05$), with an average of 0.08% N, except in long rains of 2024, under absolute control during tissue sampling and use of 67kg DAP ha^{-1} + WG21 during harvesting with an average soil total N of 0.16%N. on the other hand in the optimal pH (pH<5.5), soil total N, had no significance differences across seasons and sampling time with an average of 0.08%N except with application of

133kg DAP ha^{-1}, 67kg DAP ha^{-1} +WG3 in long rains 2024, and 67kg DAP ha^{-1}+WG21 during 2023, short rains at harvesting with an average of 0.09%N.

While in the Rift Valley, sub-optimal pH, soil total N had no differences across the season and treatments with an average of 0.15%N, except with the use of the full rate of DAP (133 kg DAP ha^{-1}), during leaf sampling in 2023, had slightly higher soil total N of 0.28%N. A similar trend was observed in the optimal pH in the same region**,** with all treatments across the season, sampling time had no significant difference, with an average of 0.18% N at ($p<0.05$) except with the use of 133 kg DAP ha^{-1} in the long rains of 2024, with 0.45%N for soils sampled at harvesting.

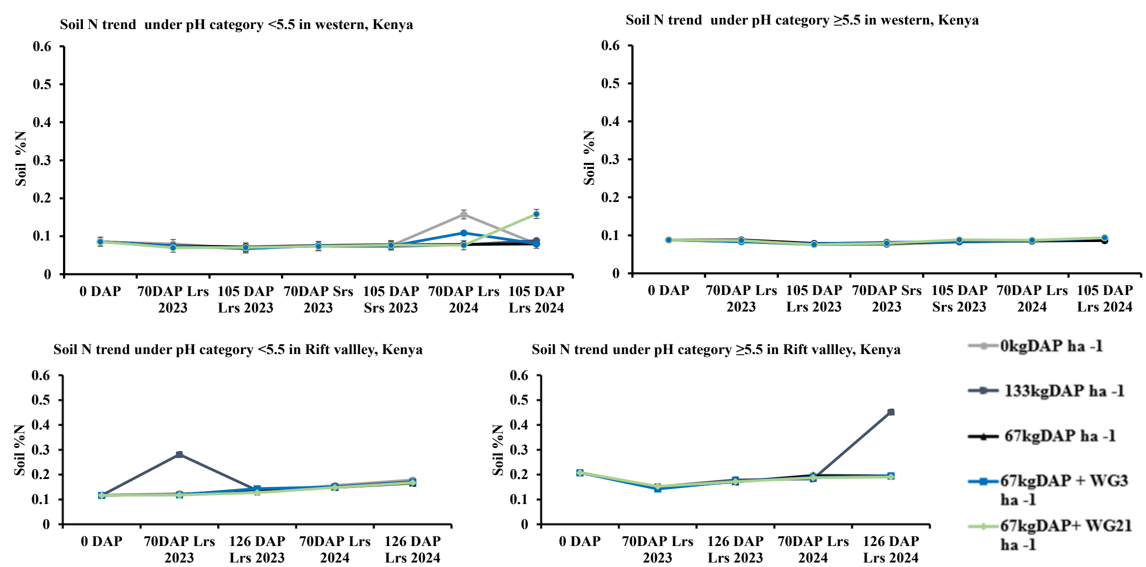

Figure 9: Effect of substituting DAP with wonderGro on soil total Nitrogen (%N) based on pH category for maize production per region.

4.6.3. Effect of partially substituting DAP with WonderGRO on soil AP

In Western Kenya, under sub-optimal soil pH, available P was high during the short rains at leaf sampling, with an average of 15.73mg kg^{-1}. There were low AP in the soil at the end of experiment 2024 at harvesting, with an average of 3.96mg kg^{-1}. Application of half rate of DAP in combination with WG3 (67 kg DAP ha^{-1} + WG3) in short rains 2023 had the highest P at leaf sampling with available P of 17.16mg kg^{-1}. In optimal pH, available P decreases in the soil from the 2023 long rain season to the 2024 long rains. Applications of half rate of DAP in combinations with wonderGro3 at harvesting, 2023 long rains recorded the highest AP with 16.39mg kg^{-1}. There was no specific trend in AP in all the seasons and per sampling time. The AP was decreased in 2024 to an average of 4.43mg kg^{-1} across the sampling times

