GREENHOUSE GAS EMISSIONS, SOIL PHYSICOCHEMICAL PROPERTIES, AND NUTRIENT USE EFFICIENCY UNDER INORGANIC-ORGANIC FERTILIZER SUBSTITUTIONS IN MAIZE AND DESMODIUM CROPPING SYSTEMS

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DECLARATION

Declaration by the Student

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

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DEDICATION

This thesis is dedicated to my nieces and nephews; Casmir Odera, Allison Latoya, Sydney Odera, Joseph Kivishi, Jones Kidini, and Triza Achieng**,** the bright stars of our family. May this serve as a gentle reminder that within each of you lies the power to dream, to learn, and to become everything you wish to be.

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ABSTRACT

Climate change continues to threaten ecosystem functions, and agriculture remains one of the major sources of greenhouse gas (GHGs) emissions responsible for global warming. However, little is known about the quantities and intensities of GHGs from major cropping systems in Kenya and, by extension, in Sub-Saharan Africa. This study was aimed to quantify GHG emissions - carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) fluxes from soil. It also assessed the optimal organic-inorganic fertilizer substitution in maize (Zea mays) and desmodium (Desmodium uncinatum) cropping systems that enhance crop yields and lead to reductions in GHG emissions. The static chamber method was used from April to November 2024. The experiment consisted of six fertilizer substitution ratios (0 0, 25 75, 50 50, 75 25, 100 0, and 0 100% FYM-inorganic N equivalence) arranged in a randomized complete block design with four replications. Soil chemical parameters (NH_4^+, NO_3^-, pH, N, P, and C), plant nutrient uptake, and agronomic and recovery efficiencies were assessed. Results showed that desmodium yield responded positively to increasing Farmyard manure substitution levels ($p < 0.0001$), with biomass rising under higher organic inputs. Despite these, N_2O emission factors and yield-scaled emissions remained consistently low across fertilizer treatments, indicating efficient nitrogen utilization and minimal gaseous losses. The net global warming potential did not vary significantly among treatments. Greenhouse gas intensity declined sharply from the control to the 75,25 fertilizer treatment, representing approximately a 70% reduction. Maize grain yield was highest under the 50,50 (50% FYM, 50% inorganic fertilizer), indicating a strong synergistic effect between organic and mineral nutrient sources. Emission factors increased by nearly 20% relative to the control. Net global warming potential also increased progressively with higher Farmyard manure substitution, showing an approximately 40.7% increase. Despite these increases, the 50,50 treatment achieved the most favorable balance between productivity and emissions, producing the highest maize yield with comparatively lower EF and greenhouse gas intensity (GHGI). Combined FYM–inorganic treatments, particularly 25,75 and 75,25, significantly improved soil nutrient status, enhanced N and P uptake, and increased maize and desmodium yields compared to sole applications. FYM-rich combinations improved moisture retention and microbial activity, sustaining nutrient release, while inorganic fertilizers ensured rapid early growth. Intercropping enhanced biological nitrogen fixation and nutrient recovery, leading to higher agronomic efficiency and resilience under moisture-limited conditions.

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CEC – Cation Exchange Capacity

CH_4 – Methane

CO_2 – Carbon Dioxide

FYM – Farmyard Manure

GDP – Gross Domestic Product

GHGs – Greenhouse Gases

GWP – Global Warming Potential

IPCC – Intergovernmental Panel on Climate Change

NUE – Nutrient Use Efficiency

NH_4^+ – Ammonium

N_2O – Nitrous Oxide

OFs – Organic Fertilizer

OM – Organic Matter

RCBD – Randomized Complete Block Design

SSA – Sub-Saharan Africa

SOC – Soil Organic Carbon

TOC – Total Organic Carbon

TSP – Triple Superphosphate

CHAPTER ONE

INTRODUCTION

1.1 Background Information

Global atmospheric levels of greenhouse gases (GHG), specifically carbon dioxide (CO_2), nitrous oxide (N_2O), and methane (CH_4), have increased over time (IPCC, 2014). The rise in CO_2, CH_4, and N_2O is primarily driven by human activities. Agriculture contributes between 14% and 17% to global anthropogenic GHG emissions (Carlson *et al*., 2017). When broken down by gas, agriculture accounts for 13% of global CO_2 emissions, mainly from land use changes; 50% of global CH_4 emissions, mainly from rice farming and enteric fermentation; and about 60% of global N_2O emissions, mainly from the application of nitrogen fertilizers (Macharia *et al.*, 2020). These three gases, CO_2, CH_4, and N_2O, are responsible for roughly 80% of the current global radiative forcing (Myhre *et al*., 2017), which drives global warming and leads to changes in climate conditions (IPCC, 2013). According to the (IPCC 2014), ongoing emissions will lead to further warming and persistent changes across all components of the climate system, increasing the likelihood of severe, widespread, and irreversible impacts on people and ecosystems. Net soil CO_2 results from two main respiration processes: autotrophic respiration from plant roots, mycorrhizal fungi, and heterotrophic respiration from the oxidation of soil organic matter (Jovani-Sancho, 2021). Nitrous oxide (N_2O) emissions primarily originate from microbial production processes under oxygen-limited soil conditions (Yao *et al.*, 2009). Net soil CH_4 flux is driven by two opposing processes: methanogenesis, which produces methane in anaerobic conditions, and methanotrophy, which consumes methane (Wachiye *et al.*, 2020).

The CO_2 and N_2O are the most important gases in upland cropping systems. At the same time, CH_4 is mainly a concern in flooded soils and livestock production systems. Although N_2O is emitted in a lesser quantity than CO_2 and CH_4, it has a greater global warming potential, 298 times that of CO_2 over 100 years (Myhre *et al.*, 2017). Besides its contribution to climate change, N_2O destroys the ozone (O_3) layer, making it vulnerable to the penetration of harmful ultraviolet solar radiation into the Earth's surface. The emission rates and quantities of these gases are influenced by several factors within a farming system and may differ considerably based on climatic conditions, soil properties, and land management (Lal, 2012).

Low fertilizer application rates for several decades have depleted soil nutrients in Sub-Saharan Africa (SSA) and contributed to relatively stagnant crop yields. One potential solution is to apply more fertilizers to improve soil fertility in SSA and enhance food security (Vanlauwe & Giller, 2006). However, increasing fertilizer application to boost crop yields may lead to elevated GHG emissions (Mosongo *et al.*, 2022a). Increased nitrogen (N) fertilization leads to increased anthropogenic nitrous oxide (N_2O) emissions, as N addition tends to stimulate both nitrification and denitrification. These processes are susceptible to soil conditions, including moisture content, pH, and temperature, which affect oxygen availability and microbial activity. Higher soil moisture, for instance, can create anaerobic conditions conducive to denitrification, thereby increasing N_2O emissions (Ayiti & Babalola, 2022).

Methane (CH_4) emissions are associated with anaerobic conditions in waterlogged soils where methanogenesis occurs. Applying fertilizers can indirectly influence CH_4 emissions by altering soil conditions that favor or inhibit methanogenic bacteria. Organic fertilizers, such as farmyard manure (FYM), can increase CH_4 emissions due to the presence of labile carbon compounds that serve as substrates for methanogens. However, when FYM is combined with inorganic fertilizers, CH_4 emissions may be mitigated due to improvements in soil structure and aeration, which reduce the formation and persistence of anaerobic microsites where methanogenesis occurs *(Linquist et al.*, 2012)

Carbon dioxide (CO_2) emissions from soils are primarily a result of soil respiration, which includes the decomposition of organic matter by soil microbes and root respiration. Applying fertilizers, like FYM, can enhance soil respiration by providing additional carbon substrates, potentially leading to increased CO_2 emissions. However, CO_2 emissions are also affected by soil management practices that influence carbon sequestration (Jat *et al.*, 2022). For instance, integrating FYM with inorganic fertilizers can improve soil organic carbon levels and reduce long-term CO_2 emissions by promoting carbon stabilization in the soil matrix (Rastogi *et al.*, 2002).

Organic fertilizers (OFs) are being strongly incentivized as a core management strategy to improve soil health and mitigate climate change through several regional and national initiatives. The use of OFs, such as compost and manure, constitutes a direct input of C to the soil, which can be stabilized through physical, chemical, and biochemical mechanisms contributing to long-term storage of C in soils (i.e., C Sequestration) (Lazcano *et al.,* 2021). However, in SSA agricultural systems, organic manures cannot wholly replace the use of mineral fertilizers. Organic manures often have slow nutrient release rates and may not meet the immediate nutrient demands of high-yielding crops in SSA regions. This is where mineral fertilizers play a critical role by providing readily available and targeted nutrients that can support optimal plant growth, development, and yield. Mineral fertilizers can address specific nutrient deficiencies in soils, enhance crop productivity, and help farmers achieve higher yields to meet the demands of food security. By integrating both organic manure and mineral fertilizers in a balanced and sustainable manner, farmers in SSA can harness the synergistic benefits of these inputs.

Combining organic and inorganic fertilizer applications can help reduce the use of inorganic fertilizers and increase soil fertility. Furthermore, judicious management of these inputs, such as split application and 'micro-dosing,' can help reduce emissions from agricultural fields and subsequently mitigate the effects of climate change. However, the most suitable proportions of organic and inorganic fertilizer on greenhouse gas (GHG) emissions is unknown. This study was aimed to identify the optimum ratio of inorganic fertilizer to organic fertilizer in a maize–desmodium cropping system in Elgeyo Marakwet, Kenya, to attain high grain yields and low GHG emissions.

1.2 Statement of the Problem

The continuous use of inorganic fertilizers in agriculture has been identified as a significant contributor to greenhouse gas (GHG) emissions, which exacerbate climate change. In Sub-Saharan Africa (SSA), agriculture accounts for a substantial share of total GHG emissions, with estimates indicating that agriculture contributes about 14% of global emissions due to reliance on traditional farming practices and inorganic inputs (FAO, 2020). In Kenya, where agriculture accounts for approximately 33% of the GDP and employs 70% of the rural population (World Bank, 2022), climate change impacts pose a significant threat to food security and farmers' livelihoods. Despite the critical need for sustainable farming practices, there are limited studies focused on integrating food and fodder production systems, particularly in regions like Elgeyo Marakwet County. Additionally, there is a lack of empirical data on the optimal rates of substituting inorganic fertilizers with farmyard manure, which would increase crop yields (both food and fodder) while also reducing concomitant GHG emissions per unit yield. Addressing this gap through scientific research will provide crucial insights for farmers, helping mitigate the adverse effects of climate change while enhancing agricultural productivity.

1.3 Justification of the study

Inorganic fertilizers are associated with significant GHG emissions, particularly nitrous oxide (N_2O), resulting from nitrogen fertilizer application. Farmyard manure contributes to soil organic carbon sequestration, enhancing soil health and fertility. The incorporation of organic matter into the soil can improve soil structure, water retention, nutrient cycling, and microbial activity, leading to long-term carbon storage in the soil. Intercropping of cereals (such as maize) with legumes like Desmodium offers a strategic combination. Maize is a staple food in Kenya, critical for food security, while desmodium serves as an excellent fodder crop, enhancing livestock productivity. Intercropping offers additional benefits, including improved soil cover and enhanced nitrogen fixation, which reduces the need for external nitrogen inputs. Elgeyo Marakwet County, characterized by agro-pastoral communities, faces challenges related to soil degradation, nutrient depletion, and the impacts of climate change. It also presents a unique case for this study due to its diverse agro-ecological zones and soil types, which have distinct physical and chemical properties that influence nutrient availability and GHG emissions. Conducting this study in this region will provide tailored recommendations for sustainable agriculture that mitigate GHG emissions while enhancing crop and livestock production, thereby supporting the livelihoods of agro-pastoralist communities.

1.4 Objectives

1.4.1 Broad objective

To contribute towards increasing food and fodder production while minimizing greenhouse gas emissions in mixed crop and livestock systems

1.4.2 Specific Objective

i. To assess the effect of organic-inorganic fertilizer ratios on greenhouse gas emissions and crop yield in maize and desmodium cropping systems.
ii. To assess the impact of different organic-inorganic fertilizer combinations on soil chemical and physical properties.
iii. To assess the nutrient use efficiency of maize and desmodium under different inorganic-organic fertilizer combinations

1.5 Research Questions

i. What are the magnitudes and patterns of greenhouse gas emissions (CH_4, CO_2, and N_2O) from maize and desmodium cropping systems under varying fertilizer treatments?
ii. How do different combinations of inorganic and organic fertilizers affect soil chemical and physical properties in maize and desmodium cropping systems?
iii. How do various inorganic-organic fertilizer combinations influence the nutrient use efficiency of maize and desmodium, and which combination offers the most efficient nutrient uptake with minimal environmental impact?
iv. How do different inorganic-organic fertilizer combinations influence crop yield and nutrient use efficiency in maize and desmodium cropping systems?

CHAPTER TWO

LITERATURE REVIEW

2.1 Greenhouse Gases in Agriculture

2.1.1 Global Impact of GHG Emissions

Agriculture emissions contribute a large portion of total global emissions. Agricultural N_2O emissions are projected to increase by 35-60% by 2030, primarily due to increased nitrogen fertilizer use and animal manure production (FAO, 2003). Similarly, (Liu *et al.,* 2021) estimated that N_2O emissions increased by about 50% in 2020. If demands for food increase and diets shift as projected, then annual emissions of GHGs from agriculture may escalate further. However, improved management practices and emerging technologies may enable a reduction in emissions per unit of food (or protein) produced, and possibly also a reduction in emissions per capita of food consumption. If CH_4 emissions grow in direct proportion to increases in livestock numbers, then global livestock-related methane production is expected to increase by 60% by 2030 (FAO, 2003). However, changes in feeding practices and manure management could ameliorate this increase. The US EPA (2006) forecasted that combined methane emissions from enteric fermentation and manure management increased by 21% between 2005 and 2020.

Opportunities for mitigating GHGs in agriculture fall into three broad categories, based on the underlying mechanism: *reducing emissions,* which involves agriculture that releases significant amounts of CO_2, CH_4, or N_2O to the atmosphere. The fluxes of these gases can be reduced by more efficient management of carbon and nitrogen flows in agricultural ecosystems. For example, practices that deliver added N more efficiently to crops often reduce N_2O emissions, and managing livestock to make the most efficient use of feeds often reduces the amounts of CH_4 produced (Clemens & Ahlgrimm, 2001)

Nutrient management: Nitrogen applied in fertilizers, manures, biosolids, and other N sources is not always used efficiently by crops. The surplus N is particularly susceptible to the emission of N_2O (McSwiney & Robertson, 2005). Consequently, improving N use efficiency can reduce N_2O emissions and indirectly reduce GHG emissions from N fertilizer manufacture. By reducing leaching and volatile losses, improved efficiency of N use can also reduce off-site N_2O emissions. Practices that improve N use efficiency include: adjusting application rates based on precise estimation of crop needs (e.g., precision farming); using slow- or controlled-release fertilizer forms or nitrification inhibitors (which slow the microbial processes leading to N_2O formation); applying N when least susceptible to loss, often just before plant uptake (improved timing); placing the N more precisely into the soil to make it more accessible to crops roots; or avoiding N applications above immediate plant requirements.

Carbon dioxide (CO_2) is the most significant greenhouse gas (GHG) contributing to global warming and climate change. It accounts for approximately 76% of global GHG emissions, primarily originating from the burning of fossil fuels, deforestation, and land-use changes. The agricultural sector also contributes to CO_2 emissions through land-use changes and the decomposition of organic matter in soils, particularly when organic fertilizers are applied. As a result, there is a growing emphasis on adopting sustainable agricultural practices that reduce CO_2 emissions, such as optimizing fertilizer use and enhancing soil carbon sequestration to mitigate the impacts of climate change (IPCC, 2021; FAO, 2022).

Methane (CH_4) is a potent greenhouse gas with a global warming potential approximately 28-36 times greater than that of CO_2 over a 100-year period. Although CH_4 is less abundant in the atmosphere than CO_2, it plays a critical role in driving climate change due to its high radiative forcing. In agriculture, CH_4 emissions are particularly associated with livestock production and the cultivation of wetland rice. Efforts to reduce CH_4 emissions focus on improving livestock feed efficiency, enhancing manure management practices, and optimizing water management in rice fields. Reducing CH_4 emissions is crucial for mitigating near-term climate change impacts, as it could lead to significant cooling effects in the short term (Dean *et al.*, 2018)

2.1.2 Sources of Agriculture GHG

Greenhouse gas (GHG) emissions from the agricultural sector are increasing globally due to anthropogenic activities, primarily responsible for altering the Earth's climate by absorbing and re-emitting energy from the lower atmosphere. Although CH_4 and N_2O are emitted in lower quantities than CO_2, their global warming potential is 21 and 298 times greater, respectively. Agriculture accounts for nearly 12% of global anthropogenic GHG emissions. The concentration of carbon dioxide (CO_2) in the atmosphere has continued to rise and is now nearly 100 parts per million higher than it was before the Industrial Revolution. (Chataut *et al.,* 2023)

In soil, methane (CH_4) is produced through anaerobic microbial decomposition of organic molecules. Rice fields submerged in water might be a source of CH_4. Increased CH_4 emissions are caused by continuous submergence, rising organic C content, and the use of organic manure in puddled soil. Crop residue burning also contributes to the global methane budget. Ruminant enteric fermentation is another substantial source of CH_4 emissions (Rizzo *et al.*, 2015).