In Rift Valley sub-optimal pH, Planting maize without fertilizer (0 kg DAP ha^{-1}) and also the use of half the rate of DAP (67kg DAP ha^{-1}) had the lowest AP, with an average of 4.2mg kg^{-1} in 2024 at harvesting. This is due to depreciation from 2023 long rains at harvesting, which had an average AP of 10.84mg kg^{-1}. There was a drop in available P at leaf sampling, 2023 from the initial for all the treatments as shown in Error! Reference s ource not found.. In optimal pH, P availability reduces in the soil from 2023 to 2024, and this could be due to the consumption by plants. In 2023, AP was high during harvesting in all the treatments with an average of 17.84mg kg^{-1}. Application of half rate of DAP with either the formulation of WG3 or WG21 had the lowest AP in 2024, at harvesting, with an average of 9.08mg kg^{-1}. During other sampling times, across the season, there were no significant differences at ($P<0.05$) with an average AP of 10.79mg kg^{-1}.

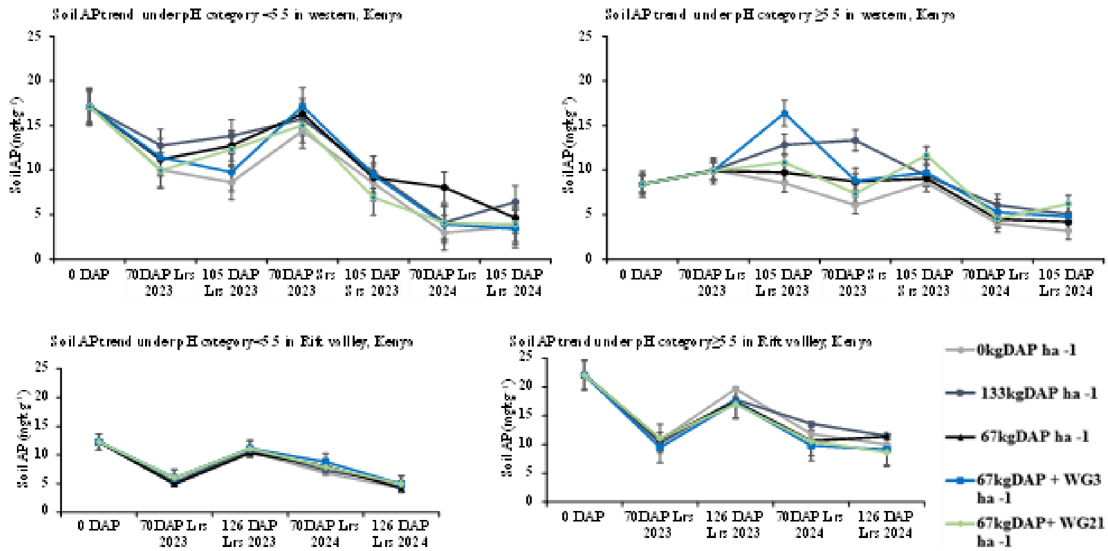

Figure 10: Effect of substituting DAP with wonderGro on soil available phosphorus (mg kg-1) based on pH category for maize production per region.

4.7 Economic analysis of the combined use of DAP and WonderGro

In sub-optimal pH for maize production in Western Kenya, short rains had the lowest VCR of 5.52, with application of Full rate of DAP (133kg DAP ha^{-1}) or use half rate of DAP (67kg DAP ha^{-1}) in combination of WG3 or WG21 had no differences with an average VCR of 4.64. Use of half rate of DAP in 2024 long rains, and application of 67kg DAP ha^{-1} +WG3 or 67kg DAP ha^{-1} +WG21 in 2023 long rains had no significant difference with an average VCR = 10.40, while sole half rate of DAP in long rains 2023 had the highest VCR = 13.28. On the other hand, in the optimal pH for maize production, similarly short rains had the lowest VCR = 3.23. The use of half the rate of DAP in combination with either WG3 or WG21 increased VCR by 28.4% and 18.30%. From the application of the full rate of DAP (133kg DAP ha^{-1}), respectively. The sole half rate of DAP had the highest VCR = 14.15 in the long rains of 2023.

In Rift Valley, sub-optimal pH for maize production, application of half rate of DAP in combination with WG21 (67kg DAP ha^{-1} +WG21) had the largest VCR of 7.54 and 8.24 for long rains 2023 and 2024, respectively. This indicates that the formulation of WG21 had better returns to the farmers in the sub-optimal pH of the Rift Valley, Kenya. This increases the VCR by 34.85% and 4.69% from 133kg DAP ha^{-1} and 67kg DAP ha^{-1}, respectively. In contrast to the optimal pH for maize production, application of a half rate of DAP had the largest VCR=12.34 with no significant difference ($p<0.05$) on average for 2023 and 2024, long rains, while both half rates of DAP in combination with WG3 or WG21 had VCR=9.58 and 9.05, respectively. There was a slight increase in VCR by 0.63 in 2024 long rain.

Table 7: The economic analysis of partially substituting DAP with WonderGro formulations(means±SE) as influenced by cropping seasons per pH category for maize production.

		VCR response for maize production in 3 consuctive seasons for western and Rift valley, kenya					
Region	**pH Category**	**Seasons**	**133kgDAP ha $^{-1}$**	**67kgDAP ha $^{-1}$**	**67kgDAP + WG3 ha $^{-1}$**	**67kgDAP+ WG21 ha $^{-1}$**	**mean††**
Western kenya	**pH< 5.5**	Long rains 2023	7.88(0.7)^{c}	13.28(1.1)^{f}	10.81(0.6)^{e}	10.27(0.6)^{de}	**10.56**
		Short rains 2023	4.36(0.3)^{a}	8.18(0.3)^{cd}	4.50(0.3)^{a}	5.06(0.2)^{a}	**5.52**
		Long rains 2024	4.90(0.5)^{a}	10.1390.6)^{de}	7.51(0.6)^{bc}	5.90(0.8)^{ab}	**7.11**
		Mean†	**5.72^{A}**	**10.53^{C}**	**7.61^{B}**	**7.08^{B}**	**7.73**
Western kenya	**pH≥ 5.5**	Long rains 2023	7.46(0.6)^{de}	14.15(1.6)^{g}	10.73(0.9)^{f}	8.94(0.5)^{ef}	**10.32**
		Short rains 2023	2.10(0.1)^{a}	4.35(1.1)^{abc}	2.77(1.0)^{ab}	3.69(0.6)^{abc}	**3.23**
		Long rains 2024	5.45(0.4)^{bcd}	10.03(0.7)^{f}	7.43(0.7)^{de}	5.72(0.6)^{cd}	**7.16**
		Mean†	**5.00^{A}**	**9.51^{C}**	**6.98^{B}**	**6.12^{AB}**	**6.90**
Rift valley	**pH< 5.5**	Long rains 2023	4.73(0.7)^{a}	6.97(1.4)^{abcd}	5.66(0.7)^{abc}	7.54(0.9)^{bcd}	**6.23**
		Long rains 2024	5.55(0.7)^{ab}	8.06(1.0)^{cd}	6.96(0.5)^{abcd}	8.24(0.7)^{d}	**7.20**
		Mean†	**5.14^{A}**	**7.52^{B}**	**6.31^{AB}**	**7.89^{B}**	**6.71**
Rift valley	**pH≥ 5.5**	Long rains 2023	8.02(0.5)^{ab}	11.60(0.8)^{d}	8.23(0.9)^{ab}	9.08(0.5)^{bc}	**9.23**
		Long rains 2024	6.40(0.6)^{a}	13.09(1.2)^{d}	10.93(1.3)^{cd}	9.02(1.0)^{bc}	**9.86**
		Mean†	**7.21^{A}**	**12.34^{C}**	**9.58^{B}**	**9.05^{B}**	**9.55**
			western(pH< 5.5)	western(pH≥5.5)	Rift Valley (pH< 5.5)	Rift Valley (pH≥5.5)	
	p-value	Seasons	<.001***	<.001***	ns	ns	
		Treatments	<.001***	<.001***	0.009**	<.001***	
		Seasons.Treatments	ns	ns	ns	0.09*	
		SE	2.484	3.182	3.008	4.001	
		CV %	30	41.70	44.8	41.90	