Nitrous oxide is produced naturally in soil through the processes of nitrification and denitrification. Nitrification is the aerobic oxidation of ammonium to nitrate by bacteria. Nitrous oxide is a gaseous intermediary in the denitrification chemical chain and a byproduct of nitrification that escapes from microbial cells into the soil and eventually into the atmosphere. The addition of nitrogen to soil via anthropogenic net nitrogen additions (such as synthetic fertilizers, organic fertilizers, crop residues, and sewage sludge) or the mineralization of nitrogen in organic soils is one of the most significant control elements in this response (Hu *et al.,* 2015).

Soil management activities, such as tillage, which generate carbon dioxide emissions through the biological breakdown of soil organic matter, are the primary source of carbon dioxide generation in agriculture. Tillage breaks up soil clumps, enhances oxygen delivery, and exposes organic matter's surface to aid in decomposition. Carbon dioxide emissions are also caused by the use of fuel in various agricultural processes and the burning of crop leftovers. Soil is the primary source of carbon dioxide generation in agriculture (Omonode *et al.,* 2007). Tillage, for example, contributes to these emissions through the biodegradation of organic materials in the soil. Tillage decomposes soil masses, increases oxygen availability, and exposes surface organic materials, promoting decomposition. Other sources of CO_2 emissions include the use of fuel for various agricultural operations and the burning of crop leftovers.

2.2 Nutrient Management in the Cropping System

Anthropogenic activities, and in particular the use of synthetic nitrogen (N) fertilizer, have doubled global annual reactive N inputs in the past 50–100 years, causing deleterious effects on the environment through increased N leaching and nitrous oxide (N_2O) (Forrestal *et al.,* (2021). Fertilizer formulations also can alter N_2O emissions. In irrigated no-till corn, N_2O emissions can be reduced by using polymer-coated urea or a combined nitrification and urease inhibitor with urea ammonium nitrate, compared with using either urea or urea ammonium nitrate alone.

Excessive, improper, and unbalanced fertilizer application, particularly of nitrogen (N), has long been a source of concern due to its environmental impacts (Luo *et al.,* 2024). Efficient nutrient management, particularly phosphorus (P), is crucial for improving crop yield while minimizing greenhouse gas emissions. In sub-Saharan Africa, declining soil nutrient levels are a significant challenge, mainly due to poor nutrient management practices among farmers (Ntinyari & Gweyi-Onyango, 2021). Some of the recommended practices that farmers can adopt lie in the 4 R principle, which entails the use of the right source (fertilizer with higher efficiency), correct rate, right timing, and right placement as expounded by (Hochmuth *et al.,* 2014). The proper placements of these fertilizers lead to fewer losses since there is a concomitant improvement in the plant uptake by making nutrients more accessible by the roots hence restricting available pathways for emissions. A viable option for reducing losses is to reduce nitrification. The use of nitrification inhibitors in the case of nitrogen use is a promising strategy that has huge potential to slow the release processes that contribute to the formation of N_2O emissions (Coskun *et al.*, 2017).

2.3 Role of Inorganic Fertilizers

The application of chemical nitrogen (N) fertilizers has made a great contribution to the increase in grain yields in the past few decades. However, while chemical nitrogen fertilizers can enhance crop yields in the short to medium term, their excessive long-term use reduces nitrogen use efficiency and limits yield gains, while also contributing to environmental problems such as soil acidification and non-point source pollution, ammonia volatilization, and nitrous-oxide emissions (Hu *et al.,* 2023).

Phosphorus fertilizers, including triple superphosphate (TSP), are equally important for plant development, particularly in root formation, energy transfer, and the synthesis of nucleic acids. Phosphorus is less mobile in the soil than nitrogen, making it prone to fixation, especially in soils with high levels of iron and aluminum oxides, such as Ferralsols and Nitisols. This fixation can render phosphorus unavailable to plants, necessitating higher application rates to meet crop demands. However, excessive phosphorus application can lead to environmental issues, such as the eutrophication of water bodies. The challenge with phosphorus fertilizers is ensuring they are applied at the right time and in the right form to minimize fixation and maximize plant uptake. Research indicates that balanced fertilization, combining organic and inorganic sources, can improve phosphorus availability and utilization, leading to better crop yields and reduced environmental impacts (Ntinyari & Gweyi-Onyango, 2021). Phosphorus (P) fertilizers can indirectly affect greenhouse gas (GHG) emissions, particularly nitrous oxide (N_2O) and carbon dioxide (CO_2), by enhancing plant growth and nitrogen uptake. Improved nitrogen uptake by plants can reduce the amount of nitrogen available for microbial processes such as nitrification and denitrification, thereby potentially lowering N_2O emissions. In soils where P is not limiting, this effect may be minimal. Increased plant biomass from P fertilization can stimulate soil microbial activity, leading to higher CO_2 emissions from soil respiration. The interaction between P and N is critical, as their combined application can both sequester carbon and enhance GHG emissions depending on soil conditions and nutrient balance (Friedlingstein *et al.*, 2022).

2.3.1 Role of Organic Fertilizers

Organic materials such as FYM supply all major nutrients (N, P, K, Ca, Mg, S) necessary for plant growth and micronutrients (Fe, Mn, Cu, and Zn). Hence, it acts as a mixed fertilizer. FYM improves the soil's physical, chemical, and biological properties. Improvement in the soil structure due to FYM application leads to a better environment for root development. FYM also improves soil water holding capacity. The fact that the use of organic fertilizers improves soil structure, nutrient exchange, and maintains soil health has raised interest in organic farming.

The effect of organic fertilizers on GHG emissions is multifaceted. Organic Fertilizers can increase soil organic carbon (SOC) content, which enhances soil health and can lead to long-term carbon sequestration. This process helps mitigate carbon dioxide (CO_2) emissions by storing carbon in the soil rather than releasing it into the atmosphere (He *et al.*, 2023). The decomposition of organic matter in these fertilizers can stimulate microbial activity, leading to CO_2 emissions from soil respiration. In anaerobic conditions, such as those found in waterlogged soils, the application of organic fertilizers can result in methane (CH_4) emissions.

The substitution of inorganic fertilizers with organic options like FYM is a critical strategy for reducing GHG emissions per unit of agricultural yield. By combining organic and inorganic fertilizers, it is possible to optimize nutrient availability for crops while minimizing the environmental impact. For instance, the use of organic fertilizers can reduce N_2O emissions by decreasing the need for high amounts of inorganic nitrogen fertilizers, which are often associated with significant greenhouse gas emissions. (Xie *et al.*, 2022).

2.3.2 Substitution Strategies

It has been demonstrated that partially or completely replacing chemical nitrogen fertilizers with organic fertilizers can enhance soil fertility, reduce nitrogen losses through leaching, and increase crop yields. (Hu *et al.*, 2023). Thus, this is considered a reasonable fertilization method and is widely adopted in various agricultural ecosystems.

Soil total organic carbon (TOC) plays a major role in soil nutrient cycling and soil microbial activities, and it has a significant positive correlation with farmland production (Zeyede *et al.,* 2020) reported that manure plus chemical fertilizer significantly improved SOC by 2.45%. However, due to the stability of TOC and high background carbon content, changes in TOC under short-term or medium-term conditions are generally not easily detected. Soil labile organic-carbon fractions refer to active organic carbon components that are easily decomposed by microorganisms and can quickly respond to land management measures, including microbial biomass carbon (MBC), dissolved organic carbon (DOC), particulate organic carbon (POC), and easily oxidized organic carbon (EOC) (Zhang *et al.,* 2021). Microbial biomass carbon is primarily affected by soil microbial biomass and plays an important role in the decomposition of soil organic matter. Dissolved organic carbon is the main energy source for soil microorganisms and can serve as an important indicator for evaluating soil microbial decomposition and nutrient availability

2.4 Impact of Cropping System on GHG Emissions

2.4.1 Maize-desmodium Intercrop

Maize (*Zea mays*) is a staple crop in sub-Saharan Africa (SSA), where it accounts for up to 30% of the calorie intake of the population (Taylor & Tanumihardjo, 2010). Maize is also the most widely cultivated crop in the region, grown in 46 out of 53 countries in SSA. Hundreds of locally adapted varieties with better yields have been developed (Abate *et al.*, 2017). These include early and extra-early maturing, those resistant or tolerant to drought, striga, or those that use nutrients efficiently (Ndayisaba *et al.*, 2021). Despite these efforts and a notable increase in the area under maize, its production is still very low. For example, data from FAOSTAT (2020) indicate a dramatic increase in harvested area under maize in the last decade (2007 to 2017). During this period, the area in which maize is grown in SSA increased by 30.2% while yield increased by 8.5% in the same period (FAOSTAT, 2020). This highlights the need for innovative cropping systems to overcome constraints to maize production.

Nutrient limitation is a major constraint in crop production in SSA. In Kenya, nitrogen (N) and phosphorus (P) are the major nutrients that limit maize productivity (Kihara *et al.*, 2016). This is attributed to continuous cropping without replenishing the depleted nutrients. The use of fertilizers is limited by high cost and limited access (Nziguheba *et al.*, 2016). Farmers who cannot apply fertilizers, therefore, rely on residues and manure application to provide N and P for plant nutrition. A limitation of this approach is that crop residues and livestock manure have low P and N content and hardly sustain maize.

Intercropping maize with legumes is one of the options used by smallholder farmers to overcome constraints associated with maize monoculture. Planting maize with legumes leads to obtaining higher yields, efficient use of growth resources, managing weeds, and insurance against total crop failure (Ndayisaba et al., 2021). The beneficial effects of legumes on soil health are documented by (Drinkwater et al., 1998) and include the addition of organic matter, biological nitrogen fixation, and improving availability of N and P in soil solution through mineralization of N and P from root exudates, dead nodules and roots, and fallen leaves.

2.5 Soil Properties and GHG Emissions

2.5.1 Soil Type: Nitisols

According to (Buragienė et al., 2019) soil properties have a major effect on the emission and exchange of GHGs. The effect of physical-mechanical, chemical, or biological properties on soil GHGs is very complex, as it is determined by various factors. Most influencing factors include soil moisture, penetration resistance, soil temperature, structure, porosity, soil organic matter, soil mineralogy, pH, and soil nitrogen. Soil temperature, soil moisture, mineral N content, soil organic matter content, and pH can directly affect GHGs from the soil surface through microbial activities (Oertel *et al.,* 2016). Increases in soil temperature lead to higher CO_2 emissions. Soil moisture influences gas diffusion and microbial activity. In dry soil, the activity of microorganisms decreases, which also affects soil respiration (Galic *et al.*, 2020). According to (Brady & Weil et al., 2016), soil organic matter occupies the largest part of carbon stocks in agroecosystems and plays a very important role in the global balance of carbon and nitrogen cycles where C: N represents an important criterion for evaluating the quality of humus, and it also directly affects the GHG emissions from the soil. High soil N concentrations, especially those following fertilization, may induce microbe-mediated N transformation processes leading to high N_2O emissions (Bouwman *et al.,* 2002). The optimal C: N in the soil is 10:1, while in terms of compost, the ideal C: N is 30, which indicates a sufficient amount of food available to micro-organisms (Ivica *et al.,* 2018). Globally, the soil is the central link in the organic biotransformation chain. As the most important "organ of the agricultural organism," the soil transforms all organic residues through decomposition (Galic *et al.*, 2020). Every transformation of organic matter ends with emissions into the environment. Several studies reported that N_2O and CO_2 fluxes increased more after the application of residues with low C: N compared to high C: N (Galic *et al.*, 2020). Soil pH is important for mineral decay, the intensity of microbiological processes, OM mineralization, solubility of substances and other physicochemical processes occurring in soil (Neina *et al.,* 2019).

Nitisols are less weathered and occur in sub-humid to humid tropical regions. They are characterized by a clayey texture, high nutrient-holding capacity, and moderate to high natural fertility (FAO, 2001). Nitisols have a higher cation exchange capacity (CEC), which enables them to retain more nutrients and provide a better environment for crop growth (De Wispelaere *et al.,* 2015). Nitisols also fix phosphorus, making it more available to plants (Elias *et al.,* 2017). The increased organic matter content and microbial activity in Nitisols can lead to higher production of greenhouse gases such as carbon dioxide (CO_2) and methane (CH_4) through organic matter decomposition and methanogenesis (Butterbach-Bahl *et al.*, 2013).

2.5.2 Soil pH and P fixation

Soil pH is a critical factor influencing phosphorus (P) availability and fixation in soils. The pH level affects the chemical forms of phosphorus in the soil and their solubility, which in turn impacts plant uptake and nutrient cycling (Havlin & Heiniger, 2020). In acidic soils ($pH < 5.5$), phosphorus tends to react with iron (Fe) and aluminum (Al) to form insoluble compounds such as iron phosphate $Fe(PO_4)$ and aluminum phosphate ($AlPO_4$). These compounds are not readily available for plant uptake, leading to phosphorus fixation (Johan *et al.*, 2021). In soils with high calcium content, such as those found in Nitisols, phosphorus can still become fixed as calcium phosphate ($Ca_3(PO_4)^2$ (Van Straaten, 2002). In alkaline soils ($pH > 7.0$), phosphorus can react with calcium to form less soluble compounds, such as dicalcium phosphate ($CaHPO_4$) and tricalcium phosphate ($Ca_3(PO_4)^2$), thereby reducing its availability to plants.

The application of inorganic fertilizers like triple superphosphate (TSP) and organic fertilizers such as farmyard manure (FYM) can impact soil pH and phosphorus fixation in different ways. Inorganic fertilizers like TSP can cause immediate increases in available phosphorus. However, in soils with low pH, the added phosphorus can quickly react with Fe and Al, leading to fixation. This process is especially common in Ferralsols because of their high Fe and Al content. Conversely, organic fertilizers like FYM can improve soil structure, boost organic matter content, and promote microbial activity, which can decrease phosphorus fixation over time (Nziguheba et al., 2016). Organic matter from FYM can form complexes with Fe and Al, reducing their reactivity with phosphorus and increasing P availability. The slow mineralization of phosphorus from organic sources can provide a more consistent release, making it less susceptible to fixation. Excessive P application can alter soil microbial dynamics and raise microbial respiration, resulting in higher carbon dioxide (CO_2) emissions from soils. While phosphorus itself is not directly connected to nitrous oxide (N_2O) or methane (CH_4) emissions, its interaction with nitrogen (N) in the soil can influence processes that produce these gases. For instance, P availability can impact nitrogen use efficiency in crops, which in turn affects N_2O emissions through nitrification and denitrification processes (Yu *et al.,* 2017).

2.5.3 Soil organic carbon

Concerns about rising atmospheric carbon dioxide (CO_2) levels and efforts to mitigate climate change have increased interest in the world's soil carbon in recent years. The soils are estimated to have a high potential for carbon sequestration due to their large capacity to store carbon, particularly since soil organic carbon is highly responsive to changes in land use for agricultural purposes. CO_2 in the atmosphere is absorbed by plants through photosynthesis, leading to the formation of biomass that eventually deposits on or within the soil as wood, leaf litter, root exudates, and root material. In well-aerated soils, most of the carbon in this plant debris is converted back to CO_2 by soil microbes (fungi, bacteria, etc.) through soil respiration. However, a portion of it is retained and stabilized in the soil to different extents. Approximately one-third of the plant carbon entering soil in temperate regions remains after one year. Along with the cycling of carbon, important plant nutrients also cycle, improving soil fertility. As organic matter is added to the soil, soil organisms process it to mineralize key nutrients into forms that plants can use (Galic *et al.,* 2020).

Soil conditions vary, and in more extreme environments (such as very acidic, dry, or wet), soil C turnover is reduced. For example, in waterlogged soils, with very low oxygen levels, decomposition is slow to non-existent, and peat forms along with other 'saturated soil' (anaerobic) decomposition products, including methane (CH_4), an important GHG. Where these conditions are maintained for centuries, such as on upland bogs and lowland fens, peat accumulates over time. However, if these peats are drained, allowing air to enter, microbial respiration is reactivated and the peat C is emitted as CO_2 at rates more than 30 t CO_2/ha/yr, although it will take many decades to lose all this stored C. Plants also respire all the time and use the sugar produced through photosynthesis to drive their metabolism in a process known as plant respiration.

2.6 Influence of Environmental Factors on GHG Emissions

2.6.1 Soil Moisture and Temperature

Soil temperature and water content are two essential factors influencing GHG emissions. Climate change can modify ecosystem biogeochemistry and affect gas emissions by raising temperatures and changing hydrological patterns. Studies indicate an increasing trend of GHG efflux as temperature and moisture levels rise within a certain range (Salimi & Scholz, 2021). Higher temperatures can speed up the decomposition of soil organic matter, microbial biomass (Kravchenko *et al.,* 2021) enzyme activities involved in the carbon cycle, and chemical reaction rates, all of which lead to higher greenhouse gas emissions. The effect of moisture on GHG emissions depends on whether conditions are aerobic or anaerobic. CO_2 emissions tend to be higher in soils with higher levels of unsaturation. Flooding reduces CO_2 emissions but raises CH_4 emissions (Zhao *et al.,* 2021). Excess moisture restricts oxygen availability, further limiting aerobic microbial activity and decreasing CO_2 emissions. It also creates anaerobic microsites that promote CH_4 emissions and N_2O release through denitrification.