Means within a pH category of a region followed by different letters differ significantly at the level of *p* < 0.05. ns means not significant at the level of *p* < .05. CV is the coefficient of variation. SE is the standard error, *, ** and * indicate the significance at 0.1, 0.01 and <0.001, respectively. †these give the aggregate effects of fertilizer used per pH category, †† these values give averages across the seasons. Lower case letters give differences in the fertilizer used across the seasons, while upper case letters give differences in the fertilizer used.**

CHAPTER FIVE

DISCUSSION

5.1. Effect of combined use of DAP and WonderGro on Maize grain yield based on pH category in the two AEZ.

Irrespective of differences in agro-ecological conditions, soil pH and seasons, all of the fertilizers applied increased yields significantly compared to the control. This shows that there is a need to apply fertilizer in maize production in all the sites. Such fertilizers would have a high potential to boost the farmer's interest, economic viability and sustainability. Soil pH is an important property of the fertilizer material applied. (Neina, 2019). In this respect, this study showed that the use of the formulations 67kg DAP ha^{-1}+ WG3 and 67kg DAP ha^{-1}+ WG21 increases maize grain yield. (Evans & Fischer, 1999) defined yield as the product mass at final harvest, with specified dry matter content. According to (Fischer, 2015) Crop yield is broadly defined as the amount of harvest product in a specific area (amount of harvest products/crop area). This collaborates with,(Adisa et al., 2018) who observed that the grain yield of maize depends on the genetic potential of the genotype used, the soil characteristics, the field management practices, and the agro-climatic factors. A study by (Naeem et al. (2018) Also revealed an increase in yield with a combination of soil conditioner (biochar and fertilizers).

5.2. Relationship of grain N content to the relative yield of maize grain

Generally, across the regions, pH category and the seasons, %N grain content was sufficient between the lower critical limit (LCL) and upper critical Limit (UCL), (0.4-0.85), indicating that N largely contributes to maize grain yield. N was applied in three splits. At planting, at 6 weeks after planting, and 10 weeks after planting (WAP), totaling to 100% N required by maize for completion of the development, and therefore, this could be the reason for the sufficiency levels of N in the grains. Nitrogen (*N*) is considered the most influential factor for maize grain yield. (Băşa et al., 2016). Higher amounts of N fertilization can increase the relative yield (RY) to some extent, but it can also cause serious environmental problems. Thus, the reduction of N fertilizer input and improved N uptake efficiency are crucial for the sustainable production of the maize crop. (Yadav1* et al., 2017a). As shown in ***Figure 5*** N grain content was sufficient across all the treatments, indicating smooth uptake of N.

5.3. Relationship of grain P content to the relative yield of maize grain

Maize productivity and yield are adversely affected by the deficiency of P in agricultural soil (Ibrahim et al., 2022). This is evident in ***Figure 6***, with maize grains not being able to adequately uptake P as a nutrient. Phosphorus (P) deficiency is a major yield-limiting factor for maize crop production in acid soils. Specifically, the utilization rate of P fertilizer in these soils is low, and the excessive application of P fertilizer has created significant environmental and economic issues. (Bindraban et al., 2020; Penuelas et al., 2023). The primary forms of phosphorus uptake by plants are HPO_4^{2-} and $H_2PO_4^-$ (Mwende Muindi, 2019b). Their concentrations in the soil solution are so low that they cannot satisfy the requirements for normal plant growth. (Penn & Camberato, 2019). Not all of the P contained in fertilizers is accessible for plants to utilize (Blackwell et al., 2019). Improving the utilization rate of P remains a challenge. (Han et al., 2022). Maize absorbs and utilizes P through a complex process, and a series of mobility and transformation processes occur in P fertilizer after the applied P fertilizer enters the soil. (Wen et al., 2016). Soil pH plays a major role in P availability for plant uptake from the soil. Very high or too low Soil pH renders P unavailable due to fixation.

5.4 Maize harvest index (HI)

Harvest index was calculated as the ratio of grain yield as dry matter to the total dry matter of the above-ground biomass. HI is the basis for maize grain yield formation (W. Liu et al., 2020). In order to reflect the performance of grain yield, the HI of different pH categories per region was calculated. The grain yield and the above-ground biomass were determined for individual plots and per site. HI of maize produced in a favorable environment is about 0.5 (50%), and this is confirmed in western Kenya in sub-optimal pH, with the application of 67kgDAP+WG21ha^{-1}in 2023 and 2024 long rains and also in the Rift Valley under the same pH category with application of 67kgDAP+WG21ha^{-1} and 67kgDAP+WG21ha^{-1}in 2024 long rains.