Soil moisture plays a vital role in controlling CH_4 oxidation and emissions (Hao *et al.*, 2025). Higher moisture levels lead to increased CH_4 emissions, reaching a peak at 100% WHC. Excess moisture can lower oxygen availability, encouraging anaerobic decomposition by methanogens and thus boosting CH_4 production. Conversely, under low moisture conditions, CH_4 emission rates may decline due to enhanced CH_4 oxidation.

2.6.2 Seasonal Variations

The dry season's drought and rewetting events greatly affect biogeochemical processes in soils and influence carbon and nitrogen cycles. After rewetting, large bursts of CO_2 are released from the soil into the atmosphere, known as the “Birch effect” (Birch 1958). Similar emission bursts have been observed for N_2O fluxes in tropical forests at the start of the wet season. Overall, the length and intensity of the dry season, along with weather patterns from the previous wet season, significantly determine the size of these high C and N emission bursts in ecosystems. Increased N_2O emissions associated with rewetting events during El Niño years have also been recorded in tropical forests. Given the high global warming potential (GWP) of N_2O (GWP = 298; IPCC, 2014), these emissions likely decrease the overall greenhouse gas sink. These pulses often make up a large part of the annual soil CO_2 and N_2O fluxes, greatly impacting net ecosystem exchange (NEE) in dry ecosystems and the overall greenhouse gas budget (Calvo-Rodriguez et al., 2021).

2.7 Nutrient Use Efficiency

Nutrient use efficiency (NUE) is crucial for agricultural sustainability, as it directly impacts greenhouse gas (GHG) emissions, including carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). High NUE indicates that plants effectively utilize the applied nutrients, thereby reducing environmental losses. On the other hand, low NUE often results in excess nitrogen (N) and phosphorus (P) in the soil, which can increase GHG emissions. Inefficient nitrogen use raises N_2O emissions through enhanced nitrification and denitrification, especially under conditions of high soil moisture and low oxygen levels (Mosongo *et al.,* 2022b). Likewise, poor phosphorus management can increase CO_2 emissions by altering soil microbial activity and carbon cycling, as microbial respiration rises in response to P-driven shifts in soil organic matter dynamics *(Wu et al.,* 2024). The interaction between N and P can also affect CH_4 emissions, particularly in waterlogged soils where methanogenesis is encouraged. Therefore, improving NUE through careful fertilizer management is crucial for reducing the GHG footprint of agricultural systems while maintaining high productivity.

CHAPTER THREE

METHODOLOGY

3.1 Study Area

This was an on-farm study conducted in the Marakwet West and Keiyo North sub-counties of Elgeyo Marakwet County within latitude 0° 20′ to 1° 30′ north and longitude 35° 0′ to 35° 45′ east. The county is situated in Kenya's Rift Valley and covers an area of 3,029.6 km², representing 0.4 % of Kenya’s total land area. The county is mainly characterized by mixed crop, livestock, and agro-pastoral production systems, with key food crops including maize, beans, and green grams. The primary livestock enterprises are cattle (both dairy and beef), goats, sheep, and poultry (County Government of Elgeyo Marakwet, 2018).

The area is situated at an altitude of 2804 Meters above sea level. Its climate varies from cool in the highlands, mild on the escarpment, too hot in the lowlands, with an annual mean temperature of 20.47 °C and rainfall of 127 mm spread over two rainy seasons. Figure 1 displays the map of the study site.

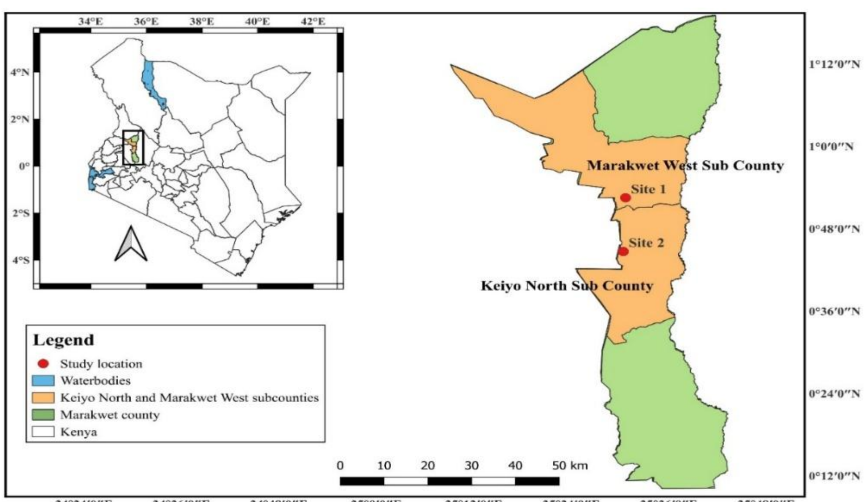

Figure 1: A map of Elgeyo Marakwet County showing Study site.

3.2 Experimental Setup

The experiment was initiated in April 2024; the trial was laid out in a factorial experimental setup-in Randomized Complete Block Design as shown in figure 2. Treatment comprised Farmyard manure (FYM) and inorganic fertilizers substitution at various rates, under three cropping systems namely, sole maize, sole desmodium, and maize-desmodium intercrop. Out of the six fertilizer substitution treatments, four were selected for greenhouse gas (GHG) measurement to represent key substitution gradients between inorganic and organic sources while maintaining experimental manageability. these comprised of: (i) 0 FYM and 0 Inorganic – No fertilizer (Control); (ii) 25 75 - 25% of 30kg Pha^{-1} supplied by FYM, and 75% of 30kg Pha^{-1} supplied by Inorganic fertilizer; (iii) 50 50 - 50% of 30kg Pha^{-1} supplied by FYM and 50% of 30kg Pha^{-1} supplied by Inorganic fertilizer and (iv) 75 25 -75% of 30kg Pha^{-1} supplied by FYM, and 25 % of 30kg Pha^{-1} supplied by Inorganic fertilizer. Fertilizer application rates in this experiment were calculated based on the phosphorus (P) requirement to avoid oversupplying other nutrients, particularly potassium (K) and nitrogen (N). When N was used as the basis for calculation, it resulted in excessive application of both P and K due to the fixed nutrient ratios in the manure–fertilizer blends. This would have exceeded the intended target rates of 100 kg N ha^{-1}, 30 kg P ha^{-1}, and 60 kg K ha^{-1}. We applied Farrmyard manure (FYM), Urea, Triple Superphosphate (TSP), and Muriate of potash (MOP). The plots measured 5m by 4.5 m and the whole experimental plot will be 61 m by 32.5 m. The maize variety planted was H6213 with a spacing of 75 cm inter-row and 25 cm intra-row. The desmodium variety was desmodium silverleaf with a spacing of 35 cm inter-row and drilled in line. Land preparation consisted of the incorporation of FYM and inorganic fertilizer before planting. Two maize seeds were planted per hole and later thinned to one to attain the recommended 44,444 plants spacing per hectare.

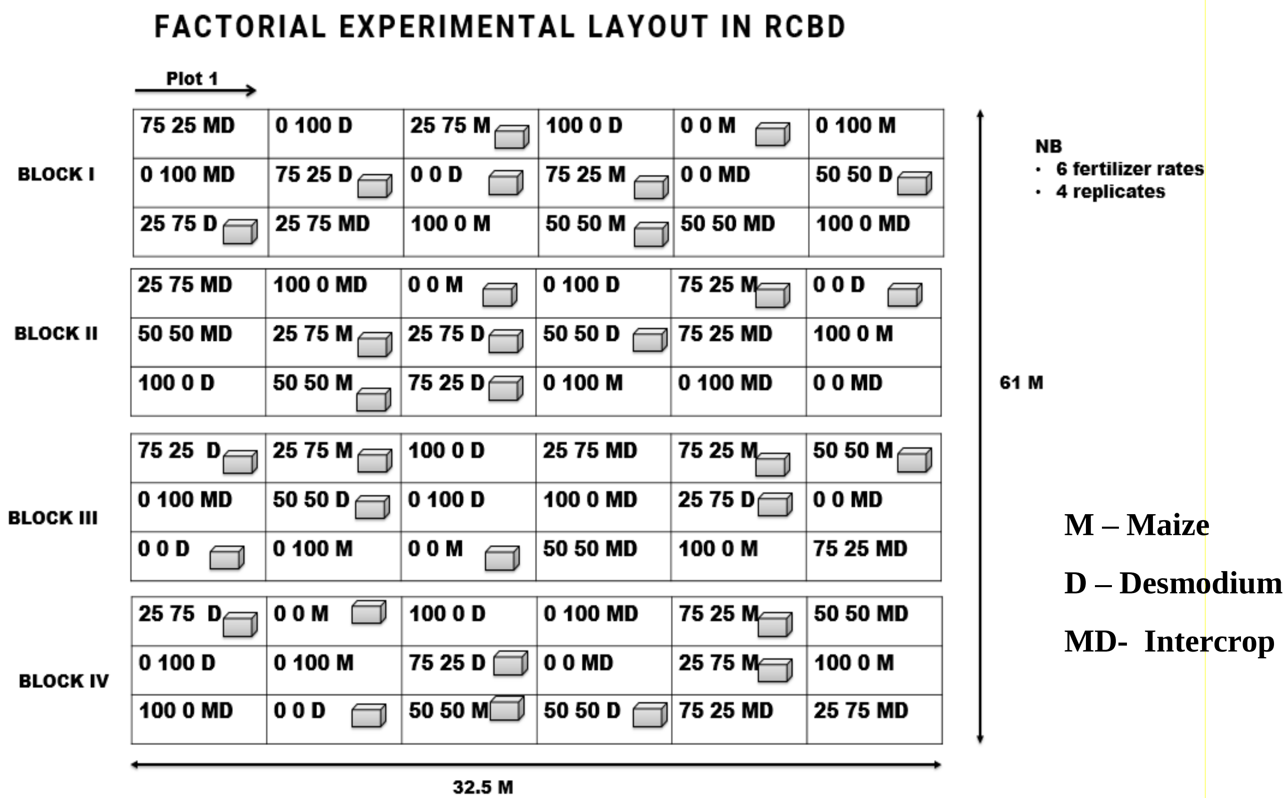

Figure 2: Experimental Layout: Factorial arrangement in RCBD.

KEY: 0,0 - 0 FYM, 0 Inorganic – No fertilizer (Control)

25, 75 - 25% of 30kg Pha^{-1} supplied by Farmyard Manure 75% of 30kg Pha^{-1} supplied by Inorganic fertilizer

50, 50 - 50% of 30kg Pha^{-1} supplied by Farmyard Manure, 50% of 30kg Pha^{-1} supplied by Inorganic fertilizer

75, 25 - 75% of 30kg Pha^{-1} supplied by Farmyard Manure 25 % of 30kg Pha^{-1} supplied by Inorganic fertilizer

100, 0 - 100% of 30kg Pha^{-1} supplied by Farmyard Manure 0% of 30kg Pha^{-1} supplied by inorganic fertilizer

0, 100 - 0 % of 30kg Pha^{-1} supplied by Farmyard Manure 100 % of 30kg Pha^{-1} supplied by Inorganic fertilizer

3.3 Soil Sampling and Analysis

Soil samples from each plot were collected once every four weeks throughout the season, using a regular five (5) cm wide soil auger to a depth of 0-20 cm and 20-40 cm. Plastic zip-lock bags were used (Okalebo *et al.*, 2002)

Soil moisture content was estimated by drying 10 g of soil at 80°C for 24 hours, with the weight change from the fresh soil expressed as a percentage of the final dry soil's weight. 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.

Weighed 10.0 g of freshly sampled soil into a plastic shaking bottle for Colorimetric determination of ammonium (NH_4^+)**.** Added 100 mL of 0.5 M K_2SO_4 extracting solution. Stoppered and shook the contents for 1 hour. Dissolved 4.714 g of ammonium sulfate ($(NH_4)_2SO_4$) in a 1000 ml volumetric flask and topped up to the mark with distilled water. Diluted 50 g of the stock solution in 500 ml of distilled water and made to the mark. Using a micro-pipette, took 0.2 ml of the sample extract, blanks, and standard series into clearly labeled test tubes. Added 5.0 ml of reagent N1 and let it stand for at least 15 minutes, then vortexed. Added 5.0 ml of reagent N2 and vortexed again. Allowed the mixture to stand for 1 hour, then measured the absorbance at 655 nm.

For Nitrate (NO_3^-) 0.5 ml of the sample extract was transferred, blanks, and the standard series K_2SO_4 soil into properly labeled test tubes. Added 1.0 ml of salicylic acid to each test tube, mixed thoroughly, and waited for 30 minutes. Added 10 ml of 4M sodium hydroxide to each test tube, mixed well, and left for 1 hour to allow full yellow color development. Measured the absorbance at a wavelength of 419 nm.

The available P was extracted using the Olsen method, where 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 polyethylene 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 colorimetric P measurements, with standards and sample absorbance measured at 880 nm wavelength.

The total amount of carbon was determined using the Black and Walkey wet oxidation method, in which 0.3 g of soil was oxidized with a mixture of sulfuric acid and aqueous potassium dichromate ($K_2Cr_2O_7$) at 155°C for 30 minutes. After complete oxidation from the heat of solution and external heating, the remaining $K_2Cr_2O_7$ in the oxidation was titrated against ferrous ammonium sulfate, and the endpoint was reached when the color of the mixture changed from greenish to brown. The difference between the added and unused $K_2Cr_2O_7$ provided a measure of organic carbon content.

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 for 60 minutes, followed by adding three successive 1 ml portions of hydrogen peroxide in the cooled content. Heating was then continued to rise 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 taken for colorimetric determination of total N, where absorbency was measured at 650 nm.

3.4 Plant Sampling and Analysis

Maize and Desmodium Biomass Measurement

Maize biomass was determined by sampling 16 plants within each 3 m x 3 m plot. Leaves were sampled at silking (15 weeks after planting), while grains and stovers were collected at harvest, air-dried for twenty-one days, and the dry weight was recorded. Desmodium biomass was measured by sampling eight rows of 3 m x 3 m within each plot. The data collected from maize and desmodium biomass measurements were used to compare the effects of different fertilizer treatments on crop performance and to identify the best fertilizer management practices that increase crop yield. Biomass measurements were essential in calculating the nutrient use efficiency (NUE). The total Biomass produced (both maize and desmodium) under different fertilizer inputs can indicate how efficiently the crops use the available nutrients. Formulae I to iv adopts the formula described by (Congreves *et al.*, 2021)

i. Grain Yield Determination

The number of plants in each effective sampling area was counted manually and recorded. Total and subsample fresh weights of the heads were measured per net effective area. The subsample was taken to the University of Eldoret for air drying in the greenhouse. The dry weights of the subsample were then measured. Grains were separated from stovers, and their dry weights were recorded. The grain yields were expressed in tons per hectare ($t\ ha^{-1}$).

$$Grain\ yield\ (t\ ha^{-1})$$

$$= \left(\frac{total\ sample\ fresh\ weight\ of\ cobs\ \times sub\ sample\ dry\ grain\ weight}{sub\ sample\ fresh\ weight}\right)$$

$$\times 10{,}000\ m^2\ /9\ m^2$$

(i)

ii. Agronomic Use Efficiency

It was determined by calculating the difference in grain yield with N application and without it, and then dividing the results by the amount of N applied, indicated by the following formula.

$$Agronomic\ N\ use\ efficiency)$$

$$= \left(\frac{grain\ yield\ with\ N\ application - grain\ without\ N\ application}{amount\ of\ N\ applied}\right)$$

(ii)

iii. Grain N and P Uptake

Dry grains were sampled in each treatment after harvesting period and ground into fine powder before analysis for P and N content as per the laboratory manual by (Okalebo et al., 2002). The amount of N and P uptake was calculated and expressed in kilograms per ha as indicated in the formulae.

$$Nitrogen\ uptake\ \left(kg\ ha^{-1}\right) = \left(\frac{N\ content\ \left(\frac{mg}{kg}\right)}{1000000}\right) \times yield\ \left(kg\ ha^{-1}\right)$$

(iii)

iv. Apparent Recovery Efficiency

It was determined by calculating the difference in total N uptake in above-ground biomass with and without N fertilization. The net amount of N absorbed was then divided by the amount of nutrient applied.

$$Apparent\ \ recovery\ efficiency(\%)\ =$$

$$\left(\frac{Total\ N\ uptake\ of\ fertilized\ plants - Total\ N\ uptake\ of\ unfertilized\ plant}{Ferilizer\ N\ applied}\right)*100$$

(iv)

Lab analysis: Nitrogen and Phosphorus Analyses

From each powdered sample of leaves, stovers, and grains, 0.3 g was mixed with 4.4 ml of digestion mixture (composed of hydrogen peroxide, sulfuric acid, selenium, and salicylic acid) and stored at 2°C in digestion tubes. The mixture was digested in a block digester at 360°C for 2 hours. After digestion, the mixture was cooled and transferred to 50 ml volumetric flasks. The solution was made up to volume with distilled water, and 5 ml aliquots were taken for analysis. Percentage N and P were determined separately using the colorimetric method described by (Okalebo et al., 2002). Using a spectrophotometer, N absorbance was measured at 650 nm, while P absorbance was determined at an 880 nm wavelength.

3.5 Greenhouse Gases Sampling

3.5.1 Chamber Design

Greenhouse gas fluxes was estimated using manually sampled non-flow-through, non-steady state chamber methodology. Briefly, thirty-two opaque plastic bases were installed 7.5 cm into the ground in four fertilizer treatments and replicates for sole desmodium and sole maize, immediately after tillage, and left in the field for the entire growing season. The height of the chamber was measured from the outside to ensure slight changes caused by soil compaction are captured. During deployment, vented and ventilated opaque plastic lids (25 × 35 × 12.5 cm) were fastened to the bases with clamps to ensure an airtight seal, as shown in Figure 3. All openings were lined with a rubber septum to ensure the chamber is airtight.

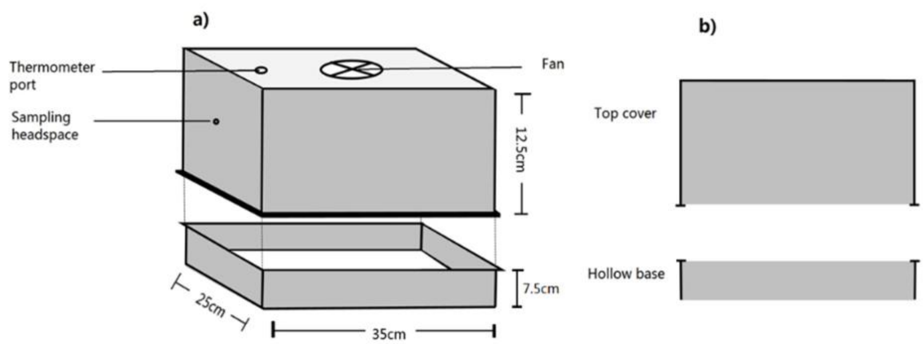

Figure 3: GHGs Chamber Design (Mosongo et al., 2022b)

3.5.2 Gas Sampling Protocol

Gas samples were collected between 7:00 am and 4:00 pm to minimize temperature changes during chamber deployment and because fluxes measured during this period better represent daily mean fluxes. The top of the chamber was also lined with reflective duct tape to reduce temperature fluctuations. Gas samples were drawn at 10-minute intervals starting at T0 (immediately after closing the gas chamber) and ending at T30 (30 minutes after sealing the chamber) (Parkin & Venterea, 2010). During each sampling, 30 ml of gas was extracted with a propylene syringe fitted with a luer lock from each of the two replicates per plot, and all 60 ml were injected into a 20-ml pre-evacuated glass vial for storage. Ambient air temperature was measured directly using a thermometer inserted into an airtight port on top of the chamber. Sampling occurred biweekly throughout the rest of the growing season from April 2024 to November 2024.

3.5.3 Greenhouse Gas Measurements

Gas concentrations of the three greenhouse gases, N_2O, CO_2, and CH_4, were measured using SRI gas chromatographs (8610C; SRI) at the Mazingira Centre at the International Livestock Research Institute (ILRI) in Nairobi, Kenya. A flame ionization detector (FID) was employed for CH_4 and CO_2 (after passing through a methanizer), while an electron capture detector (ECD) was used for N_2O. Hayesep-D packed columns facilitated the operation of the chromatograph, with N_2 (flow rate of 30 mL min−1) serving as the carrier gas for both detectors. The oven temperature was maintained at 65°C, with the methanizer and ECD set at 350°C. The GC peak areas were converted to concentrations by comparing them to standard gases with known levels of CO_2, CH_4, and N_2O. A linear regression approach was used to calculate CH_4 and CO_2 concentrations, while a power function was employed for N_2O concentration.

3.5.4 GHG Flux Calculations

Flux Calculations

$$F = \frac{b \times Mw \times V_{Ch} \times 60 \times 10^6}{A_{Ch} \times V_m \times 10^9}$$

(iv)

Where

b = slope of increase or decrease in concentration (ppb min^{-1})

Mw = molecular weight of component of the compound (g mol^{-1})

V_{ch} = chamber volume (m^3)

A_{ch} = chamber area (m^2)

V_m = corrected standard gaseous molar volume (m^3 mol^{-1})

3.5.5 Emissions Intensities

N_2O Emission Factors (EF%)

It is the proportion of applied N lost as N_2O, calculated as:

$$\boldsymbol{EF}\ (\%) = \frac{\boldsymbol{N2O\ fertilized - N2O\ control}}{\boldsymbol{N\ applied}}\ \mathbf{x\ 100}$$

(vi)

Net Global Warming Potential (Net GWP, Mg CO_2-eq ha^{-1})

It is the sum of cumulative CH_4, CO_2 and N_2O fluxes converted to CO_2 equivalents, calculated as:

$$\textbf{Net GWP} = \sum(\boldsymbol{CH4 + CO2 + N2O})\boldsymbol{emissions}$$

(vii)

Green House Gas Intensity (GHIG, Kg CO_2-eq kg^{-1} yield)

It is the Net GWP normalized by yield, indicating system efficiency, calculated as:

$$\boldsymbol{GHGI} = \frac{\boldsymbol{Net\ GWP}}{\boldsymbol{Yield}}$$

(viii)

Yield Scaled Emissions (YSE)

It is the emissions (for each gas) per unit of yield (e.g., g N_2O/kg yield), calculated as:

$$\boldsymbol{YSE} = \frac{\boldsymbol{Cumulative\ Gas\ Emissions}}{\boldsymbol{Yield}}$$

(ix)

3.6 Meteorological Data

Meteorological data was collected from the nearest meteorological station in Iten, Marakwet County. This includes rainfall, air temperature, and relative humidity. Also, soil moisture content and soil temperature measurements was carried out adjacent to each chamber during gas sampling.

3.7 Statistical Analyses

Cumulative flux data (model residuals) were checked for normality using the Shapiro–Wilk test, and it was confirmed to be normal at a 95% confidence interval without transformation. The effects of treatments, blocks, and cropping systems on the cumulative GHG fluxes were tested using a mixed linear model from the lmerTest package in R (R Core Team, 2016), with treatments and cropping system as factors. Correlations between cumulative annual soil GHG fluxes (CH_4, CO_2, and N_2O) and soil properties (C, N, C/N ratio, and moisture), total biomass (stovers, leaves, and grain yields), and Inorganic nitrogen intensities (ammonium (NH_4^+-N), nitrate (NO_3^--N), and total N (NH_4^+-$N^+NO_3^-$-N)) for all plots during both seasons (n = 72) were examined using Pearson's correlation.

CHAPTER FOUR

RESULTS

4.1 Soil Physical and Chemical Characteristics

4.1.1 Initial Soil Characterization

Initial soil characterization of the experimental site is presented in Tables 1 and 2. Soil pH from both sites were moderately acidic with a pH of 4.9 – 5.1 and 5.2 – 5.3 for Marakwet west and Keiyo North respectively. Total N was low in Marakwet west (0.12%) and in Keiyo North (0.10%), while that of available P was low (< 10 mg kg^{-1}) in both sites. Organic carbon levels were moderate in both sites with values ranging 2.1- 2.78%. The soils were classified as sandy clay loam in Marakwet West and clay loam in Keiyo North.

Table 1: Initial physiochemical properties in the soil before experimental setup; Site 1 (Marakwet West)

Soil Depth (cm)	Bulk Density (g cm^{-3})	pH	Total Nitrogen (%)	Av. Phosphorus (mg kg^{-1})	Organic C (%)	Texture
0-20	1.03	5.1	0.13	7.456	2.78	Sandy clay loam
20-40		4.9	0.12	5.029	2.54	

Values are means (n = 3)

Table 2: Initial physiochemical properties in the soil before experimental setup; Site 2 (Keiyo North)

Soil Depth (cm)	Bulk Density (g cm^{-3})	pH	Total Nitrogen (%)	Av. Phosphorus (mg kg^{-1})	Organic C	Texture
0-20	1.22	5.3	0.11	9.06	2.64	Clayloam
20-40		5.2	0.09	6.112	2.20	

Values are means (n = 3)

4.3 Rainfall and Temperature

Rainfall distribution is shown in Figure 4 with the long rains running from April through August while the short rains occurred from September through December). Temperature ranged between 17 °C (minimum) and 24 °C (maximum) with minimal fluctuations throughout the year.

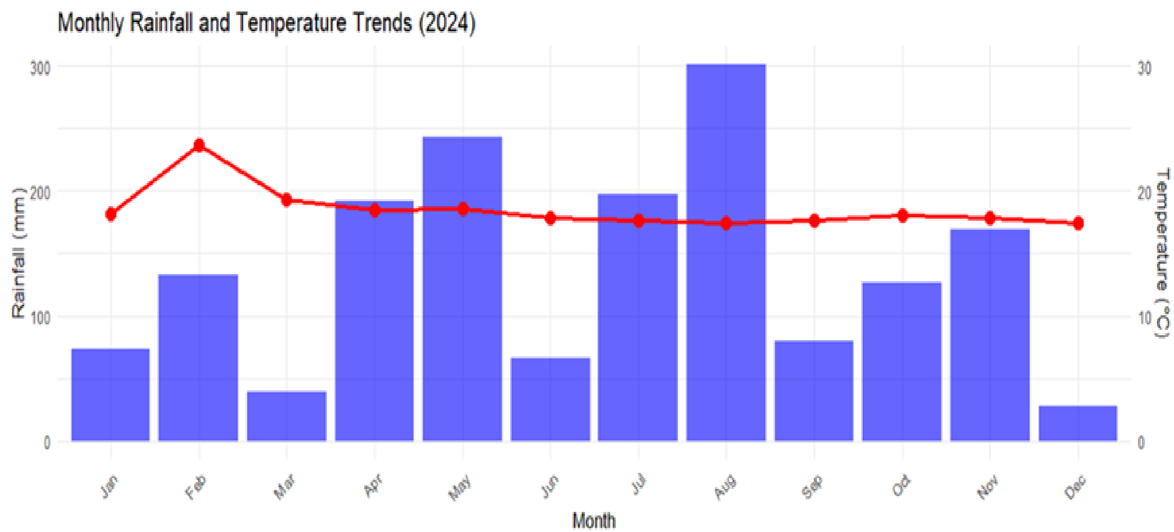

Figure 4: Monthly rainfall, maximum and minimum temperatures for Marakwet County in 2024

4.4 Soil Nutrient Dynamics

4.4.1 NO_3-N Concentration

Nitrate-N (NO_3^--N) dynamics showed a clear temporal pattern across all fertilizer rates and cropping systems. At both Site 1 (Figure 5) and Site 2 (Figure 6), NO_3^--N concentrations peaked between DAP 30 and DAP 90 in the 0–20 cm soil layer and steadily declined toward harvest (DAP 210). Peak concentrations ranged from 35 to 55 mg/kg at depths of 0–20 cm, while at depths of 20–40 cm, they ranged from 20 to 60 mg/kg, with the steepest declines observed in maize-dominated systems.

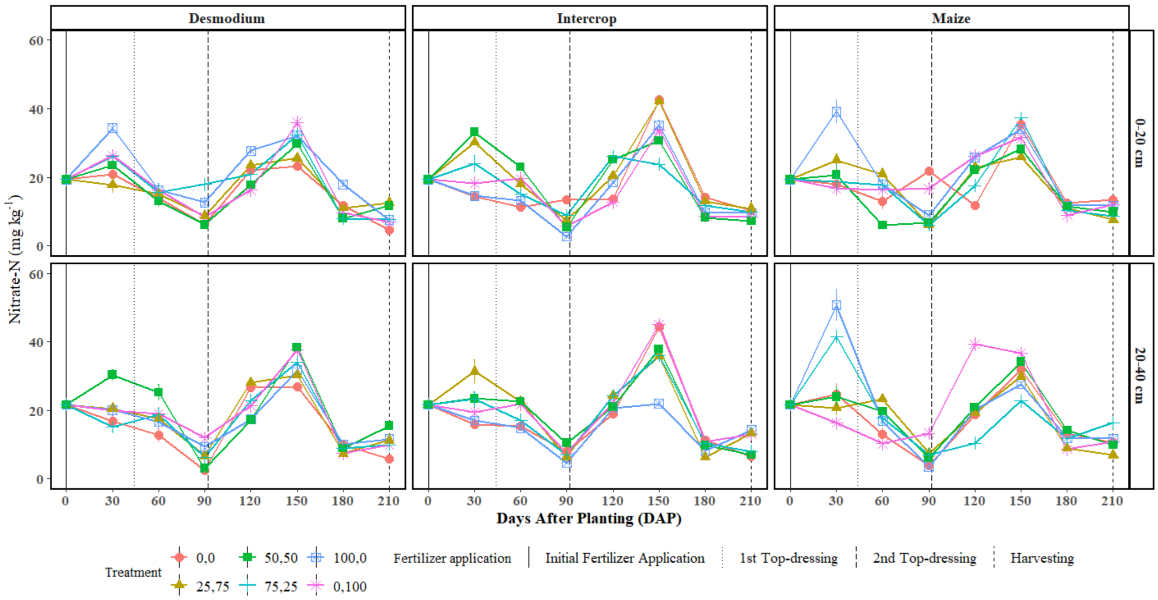

Figure 5: Soil Nitrate (mg kg^{-1} soil), for Maize, Desmodium and Intercrop Cropping System at 0- 20, 20-40 cm depth. Site 1

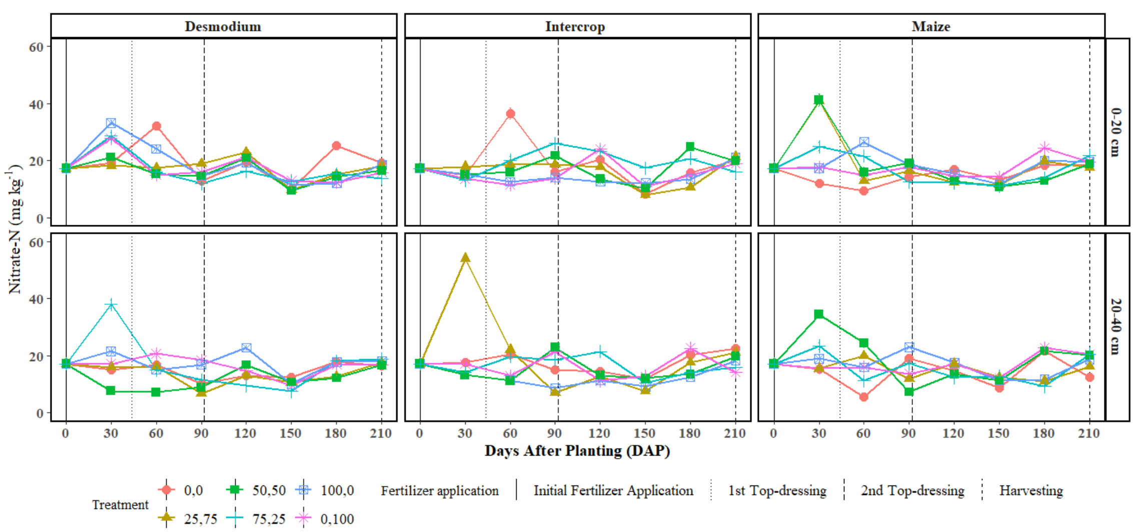

Figure 6: Soil Nitrate (mg kg^{-1} soil), for Maize, Desmodium and Intercrop Cropping System at 0- 20, 20-40 cm depth. Site 2

Fertilizer rates exhibited apparent influence on NO_3-N dynamics. Rate 0,100 (100% inorganic) and 25,75 (25% FYM, 75% inorganic) recorded the highest early-season nitrate levels, with concentrations exceeding 55 mg/kg at DAP 30–60, particularly in maize plots. However, such peaks were short-lived, dropping sharply after DAP 60. In contrast, fertilizer rate 75,25, and 100,0 (FYM-dominant treatments) demonstrated moderate and more stable NO_3^- curves**,** peaking at 40 mg/kg and declining gradually. The control (0 0)**,** which received no fertilizer, maintained the lowest NO_3^- concentrations (<25 mg/kg).

The sole maize system showed the highest NO_3^--N concentrations, especially at 0–20 cm and during DAP 30–90. The most pronounced peaks occurred under 0,100 and 25,75 fertilizer rates. In FYM-rich treatments, notably 50,50 and 75,25, maize plots still recorded high nitrate levels (40–50 mg/kg), though with a more gradual decline. Desmodium plots consistently had lower NO_3^- levels, generally ranging from 20 to 45 mg/kg, with smaller fluctuations throughout the season. the 50,50 and 75,25 combinations.