HI performed differently in different regions; this is also confirmed by (G. Liu et al., 2017; Zhou et al., 2016). Although some studies showed that the impact of HI varied with environmental conditions (e.g., locations or ecological sub-regions) (Xu et al., 2017). Also, maize harvest index was being influenced by growing conditions, especially in the short rains of western Kenya. It is therefore important to confirm the respective contribution of HI under different yield levels for further sustainable high grain yield.

5.4 Nitrogen uptake efficiency

Efficient N use often results from improved N recovery due to minimal losses of N to the environment through denitrification, leaching, and volatilization (Yadav1* et al., 2017b). Maize nitrogen uptake efficiency (NUE) is estimated globally to be 33%, in part due to loss of fertilizer N from leaching below the root zone, denitrification, and soil- and plant-derived volatilization (Davies et al., 2020; Govindasamy et al., 2023b).

The highest NUE is an important variable for determining the performance of maize crop production systems in terms of the utilization of applied N, and enhancing this variable can contribute to environmentally friendly maize production systems by improving synergy between nutrition and soil productivity, increasing farmer profit and protecting soil quality (Gheith et al., 2022; Shah & Wu, 2019c).

Therefore, treatments that have higher NUE could decrease potential N leaching into the lower horizons beyond the maize plant root reach, which is evidenced in the Rift valley sub-optimal pH during the long rains of 2024 with application of 67kg DAP+WG3 ha^{-1} and 67kg DAP+WG21 ha^{-1} with 0.50kgN uptake kg^{-1}N and 0.49kgN uptake kg^{-1}N, respectively and also in optimal pH in the same region under the application of 67kg DAP+WG3 ha^{-1} with 0.54kgN uptake kg^{-1}N. The NUE results of this research are in accordance with the findings by (Shi et al., 2023)

5.5 Phosphorus uptake efficiency

Phosphorus is an essential nutrient for plant growth (Malhotra et al., 2018). But uptake from soil can be difficult and therefore, an important limiting factor in achieving optimal yields in agriculture (van de Wiel et al., 2016). Due to the high phosphate-fixing capacity of most soils, phosphate availability to plants is always problematic(Van De Wiel et al., 2016). Basic mechanisms of PUE can be distinguished: the plants' ability to take up P from the soil and the efficiency of allocation/ mobilization of P within the plant for sustaining biomass production, often referred to as external and internal PUE, respectively (Nadeem et al., 2022). Improving internal PUE will lead to more resource-efficient use of P than just increasing uptake of potentially scarce P. Nevertheless, upon P limitation, photosynthesis is quickly affected, so there are limitations to the mobilization of the stored P and which affects yields (Balemi & Negisho, 2012). Cereals take up 2-3 kg P for each ton of grain yield produced, 70-80% of which is removed from the field with the grain (Dhillon et al., 2017). In modern cereal production systems with no severe P fixation, management should aim to achieve an AEP of 30-50 kg grain/kg P applied. This requires a RE_p or (PUE) of 0.15-0.30 kg/kg. On average, application of half the rate of DAP in combination with WG3 or WG21 had the highest PUE across the pH category and AEZ compared to other treatments. Continued reliance on large P fertilizer inputs to maximize maize production to meet increasing demand for food is both inefficient and unsustainable in the long term (Schröder et al., 2011)

5.6 Agronomic efficiency of N (AGn) and partial factor productivity of N (PFPn)

Agronomic efficiency is the amount of harvestable product per kg of applied specific nutrient. The efficiency closely reflects the production impact of applied fertilizer as it measures grain yield increment per kg of applied nutrient and relates directly to economic return, making it a good short-term indicator (Jama et al., 2017a). Typical AGn levels of N for cereals range from 15–30 kg grain kg^{-1} N, with lower levels suggesting that Management changes could either boost crop response or lower input costs. Efficient N use can be defined as maximum returns per unit of N applied (Yadav1* et al., 2017c). Judicious use of N is a key factor in the maize-based system of Kenya for sustainable agriculture (Nduwimana, 2020). Matching the N requirement of the maize crop, which is dynamic during its growth period, is essential to increase the AGn efficiency. Nitrogen application in splits up to silking significantly improves the vegetative and reproductive growth of maize and better utilization of the nutrient(Nasielski & Deen, 2019)

Adoption of inefficient N management practices is responsible for the low partial factor productivity and agronomic efficiency. Partial factor productivity of nitrogen (PFPn) and agronomic efficiency of nitrogen (AGn) are important measures of nutrient use efficiency, as they provide an integrative index that quantifies total economic output relative to the utilization of all nutrient resources in the maize production system (Y. Liu, 2022). Decline in partial productivity for N has been reported in cereal-based systems, leading to higher investment in N to maintain higher yields, especially by use of the Full rate of DAP (133kg DAP ha^{-1}). At the same time, the situation is proven otherwise by the application of a half-rate DAP, in addition to either WG3 or WG21.

Agronomic efficiency of N can be increased by increasing plant uptake and use of N and by decreasing N losses from the soil-plant system (Govindasamy et al., 2023c; Yadav1* et al., 2017d). The aim of quantifying the effect of N alone in DAP is to explain the effect of N in maintaining high levels in maize productivity with minimum nitrogen input to maize crop, especially with the sole application of half the rate of DAP (67kgDAP ha^{-1}) improve the agronomic efficiency of N. These results are comparable to results drawn from a review by (Meng et al., 2016), who suggested that efficient use of N for maize production is important for increasing maize grain yield.

5.7 Agronomic efficiency of P (AG_p) and partial factor productivity of N (PFP_p)

Phosphorus use efficiency is the product of P uptake efficiency and P utilization efficiency. It measures the amount of grain produced per unit of available P in the soil. It is a nonrenewable resource that must be used efficiently to maximize returns and ensure its use in a maize production system. Agronomic efficiency of P is influenced by the levels of control yields, N application, plant-available soil available P, and P application rates. Other factors include the fixation of the applied fertilizer

According to (Yadav, 2003)Partial factor productivity (PFPp) and agronomic efficiency (AGp) are useful measures of P use efficiency as they provide an integrative index that quantifies total economic output relative to the utilization of the nutrient resources in the system. According to (Cassman et al., 1996) PFPp and AGp can be increased by increasing the amount, uptake and utilization of available nutrients, and by increasing the efficiency with which applied nutrients are taken up by the crop and utilized to produce grain.

The improvement in phosphorus use efficiency following the combined application of DAP and WonderGro in all pH categories per region. This report appears consistent with previous reports by (Endris, 2019) on the use of organic tithonia biomass in combination with TSP. Considering the role of organic residues in reducing soil P adsorption capacity, the PFPp was larger in optimal soil pH, while this was reversed in AGp, as shown in **Table 6** above.

Improvement in the efficiency of applied inorganic phosphorus should normally be expected when integrated with organic soil conditioners. The result generally shows the positive role of WonderGro, especially in the acidic conditions of the western and Rift Valley of Kenya.

5.8. Effect of combined use of DAP and WonderGro on soil parameters

Despite the reduction in soil pH in western Kenya, the Rift Valley side experienced a steady rise in pH towards the end of the 2024 cropping season. Even though these soils have good mechanisms for pH buffering capacity, which depends on soil types, the degree of soil weathering, and elements released to the solution during the weathering process. The western soils are quite poorly responsive, dominated by Acrisols in comparison to the rift valley soils, dominated by Ferralsols and Nitisols. According to (Zama et al., 2022). Very acidic soils render N and P unavailable for plant uptake by slowing down the nitrification process and through P fixation, respectively. Similarly, (Timofeeva et al., 2022) reported that micro-organisms that are important in the solubilization of organic P compounds and N mineralization are also inhibited in these acid soils. The soil was measured on a 2.5:1 water-to-soil suspension using a pH meter. Despite the reduction in soil pH in western Kenya, the Rift Valley side experienced a steady rise in pH towards the end of the 2024 cropping season. Even though these soils have good mechanisms for pH buffering capacity, which depends on soil types, the degree of soil weathering, and elements released to the solution during the weathering process. The western soils are quite poorly responsive, dominated by Acrisols in comparison to the rift valley soils, dominated by Ferralsols and Nitisols.