4.4.2 NH_4^+N Concentration

The cropping system had a highly significant effect on NH_4^+ ($p < 0.001$).

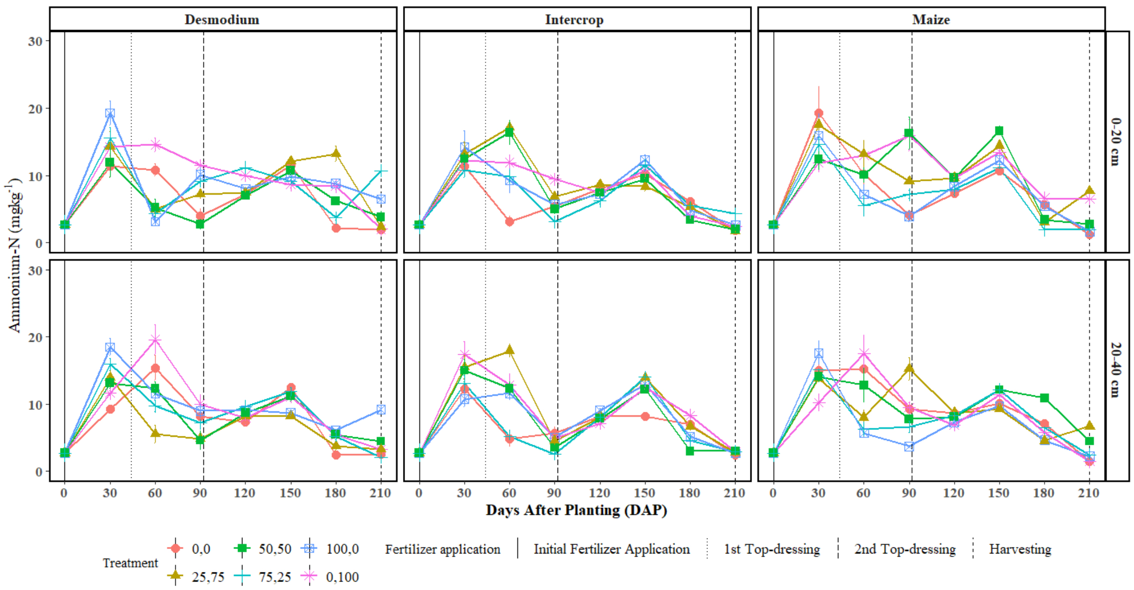

Figure 7: Soil Ammonium (mg kg^{-1} soil), for Maize, Desmodium and Intercrop Cropping System at 0- 20, 20-40 cm depth. Site 1

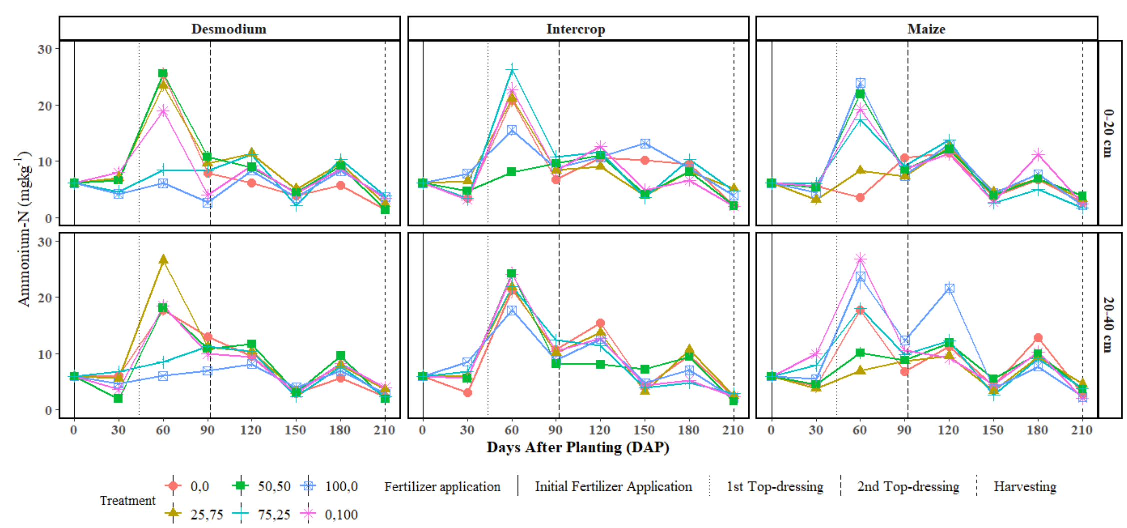

Figure 8: Soil Ammonium (mg kg^{-1} soil), for Maize, Desmodium and Intercrop Cropping System at 0- 20, 20-40 cm depth. Site 2

Ammonium-N levels fluctuated over time as shown in figure 7 and 8, with peaks observed between DAP 60 and 90, especially in the 0–20 cm soil layer. These peaks aligned with periods immediately after basal fertilizer application and the first topdressing, both of which involved urea. The surface soils showed a range of 3.5–7.5 mg/kg, while in the 20–40 cm depth, values were generally lower (2.0–5.0 mg/kg), indicating limited vertical movement and more microbial activity in the upper layer. After DAP 120, a gradual decrease in NH_4^+ concentrations were observed across all cropping systems and sites.

Treatment 100,0 (FYM-only) and 75,25 (75% FYM + 25% inorganic) combinations consistently recorded the highest NH_4^+ concentrations, with peaks reaching 22.5 mg/kg at DAP 60–90 in surface soils. Maize plots showed early peaks in NH_4^+ (DAP 30–60), followed by a sharp decline by DAP 150, especially in the 0 100, 100 0, 25 75, and 75 25 fertilizer combinations. The decline was more noticeable at Site 2. Maize's quick early biomass growth contributed to this pattern. Peak NH_4^+ levels for maize ranged from 15 to 25 mg/kg in the surface layer application.

Desmodium systems maintained higher NH_4^+ concentrations for a longer period into the season, especially under 25,75, 75,25, and 100,0 fertilizer rates. The NH_4^+ concentrations peaked at 25 mg/kg around DAP 60 and remained above 5 mg/kg even at DAP 150 in some plots.

The NH_4^+ concentrations were consistently higher in the 0–20 cm soil layer, where most fertilizer was applied and microbial activity is focused. At 20–40 cm, levels were generally lower at 1.5–2.0 mg/kg.

4.4.3 Soil pH

Fertilizer treatment significantly affected soil pH ($p < 0.001$), with FYM-based treatments maintaining higher pH levels (6.3–6.5), while plots receiving 100% inorganic N (urea) showed lower pH (5.2). there was a significant interaction between fertilization regime (rate) and cropping system ($p < 0.001$). The pH values were consistently higher in the surface layer (0–20 cm) than in the subsoil (20–40 cm) as shown in figure 9 and 10. Throughout the cropping season, a trend of pH increase was observed around DAP 90 and DAP 180, coinciding with topdressing fertilizer applications.

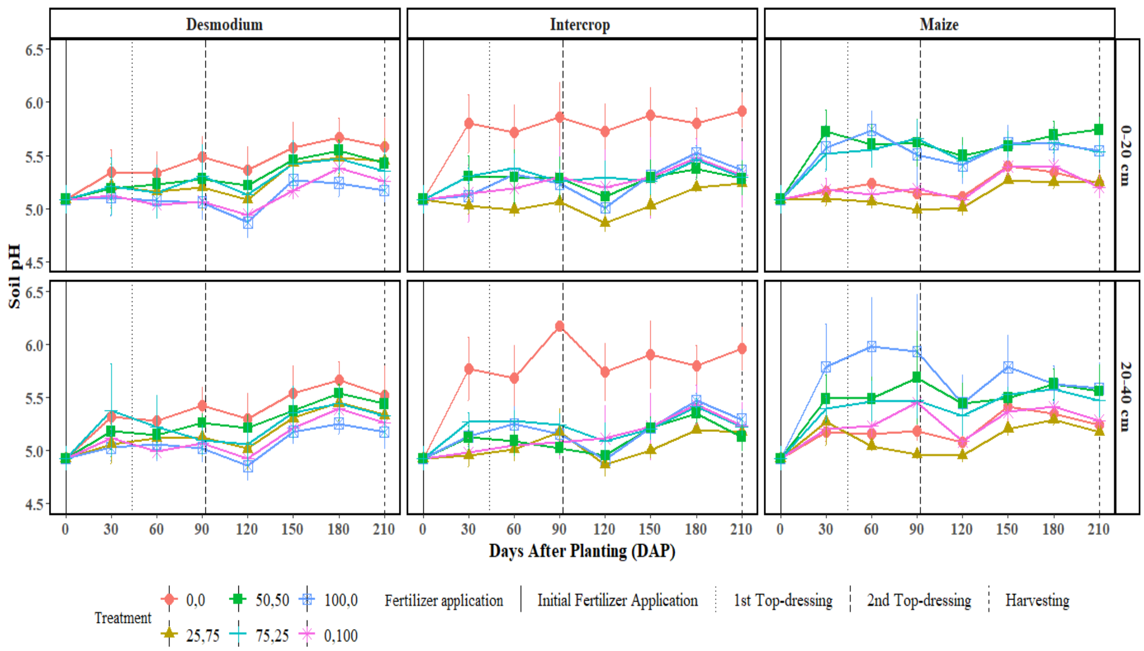

Figure 9: Soil pH, for Maize, Desmodium and Intercrop Cropping System at 0- 20, 20-40 cm depth. Site1

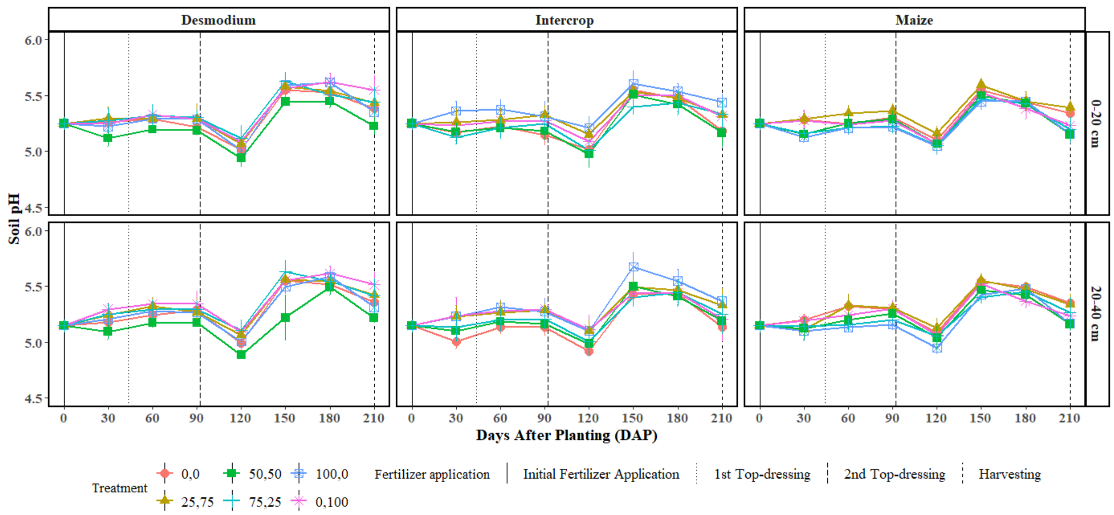

Figure 10: Soil pH, for Maize, Desmodium and Intercrop Cropping System at 0- 20, 20-40 cm depth. Site 2

Plots with 100% inorganic fertilization (0,100), especially in maize monoculture, showed acidification, with pH values nearing the lower limit of 5.0 at greater depths.

4.5 Available Phosphorus

Fertilizer treatments had a statistically significant effect on available phosphorus at 0–20 cm in Site 1 ($p < 0.05$), where FYM-rich plots (75,25 and 50,50) exhibited higher P levels (mean > 10 mg/kg). At deeper depths and in Site 2, differences were not significant ($p > 0.05$), as shown in Figure 11. Across the three cropping systems, available phosphorus (P) concentrations displayed clear temporal trends. Values increased significantly from DAP 0 to DAP 90–150, then slightly decreased by harvest (DAP 210). Available P ranged from as low as 4 mg/kg in 0,0 (control) to over 20 mg/kg in 50,50 and 75,25 fertilizer regimes, at peak times (DAP 150).

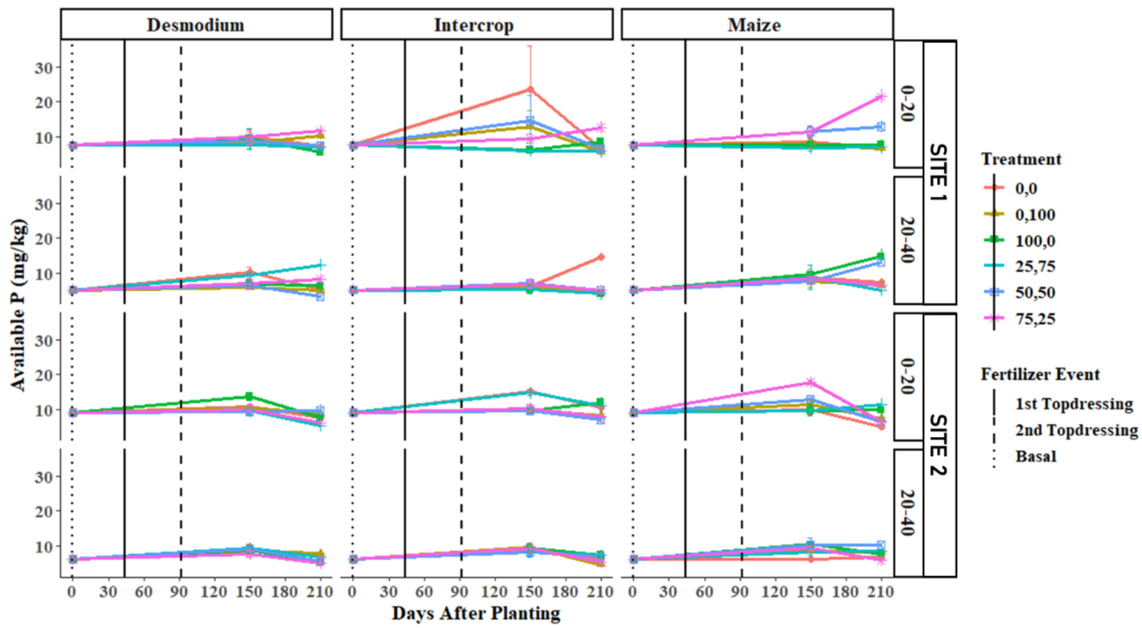

Figure 11: Soil Available Phosphorus (mg/kg), for Maize, Desmodium & Intercrop Cropping System at 0- 20, 20-40 cm depth

Soils under 50,50 and 75,25 fertilizer regimes consistently recorded the highest available P, peaking at approximately 22–25 mg/kg at DAP 150 in Site 1 and slightly lower in Site 2. In 0,0 control, P remained lowest (4–6 mg/kg).

Desmodium plots consistently maintained higher available P, especially at the 0–20 cm depth. Peak values in 75,25 and 50,50 reached up to 24 mg/kg at DAP 150, declining slightly to 18 mg/kg at harvest. DAP 180–210, even under 50,50 and 75,25. Although values reached 20 mg/kg at DAP 150, they dropped to 12–14 mg/kg at harvest. Deeper layers (20–40 cm) under maize often remained below 10 mg/kg.

4.6 Soil Total Nitrogen

There were no statistically significant differences in total soil nitrogen across treatments at either depth or site (ANOVA $p > 0.05$). However, numerical means suggested that the 75,25 and 50,50 fertilizer rates consistently maintained higher nitrogen values across depths. Total nitrogen (%) exhibited a clear temporal pattern across all cropping systems and treatments as shown in (Figure 12). The initial values at DAP 0 were relatively consistent and low

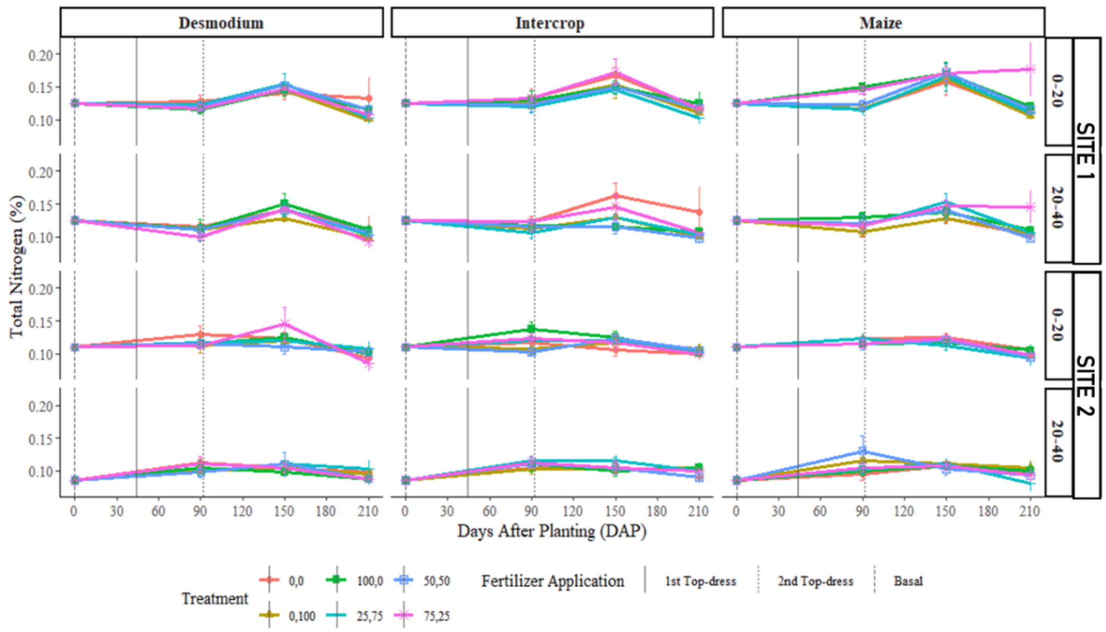

Figure 12: Soil Total Nitrogen (%), for Maize, Desmodium and Intercrop Cropping System at 0- 20, 20-40 cm depth

The 50,50 (50% FYM + 50% inorganic) and 75,25 fertilizer combinations maintained the highest total N concentrations throughout the season. This trend was observed across both depths and both sites**.** The intercrop system exhibited intermediate but stable nitrogen levels, closer to desmodium than maize. Total N increased steadily with DAP, particularly under the 50,50 and 75,25 fertilizer rates. Maize plots had lower total N, especially under 0,0 and 0,100 rates, with a sharper decline after DAP 150. Only the 50,50 and 75,25 fertilizer combinations buffered against this decline, reinforcing the benefit of organic input.