Generally, these soils are highly weathered and exhibit widespread nitrogen (N) and phosphorus (P) deficiencies. In these acidic conditions, there are interactions of growth-limiting factors for plants. Maize growth can be limited by either the dominance of Al or Fe ions that fix P, rendering it unavailable for uptake by maize (J. Zhu et al., 2018). Poor soil fertility management, which has translated into P removals exceeding P additions, is also a huge contributor to soil P depletion. The low soil N reported in this study, especially at the initial sampling especially at the initial was partly because small-scale farmers rarely apply the recommended N fertilizer rates to replenish the nutrients removed through crop harvests. N is also believed to be prone to losses either by leaching or volatilization (Huang et al., 2017). Interestingly, maize grains show sufficiency in N, and this could be a result of sufficient uptake by the maize plant, rendering soil N low after the application of fertilizers.

The soil available P levels at crop harvest were below the critical P level for maize (10 mg kg^{-1}) across the pH category and regions. This implies that P input would be necessary to enhance crop responses. One of the key nutrients limiting crop production is phosphorus (P). Overcoming P deficiency in smallholder farming in SSA faces many challenges, mainly because the causes of P deficiencies vary, and viable options to replenish soil P have limitations (Lal & Stewart, 2016)

5.9. Economic analysis of the combined use of DAP and WonderGro

For every undertaken agricultural intervention, it is necessary to carry out an economic evaluation of the access performance of the applied product with the aim of either implementing or revising the proposed technology and making it more realistic and consistent with the farmers, with the aim of facilitating adoption. Cost and return analysis are the most commonly used methods for economic analysis for treatment combinations, which are used to determine the impact of new technology. In this case, it was done to determine if the farmer would be willing to invest in the combined use of DAP and WonderGro, which showed potential in increasing maize grain yields. According to (Jama et al., 2017b) the economic benefit of fertilizer use is affected by fertilizer cost, grain prices, and ultimately, how maize responds to fertilizer application. Investing in these fertilizers shows net profit with a VCR >2. Generally, the use of half the rate of DAP (67 kg DAP ha^{-1}) had the highest returns, which is mainly due to the reduced cost of the fertilizers. Investing in half the rate of DAP in combination with WonderGro21 in sub-optimal pH in the rift valley region had the best returns with VCR of 7.54 and 8.24 for long rains 2023 and 2024, respectively, and this would attract adoption by farmers in the region.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 Conclusion

The study reveals that maize, just like other crops, requires well-balanced nutrition for better grain yields, as confirmed by increased maize grain yield with fertilizer application. Application of half rate of DAP with WonderGro (67 kg DAP ha^{-1}+ WG3 or WG21) generally competed with full rate of DAP (133 kg DAP ha^{-1}), indicating its ability and potential in yield boost. This study also established that applying DAP alongside wonderGro would increase uptake efficiency, agronomic efficiency and partial factor productivity of the nutrients N and P under maize production. These aspects are very important by ensuring proper nutrient availability in the maize products and therefore ensuring nutrition. Soil pH is also found to be an important aspect, as the values of these parameters vary depending on the pH (optimal or sub-optimal). Therefore, adopting WonderGro use would significantly boost the productivity of maize for the farmers.

The economic analysis indicates that fertilizer use results in attractive economic returns on investment (VCR>2) irrespective of the pH, sites, agroecological zone, or fertilizer applied. Because WonderGro is less expensive than DAP, substitution of 50% of the DAP with WonderGro tended to give higher VCRs than the full rate of DAP, which means that farmers can reduce their input costs by using WonderGro. However, the sole application of half the rate of DAP tended to have higher VCRs than all other fertilizer treatments, which means farmers could make substantial savings by reducing the DAP fertilizer rates by 50% without loss of yield

6.2 Recommendations

WonderGro is an option to be used in partial substitution of DAP, with the use of 50% wonderGro and 50% DAP for maize production. Though the following suggestions would suit the product for further research.