4.7. Soil Total Organic Carbon

Soil organic carbon was minimally impacted by fertilizer treatments at both depths (Site 1 $p = 0.078$; Site 2 $p = 0.069$). The highest carbon levels were seen under 75,25 and 100,0 fertilizer combinations (means = 2.93% and 2.91%, respectively). Site 1 generally exhibited slightly higher SOC than Site 2 across treatments and cropping systems, especially at DAP 90 and 150. In both sites, the 0–20 cm layer contained 30–50% more carbon than the 20–40 cm layer.

Across all cropping systems and treatments, SOC was consistently higher at 0–20 cm than at 20–40 cm. Plots receiving high FYM inputs, 75,25 (75% FYM) and 100,0 (100% FYM), recorded the highest SOC concentrations, reaching up to 2.1% in topsoil by DAP 150, particularly under Desmodium and intercrop systems.

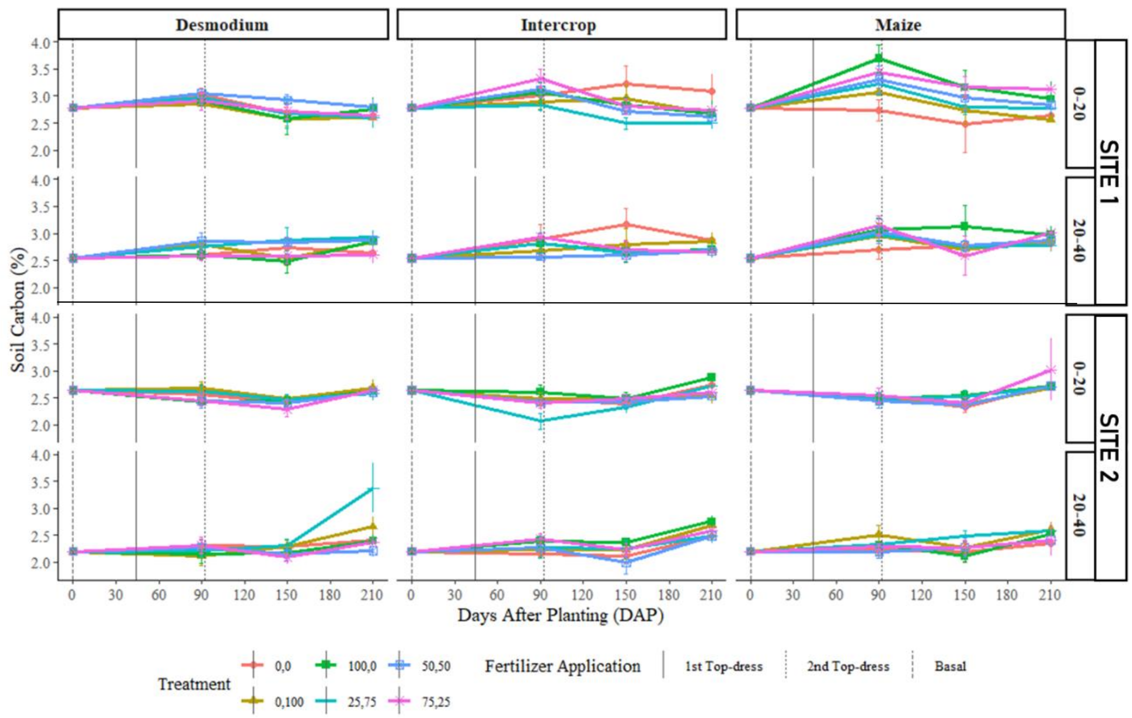

Figure 13: Soil Carbon (%), for Maize, Desmodium and Intercrop Cropping System at 0- 20, 20-40 cm depth.

Plots under 0,0 (no fertilizer) and 0,100 (100% inorganic fertilizer) had the lowest SOC values across all sites and depths, generally remaining below 1.0%**.** The 25,75 and 50,50 fertilizer rates, which combined FYM with mineral fertilizers, showed intermediate SOC levels (1.2–1.7%). The Desmodium cropping system consistently exhibited the highest SOC values, especially at the 0–20 cm depth and during the mid-season (DAP 90–150). Peak SOC levels in desmodium plots with 75,25 and 100,0 reached approximately 2.1%, which was significantly higher than maize or intercrop. The FYM-rich combinations under intercropping (50,50 and 75,25) maintained stable SOC levels throughout the season.

4.7 Greenhouse Gas Emissions

4.7.1 Methane, Carbon Dioxide and Nitrous Oxide emissions

Results for CO_2, CH_4 and N_2O fluxes in the soil are presented in Figure 14. Under the desmodium crop, CH_4 fluxes remained low across all treatments throughout the growing season, with a slight emission of 0.2 mg C m^{-2} h^{-1} at planting (day 0) in the 50,50 (50% FYM, 50% Inorganic) after which CH_4 fluxes declined rapidly and remained negligible through to harvest. CO_2 fluxes began low 30–50 mg C m^{-2} h^{-1} at planting 0-14 DAP (Days After Planting), then rose steadily and peaked at 120 mg C m^{-2} h^{-1} between 140–154 days after planting (DAP) under the 25,75 (25% FYM, 75% Inorganic), and 50,50 (50% FYM, 50% Inorganic), fertilizer rates before gradually declining. Generally, emissions were higher at the end of the season compared to the beginning of the season for CO_2. N_2O fluxes peaked early at 75 µg N m^{-2} h^{-1} at 14 DAP under 75,25 (75% FYM, 25% Inorganic). However, fluxes declined to ≤20 µg N m^{-2} h^{-1} after 28 DAP and remained low throughout the season.

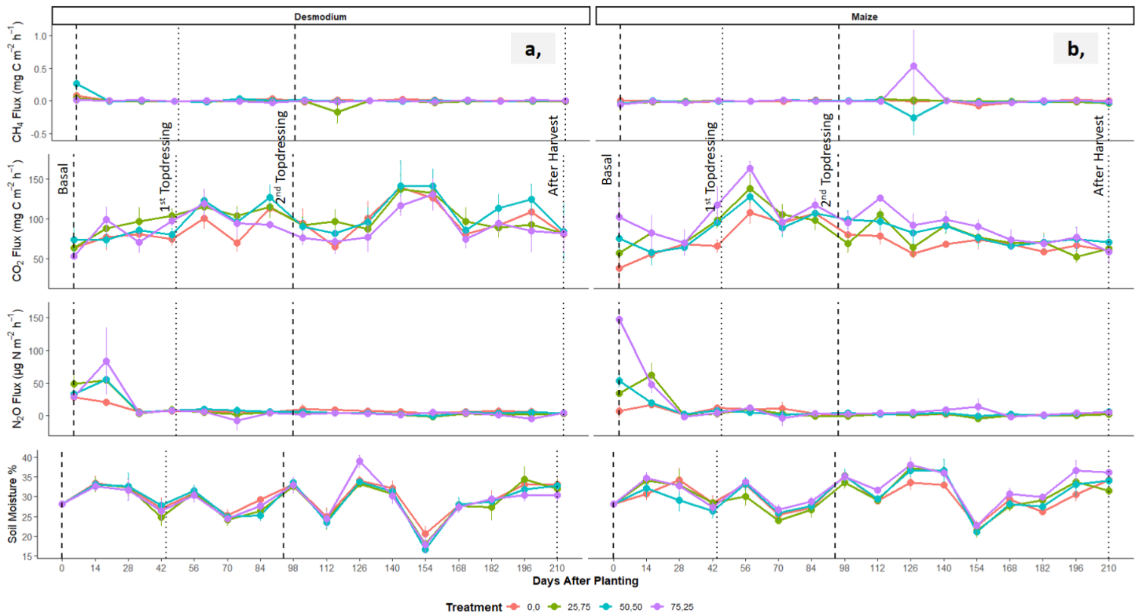

Figure 14: Mean CH_4, CO_2, N_2O and Soil Moisture under the (a) desmodium and (b) maize crop during the 2024 cropping season in Elgeyo Marakwet County. The treatment 25,75 refers to 25% FYM and 75% Inorganic fertilizer, and analogously for the other treatments.

Under maize crop, CH_4 fluxes were low at 0.1 mg C m^{-2} h^{-1}, with a sharp but isolated spike of 0.5 mg C m^{-2} h^{-1} at 126 DAP under the 75,25 (75% FYM, 25% Inorganic) treatment at day 128 (Figure 14). Fluxes were otherwise at background level throughout the season. CO_2 fluxes started near 40 mg C m^{-2} h^{-1} at planting and increased sharply, peaking earlier than in desmodium, around 56 DAP at about 150 mg C m^{-2} h^{-1} in the 75,25 (75% FYM, 25% Inorganic) fertilizer rates, before decreasing toward harvest. N_2O emissions showed a distinct temporal pattern**,** with the highest flux observed immediately after fertilizer application at 0 days after planting (DAP)**.** The 75,25 (75% FYM + 25% inorganic fertilizer) treatment recorded a peak emission of 150 µg N m^{-2} h^{-1}**,** followed by a sharp decline by day 14, after which fluxes remained near zero for the remainder of the season, except for a minor rise of 35 μg N m^{-2} h^{-1} around day 154 in the same treatment.

4.7.2 Cumulative Greenhouse Gas Emissions

Figure 14b, shows the cumulative GHG emissions as observed under the desmodium and maize crops during the study period. Cumulative CH_4 fluxes were low and did not differ significantly between the two crops ($p = 0.89$), fertilizer treatments ($p = 0.54$), or their interaction ($p > 0.05$). Mean values for both crops ranged approximately from −1 to +1 kg CH_4-C ha^{-1}, with overlapping standard-error bars across all treatments. Cumulative CO_2 emissions were significantly higher under the desmodium crop than under the maize crop ($p = 0.0054$). Cumulative CO_2 emissions under Desmodium ranged from 4500 to 5300 kg CO_2-C ha^{-1}; higher than that under maize, which ranged between 3700 and 5,000 kg C ha^{-1}. No fertilizer treatment effects ($p = 0.222$) were observed in cumulative CO_2 fluxes under both crops. Similarly, no interactions ($p = 0.115$), in CO_2 emissions were observed between crop and fertilizer.

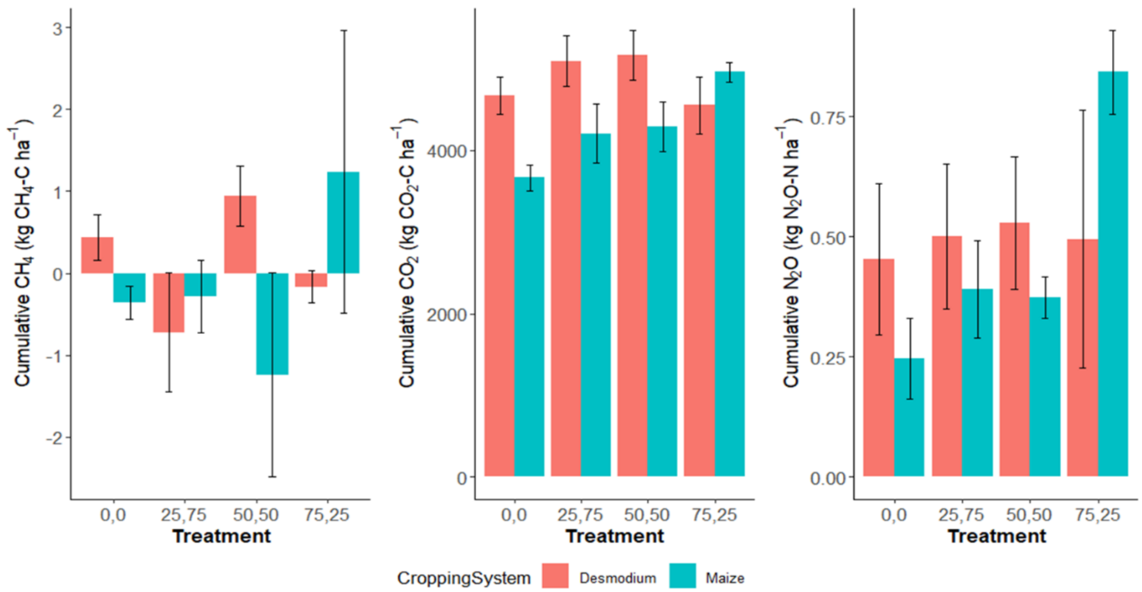

Figure 14b: Cumulative CH_4, CO_2 & N_2O under maize and Desmodium crops during the study period up up-scaled to a year. The treatment 50,50 refers to 50% FYM and 50% Inorganic fertilizer, and analogously for the other treatments.

4.7.3 Greenhouse Gas Emissions Intensities under the different crops

Table 3 below shows greenhouse gas emission intensities under desmodium and maize crops, respectively. Under the desmodium crop; Desmodium yields, showed a strong positive response to increasing FYM substitution ($p < 0.0001$), rising from 2.8 t ha^{-1} in the control (0,0) to 8.9 t ha^{-1} under the 75,25 (75% FYM, 25% Inorganic), treatment**.** N_2O EF were 0.15 to 0.18 % ($p = 0.88$). Despite the relatively low emissions, Net Global Warming Potential (Net-GWP) did not differ significantly among treatments, ranging from 4690 to 5340 Mg CO_2-eq ha^{-1} ($p = 0.49$)**.** However, the sharp increase in yield substantially reduced Greenhouse Gas Intensity (GHGI) from 1706 kg CO_2-eq kg^{-1} yield at 0,0 to 520 kg CO_2-eq kg^{-1} yield under 75,25 ($p < 0.0001$). Similarly, yield-scaled N_2O emissions (YSE) ranged between 0.05 and 0.16 g N_2O–N kg^{-1} yield and did not differ significantly among treatments ($p = 0.23$), reflecting a consistent N_2O emission efficiency across the FYM substitution gradient.

Table 3. Maize & Desmodium, Yield-scaled N_2O emission (YSE), N_2O emission factors (EFs), net global warming potential (netGWP), annual yields, and greenhouse gas intensities (GHGI) under selected soil fertilization treatments.