1. Further evaluation of WonderGro performance using different maize varieties, especially in the acidic conditions of the Rift Valley
2. To test the performance of WonderGro using Straight P fertilizers to determine the extent of P Use efficiency
3. To test the performance of WonderGro using other crops, e.g., leguminous crops

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APPENDICES

Appendix I: ANOVA table for Maize grain yield in the Western sub-optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	2	110.035	55.0174	67.09	<.001
Treatments	4	126.756	31.6891	38.65	<.001
Seasons.Treatments	8	11.52	1.44	1.76	0.089
Residual	165	135.3	0.82		
Total	179	383.611			

Appendix II: ANOVA table for Maize grain yield in the Western Optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	2	121.592	60.7961	68.17	<.001
Treatments	4	120.368	30.092	33.74	<.001
Seasons.Treatments	8	15.8489	1.9811	2.22	0.028
Residual	185	164.979	0.8918		
Total	199	422.788			

Appendix III: ANOVA table for Maize grain yield in the Rift Valley sub-optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	1	1.057	1.057	0.3	0.587
Treatments	4	32.675	8.169	2.3	0.064
Seasons.Treatments	4	17.741	4.435	1.25	0.295
Residual	106	376.912	3.556		
Total	115	428.369			

Appendix IV: ANOVA table for Maize grain yield in the Rift Valley Optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	1	74.156	74.156	33.01	<.001
Treatments	4	172.007	43.002	19.14	<.001
Seasons.Treatments	4	4.613	1.153	0.51	0.726
Residual	190	426.836	2.247		
Total	199	677.612			

Appendix V: ANOVA table for Maize harvest index in the Western Suboptimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	2	0.59	0.29745	12.71	<.001
Treatments	4	2.26	0.5661	24.2	<.001
Seasons.Treatments	8	0.12	0.01463	0.63	0.756
Residual	165	3.86	0.0234		
Total	179	6.84			

Appendix VI: ANOVA table for Maize harvest index in the Western Optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	2	1.36485	0.68242	31.12	<.001
Treatments	4	0.86538	0.21635	9.87	<.001
Seasons.Treatments	8	0.17785	0.02223	1.01	0.427
Residual	185	4.05707	0.02193		
Total	199	6.46515			

Appendix VII: ANOVA table for Maize harvest index in the Rift Valley sub-optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	1	0.02042	0.02042	0.63	0.43
Treatments	4	0.37409	0.09352	2.87	0.026
Seasons.Treatments	4	0.05433	0.01358	0.42	0.796
Residual	110	3.58055	0.03255		
Total	119	4.02939			

Appendix VIII: ANOVA table for Maize harvest index in the Rift Valley Optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	1	0.26234	0.26234	19.28	<.001
Treatments	4	0.20562	0.0514	3.78	0.006
Seasons.Treatments	4	0.02222	0.00555	0.41	0.803
Residual	190	2.58473	0.0136		
Total	199	3.0749			

Appendix IX: ANOVA table for Maize value cost ratio (VCR) in the Western Suboptimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	2	641.349	320.675	51.96	<.001
Treatments	3	469.042	156.347	25.33	<.001
Seasons.Treatments	6	30.511	5.085	0.82	0.553
Residual	132	814.675	6.172		
Total	143	1955.58			

Appendix X: ANOVA table for Maize economic analysis (VCR) in the Western optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	2	1097.57	548.79	54.18	<.001
Treatments	3	550.45	183.48	18.12	<.001
Seasons.Treatments	6	85.07	14.18	1.4	0.218
Residual	148	1498.98	10.13		
Total	159	3232.08			

Appendix XI: ANOVA table for Maize economic analysis (VCR) in the Rift Valley Sub-optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	1	22.823	22.823	2.52	0.116
Treatments	3	111.637	37.212	4.11	0.009
Seasons.Treatments	3	1.286	0.429	0.05	0.986
Residual	88	796.058	9.046		
Total	95	931.804			

Appendix XII: ANOVA table for Maize economic analysis (VCR) in the Rift Valley Optimal pH category

Source of variation	d.f.	s.s.	m.s.	v.r.	F pr.
Seasons	1	15.81	15.81	0.99	0.322
Treatments	3	540.94	180.31	11.27	<.001
Seasons.Treatments	3	105.76	35.25	2.2	0.09
Residual	152	2432.88	16.01		
Total	159	3095.39			

Appendix XIII: Sample photos during planting, at 2 weeks, at 6 weeks and 10 weeks of maize development

(Source author, 2024)

Appendix XIV: Maize sample selected from various treatments in one of the sites for dry weight analysis

(Source author, 2024)

Appendix XV: Similarity report

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