Treatment	Yield (t ha^{-1})	N_2O EF (%)	Net-GWP (Mg CO_2-eq ha^{-1})	GHGI (Kg CO_2-eq kg^{-1} Yield)	N_2O YSE (g N_2O-N kg^{-1} Yield)
Desmodium					
0,0	2.8 ± 0.05 ^{c}	-	4814 ± 262 ^{a}	1706 ± 131.1 ^{a}	0.16 ± 0.057 ^{a}
25,75	6.3 ± 0.19 ^{b}	0.15 ± 0.15 ^{a}	5216 ± 330 ^{a}	839 ± 69.6 ^{b}	0.079 ± 0.022 ^{a}
50,50	6.1 ± 0.11 ^{b}	0.18 ± 0.14 ^{a}	5344 ± 317 ^{a}	864 ± 36.7 ^{b}	0.085 ± 0.02 ^{a}
75,25	8.9 ± 0.25 ^{a}	0.15 ± 0.27 ^{a}	4692 ± 417 ^{a}	520 ± 38.4 ^{c}	0.054 ± 0.029 ^{a}
p value	*<0.0001*	*0.875*	*0.485*	*<0.0001*	*0.229*
Maize					
0,0	5.5 ± 0.5 ^{ab}	-	3724 ± 161 ^{b}	693 ± 41.3 ^{a}	0.05 ± 0.01 ^{b}
25,75	9.8 ± 0.28 ^{a}	0.041 ± 0.1 ^{b}	4311 ± 388 ^{ab}	438 ± 38.3 ^{b}	0.04 ± 0.009 ^{b}
50,50	10.2 ± 0.32 ^{a}	0.025 ± 0.04 ^{b}	4360 ± 314 ^{ab}	427 ± 41.6 ^{b}	0.04 ± 0.005 ^{b}
75,25	7.3 ± 0.61 ^{b}	0.492 ± 0.08 ^{a}	5239 ± 175 ^{a}	730 ± 77.3 ^{a}	0.12 ± 0.022 ^{a}
p value	*<0.0001*	*<0.0001*	*<0.01*	*<0.001*	*<0.001*

In maize crop. Maize grain yield responded strongly to fertilizer combinations ($p < 0.0001$), recording increasing from 5.5 t ha^{-1} in the unfertilized control to a peak of 10.2 t ha^{-1} at the 50,50 fertilizer combination rates before declining to 7.3 t ha^{-1} at 75,25 fertilizer combination. The N_2O emission factor (EF) was (<0.05 %) for the first three treatments but spiked to 0.49 % at 75,25 ($p < 0.0001$). There was a 40.7% increase in Net-GWP as with values ranging from 3724 Mg CO_2-eq ha^{-1} at 0,0 (control) to 5239 Mg CO_2-eq ha^{-1} at 75,25 (75% FYM, 25% Inorganic) fertilizer rate, ($p<0.01$). Greenhouse-gas intensity (GHGI; kg CO_2-eq kg^{-1} grain) followed an inverse yield pattern, falling from 693 in the unfertilized plots 0,0 to a low of 427 at 50,50, then rising to 730 at 75,25 ($p < 0.001$). Yield-scaled N_2O emissions (YSE) remained low (0.04 and 0.05 g N_2O-N kg^{-1} grain) except at 75,25 (75% FYM, 25% Inorganic), where they tripled to 0.12 g N_2O-N kg^{-1} grain ($p < 0.001$).

4.7.4 Correlation between GHGs & Soil Properties

Figure 15 shows correlation between GHGs and soil properties across all sampling period in desmodium and maize crops. Under desmodium, CH_4 flux correlated positively with N_2O ($r = 0.35$, $p < 0.01$) and NO_3^-–N ($r = 0.31$, $p < 0.1$), but negatively with soil moisture ($r = -0.28$, $p < 0.1$). CO_2 flux displayed a weak association with N_2O ($r = 0.02$) but was positively related to soil moisture ($r = 0.30$, $p < 0.1$), soil C ($r = 0.33$, $p < 0.01$) and P ($r = 0.40$, $p < 0.01$). N_2O flux again showed a strong positive correlation with soil NO_3^-–N ($r = 0.73$, $p < 0.001$). Soil relationships followed: soil moisture positively correlated with pH ($r = 0.59$, $p < 0.001$), soil C ($r = 0.39$, $p < 0.01$) and P ($r = 0.40$, $p < 0.01$).

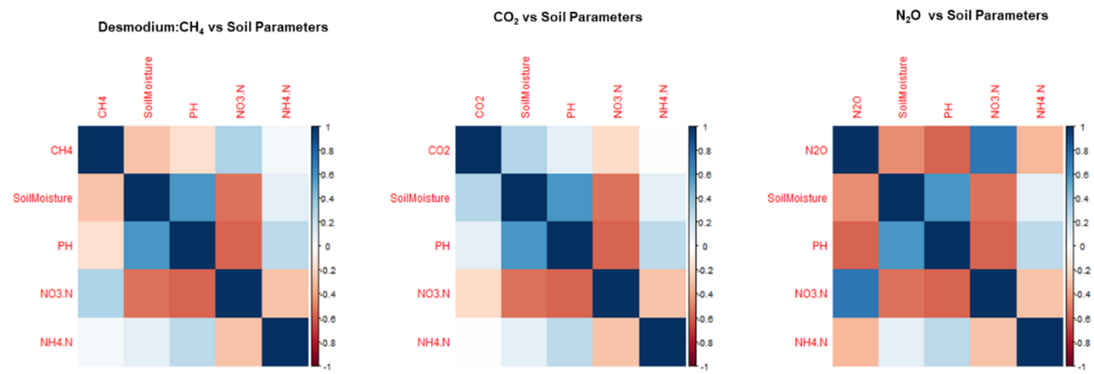

Figure 15: Pearson's correlation coefficients between cumulative GHG emissions (CH_4, CO_2, N_2O) and mean soil parameters (Soil Moisture, NH_4^+, NO_3^-, pH, total N, C and P) averaged across all monthly sampling events under desmodium crop. Blue color for positive and red for negative correlation

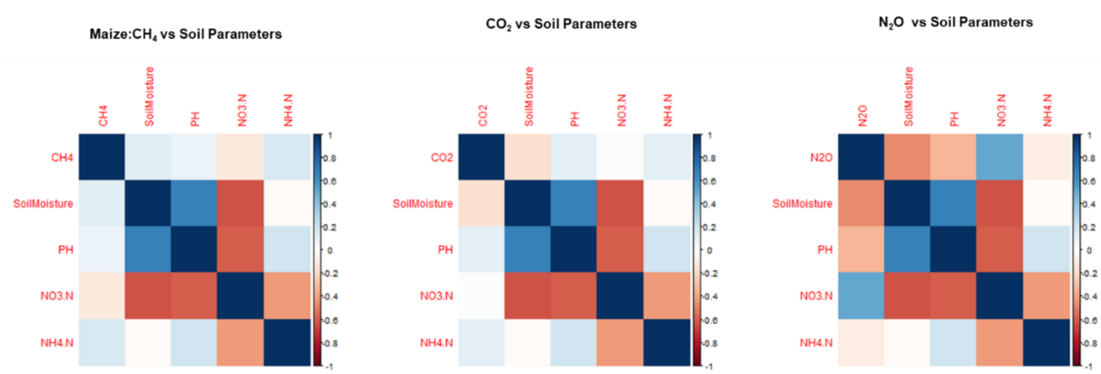

Figure 15 b: Pearson's correlation coefficients between cumulative GHG emissions (CH_4, CO_2, N_2O) and mean soil parameters (Soil Moisture, NH_4^+, NO_3^-, pH, total N, C and P) averaged across all monthly sampling events under maize crop. Blue color for positive and red for negative correlation

For maize, CH_4 flux showed only weak associations with soil factors. Correlations with soil moisture ($r = 0.13$), pH ($r = 0.08$) and NO_3^-–N ($r = -0.11$) were small and not significant, CO_2 flux was moderately and positively related to N_2O ($r = 0.45$, $p < 0.001$) but displayed negligible relationships with soil moisture ($r = -0.17$), NO_3^- ($r = -0.01$) or pH ($r = 0.12$). In contrast, N_2O flux showed clear controls. It correlated positively with soil NO_3^-–N ($r = 0.51$, $p < 0.001$) and negatively with soil moisture ($r = -0.48$, $p < 0.001$) and pH ($r = -0.33$, $p < 0.001$). Soil property interactions followed the same sequence: soil moisture correlated positively with pH ($r = 0.67$, $p < 0.001$), soil C ($r = 0.61$, $p < 0.001$) and P ($r = 0.53$, $p < 0.001$), but negatively with NO_3^- ($r = -0.63$, $p < 0.001$). Higher NO_3^- was in turn associated with lower pH ($r = -0.60$, $p < 0.001$), C ($r = -0.50$, $p < 0.001$) and P ($r = -0.42$, $p < 0.001$).

4.8 Crop Performance and Plant Nutrition

4.8.1 Maize & Desmodium Biomass Yield

a. Maize grain and stovers

Grain yield at Site 1 maize monocrop (Figure 16a) varied significantly across treatments ($p < 0.05$), ranging from approximately 6.5 t/ha in the 0,0 treatment to a peak of about 11.8 t/ha under the 25,75 treatment. Treatments 50,50 and 75,25 followed with roughly 10.5 t/ha and 9.8 t/ha, respectively, while the 100% FYM (100,0) and 100% inorganic (0,100) yielded moderate amounts (9.0 and 8.5 t/ha).

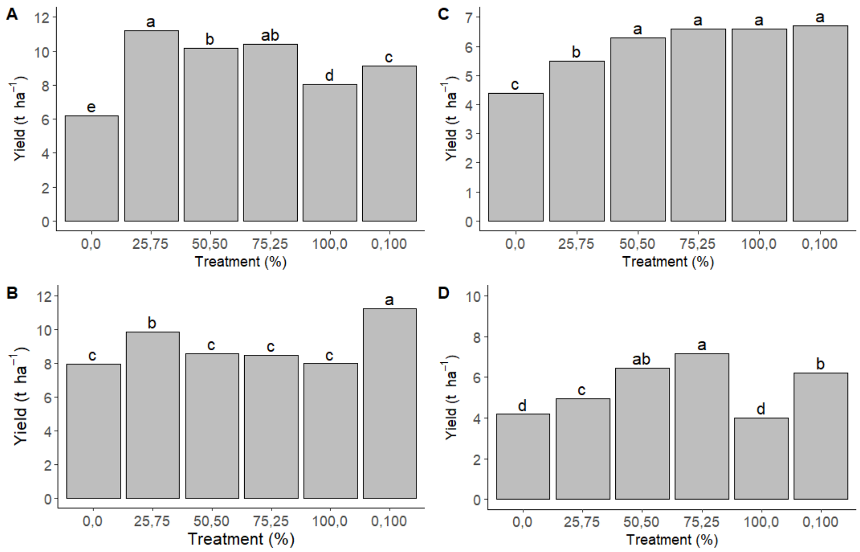

Figure 14: A & B is Site 1 Maize Monocrop and Maize Intercrop Yield, C & D is Site 2 Maize Monocrop and Maize Intercrop Yield, Respectively.

b. **Biomass Yield (t ha¹)**

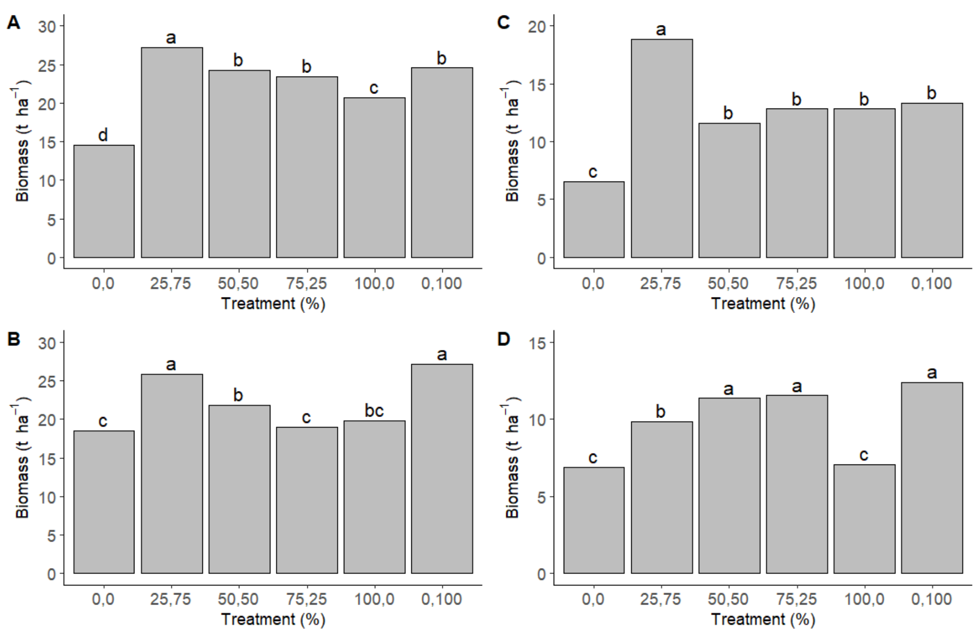

Figure 15: A & B is Site 1 Maize Monocrop and Maize Intercrop Biomass, C & D is Site 2 Maize Monocrop and Maize Intercrop Biomass, Respectively.

Above ground biomass yield followed a pattern similar to grain yield, with the highest values observed under a 25,75 ratio (28 t/ha), significantly higher than the control (0,0, 15 t/ha). Fertilizer rates 50,50; 75,25; and 0,100 all ranged from approximately 22 to 25 t/ha, with the lowest values again seen in the control and FYM-only (100,0) plots (Figure17 a). Biomass in the intercrop system ranged from 19–28 t/ha**,** with the highest values observed under 0,100 and 25,75. Unlike in grain yield, where 0,100 topped the chart, biomass was more evenly distributed across all fertilizer regimes (Fig. 17 b). Biomass yields ranged from 7 to 19 t/ha**,** with 25,75 showing the highest accumulation (19 t/ha), significantly outperforming 0,0 and 50,50 (Fig.17 c). Biomass ranged from approximately 6 to 14 tons per hectare, with the 50,50 and 75,25 fertilizer combinations. producing the highest biomass (13–14 tons per hectare), significantly more than 0,0 and 100,0 (Fig. 17 d).

c. Nitrogen Uptake (kg N ha^{1})

Nitrogen uptake in Site 1 maize monocrops varied significantly ($p < 0.05$) across treatments, with values ranging from approximately 60 kg N/ha (0,0) to about 120 kg N/ha (50,50). The 25,75, and 0,100 fertilizer rates were similar, with roughly 95 and 85 kg N/ha, respectively. In contrast, the lowest uptake was observed under FYM-only (100,0) and no-input (0,0) control (Figure 18 a). The intercrop system showed relatively higher and more consistent N uptake, ranging from about 70 to 110 kg N/ha. The 25,75 and 0,100 fertilizer combinations recorded the highest uptakes (around 105 and 110 kg N/ha), followed by other fertilizer combinations with statistically similar values. The lowest uptake was again observed in the 0,0 treatment (Figure 18 b). In Site 2 maize monocrop, nitrogen uptake ranged from about 60 kg N/ha (0,0) to approximately 90 kg N/ha (50,50, 75,25, 100,0, and 0,100), all of which were statistically similar (Figure 18 c). N uptake was consistently higher across all rates, ranging from approximately 60 kg N/ha (0,0) to around 95 kg N/ha (50,50, 75,25, 0,100). Statistically, all treatments except the control (0,0) and 25,75 performed similarly (**Figure 18d**).

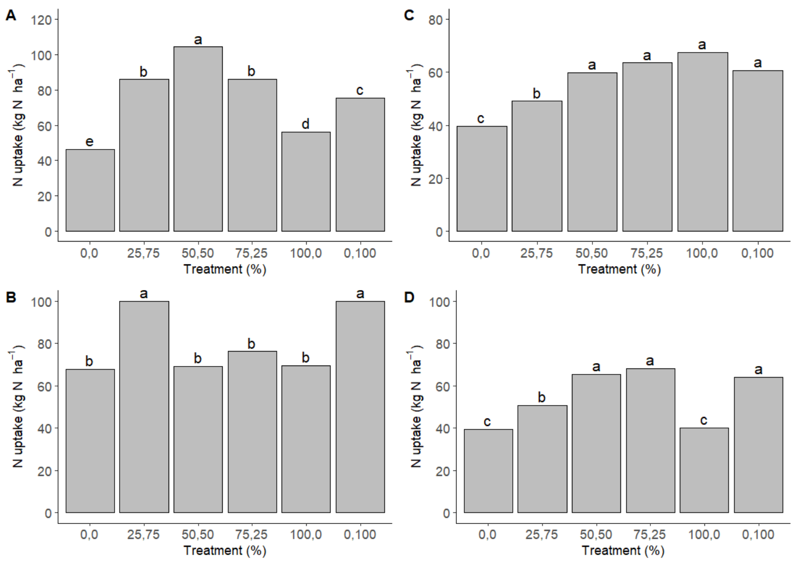

Figure 16: A & B are Site 1 Maize Monocrop and Maize Intercrop N Uptake (kg N ha^{-1}), C & D is Site 2 Maize Monocrop and Maize Intercrop N Uptake (kg N ha^{-1}), Respectively.

d. Phosphorus Uptake (kg P ha^{1})

Phosphorus uptake was significantly influenced by treatment, ranging from approximately 13 kg P/ha (0,0) to about 26 kg P/ha (50,50). The 25,75 and 75,25 fertilizer combinations followed closely at around 22–25 kg P/ha, while 100,0 and 0,100 recorded slightly lower uptakes, roughly 17–20 kg P/ha (Figure 19 a). Phosphorus uptake in the intercrop system showed less variation between treatments, with the 0,100 (inorganic only) treatment having the highest uptake (27 kg P ha^{-1}), significantly exceeding the 50,50 and 75,25 fertilizer rates (19–21 kg P ha^{-1}) (Figure 19 b). The other treatments ranged from 20 to 25 kg P/ha.

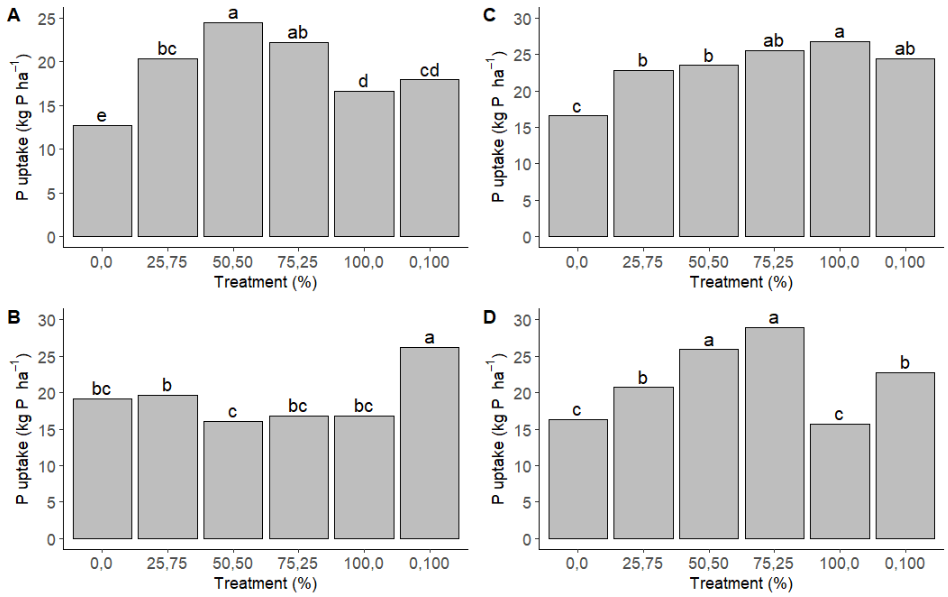

Figure 17: A & B is Site 1 Maize Monocrop and Maize Intercrop P Uptake (kg P ha^{-1}), C & D is Site 2 Maize Monocrop and Maize Intercrop P Uptake (kg P ha^{-1}), Respectively.

P uptake ranged from approximately 16 kg/ha (0,0) to 27 kg/ha (75,25) (Figure 19c), with all treatments, including FYM (50,50, 75,25, 100,0), performing well. The consistent results across different FYM ratios also suggest that even moderate levels (25,75, 50,50) are sufficient to significantly increase P uptake, especially when FYM improves soil structure and microbial phosphorus cycling.

In Site 2 intercrop, P uptake was highest under the 75,25 and 50,50 fertilizer rates (28–30 kg/ha), significantly greater than under the 0,0 and 100,0 treatments (17 kg/ha) (Figure 19 d).

e. Desmodium Biomass Yield

At Site 1, Desmodium yield varied significantly **(**p < 0.0001**)** across treatments and cropping systems. Under sole cropping, yield ranged from 1.46 t/ha (0,0) to a maximum of 5.39 t/ha (50,50)**.** The highest yield under intercrop was observed with 0,100 (FYM) at 3.52 t/ha**,** followed by 25,75 (2.51 t/ha) and 50,50 (2.34 t/ha) (Figure 20 A)**.** Notably, intercropped Desmodium in the control (0,0) recorded the lowest yield (0.77 t/ha), indicating the necessity of nutrient input.

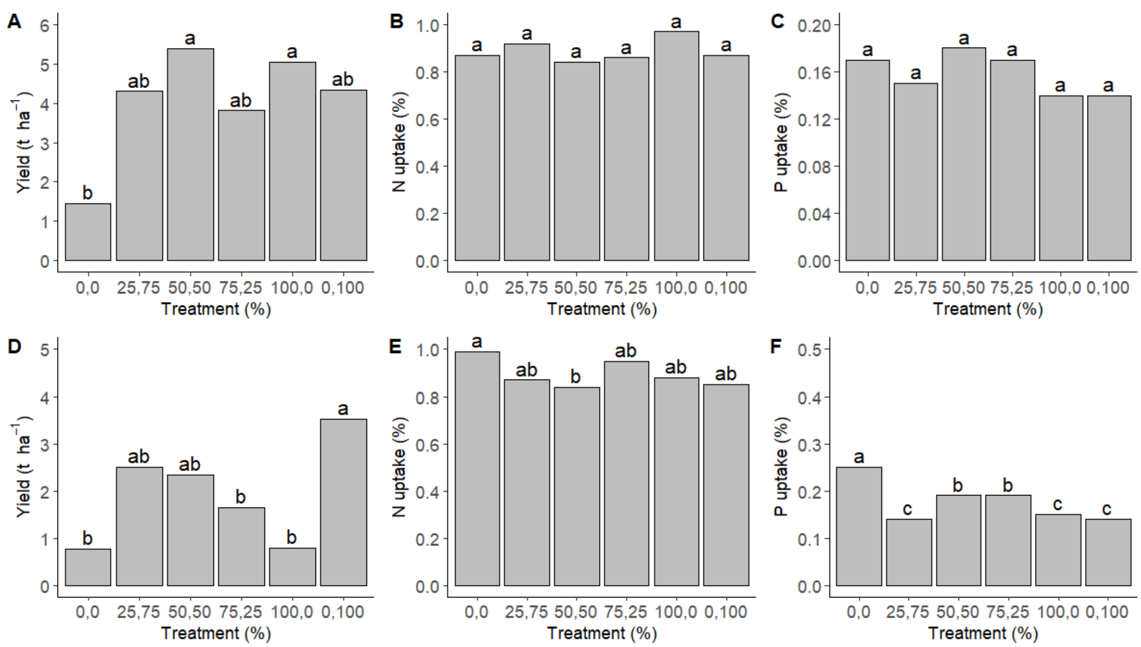

Figure 18: A-Yield (t/ ha^{-1}), B- N Uptake (kg N ha^{-1}), C- P Uptake (kg P ha^{-1}) for Site 1 Desmodium Monocrop and D- Yield (t/ ha^{-1}), E- N Uptake (kg N ha^{-1}), F- P Uptake (kg P ha^{-1}) for Desmodium Intercrop.

The significant interaction between Treatment × Cropping System (p < 0.0001) and fertilizer Treatment × Site (T × S; p < 0.0001) further confirms variability in Desmodium response due to cropping arrangements and edaphic conditions.

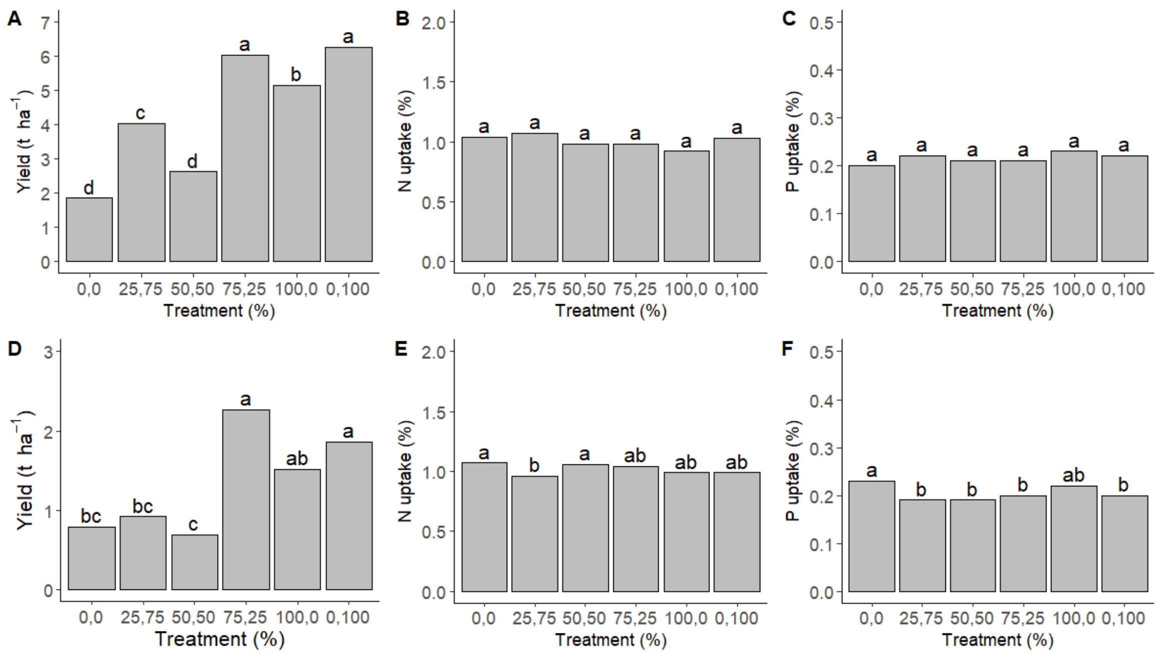

Figure 21: A-Yield (t/ ha^{-1}), B- N Uptake (kg N ha^{-1}), C- P Uptake (kg P ha^{-1}) for Site 2 Desmodium Monocrop and D- Yield (t/ ha^{-1}), E- N Uptake (kg N ha^{-1}), F- P Uptake (kg P ha^{-1}) for Desmodium Intercrop.

f. **Nitrogen Uptake (% N)**

In site 1 (Figure 20 b), nitrogen uptake was statistically not significant across treatments or systems **(**p = 0.233**),** suggesting relatively uniform %N in Desmodium tissues. However, numerically, sole Desmodium under 50,50 had the highest %N **(**0.18%**)** followed closely by 0,0 and 75,25 (both 0.17%)**,** while intercrop systems ranged between 0.14% (0,100 and 25,75) and 0.19% (50,50, 75,25**)**.

In Site 2 (Figure 21 e), a statistically significant site effect was observed (p < 0.0001)**,** with generally higher N content in intercrops **(**mean = 1.01%**)** compared to sole crops **(**0.89%**).** The highest N uptake was observed under intercrop with 50,50 and 75,25, both at 1.06–1.04%**,** whereas the lowest was under sole cropping at 0,100 (0.97%)**.**

g. **Phosphorus Uptake (% P)**

Phosphorus uptake was significantly affected by treatment ($p < 0.0001$), site ($p < 0.0001$), and T × CS ($p < 0.0001$), reflecting the sensitivity of Desmodium P content to both nutrient inputs and environment. At site 1 (Figure 20 c & f), the highest P uptake in sole Desmodium was under 0,0 (0.87%), with slightly lower values under 50,50 (0.84%) and 75,25 (0.86%). In intercrops, 0,0 and 0,100 had the highest P uptake (1.04 and 1.03%, respectively). Despite being the lowest yield treatment, control (0,0) had relatively high P %.

At Site 2 (Figure 21 c & f), both sole and intercropped Desmodium showed high P uptake across the fertilizer regimes, ranging between 0.20–0.23%. Notably, 0,0 still exhibited the highest %P in monocrop (0.99%) and intercrop (0.23%).

4.9 Nutrient Use Efficiency

4.9.1 Agronomic efficiency (AE)

The highest N agronomic efficient (AE) observed at 25,75 (40 kg grain/kg N), significantly outperformed both 100,0 and 0,100. Sole FYM (100,0) had the lowest AE. The 0,100 and 50,50 treatments showed similar intermediate AE (25–30 kg/kg). In the intercrop, fertilization regime 0,100 had the highest AE (42 kg/kg), followed by 25,75 (35 kg/kg) and 50,50 (30 kg/kg). Surprisingly, intercrop AE decreased under FYM-rich treatments (75,25, 100,0) (Figure 22).

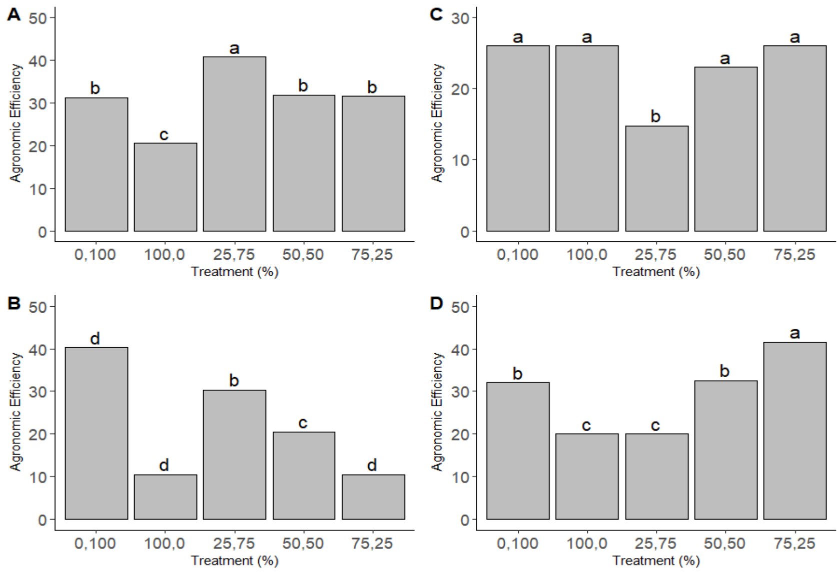

Figure 19: A & B is Site 1 Maize Monocrop and Maize Intercrop Agronomic Efficiency, C & D is Site 2 Maize Monocrop and Maize Intercrop Agronomic Efficiency Respectively.

The higher AE at 0,100 for the intercrop may reflect the legume's contribution to soil fertility through biological nitrogen fixation (BNF), reducing reliance on external N. At site 2 for maize monocrop, (Figure 22), AE was highest in the 25,75 and 75,25 combinations (around 35 kg/kg), followed by the 50,50 ratios (about 30 kg/kg). The 100,0 ratio had the lowest AE (around 15). The performance of the 25,75 and 75,25 ratios confirms that combining fast-acting N.

At site 2 intercrop (Figure 22 D)**,** the 75,25 fertilizer combinations showed the highest AE (40 kg/kg), while the 25,75 and 50,50 ratios ranged from 25 to 30. FYM-only and 0,100 had poor AE,

4.9.2 Recovery Efficiency (RE)

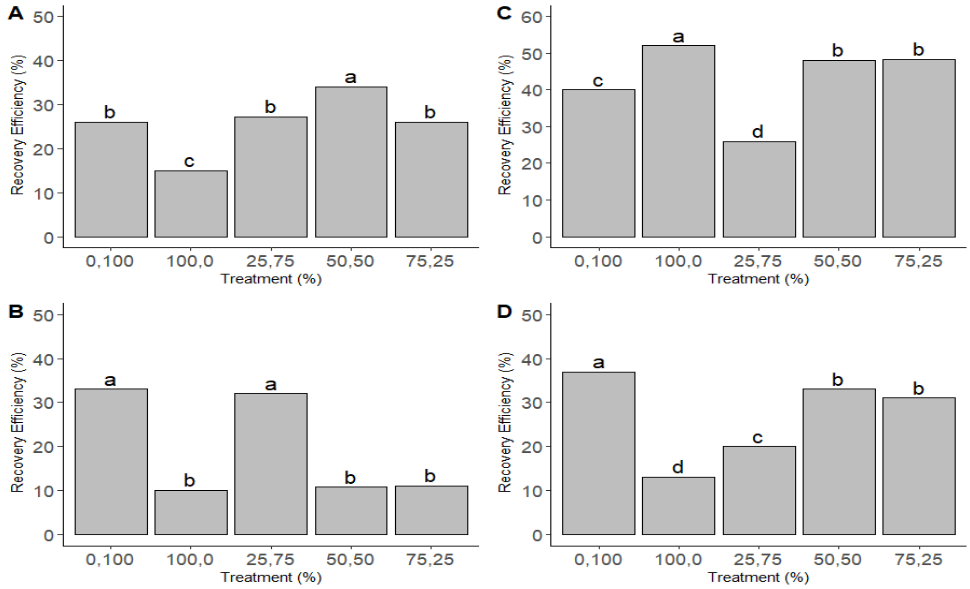

Figure 23: A & B is Site 1 Maize Monocrop and Maize Intercrop Agronomic Efficiency, C & D is Site 2 Maize Monocrop and Maize Intercrop Recovery Efficiency Respectively.

The highest RE in maize monocrop (Figure 23 a)**,** (45%) occurred under a 25,75 substitution, followed closely by 50,50 and 0,100 (35–40%)**.** 100,0 had the lowest RE (20%). RE in maize intercrop (Figure 23 b)**,** peaked at 50,50 (around 55%), followed by 25,75 and 0,100 (about 45%). 100,0 and 75,25 showed the lowest RE. In site 2 maize monocrop (Figure 23 c)**,** 0,100 and 25,75 fertilizer combinations had the highest RE (35%), making them statistically superior to other treatments. RE under 100,0 and 75,25 was again the lowest (15%), similar to trends at Site 1. In drier or cooler conditions (Site 2). Maize intercrop in site 2 (Figure 23 d)**,** RE peaked at 0,100 (40%)**,** followed by 50,50 and 75,25 (35%)**.** 100,0 had the lowest RE (15%)**,** while 25,75 was also lower (25%).

CHAPTER FIVE

DISCUSSIONS

5.1 NO_3-N Concentration

Despite visually observed differences across treatments or cropping systems (e.g., higher NO_3^- under maize or inorganic fertilizer), these differences are not statistically reliable ($P>0.05$). Similar findings were noted by (Yao *et al.,* 2019) in short-duration maize-legume systems, where rapid plant uptake and denitrification offset expected nitrate build-up under N-rich treatments. Rate 0,100 (100% inorganic) and 25,75 (25% FYM, 75% inorganic) recorded the highest early-season nitrate levels, particularly in maize plots and suggesting a rapid urea hydrolysis and subsequent nitrification, which results in substantial nitrate buildup before full canopy development. However, such peaks were short-lived, likely due to nitrate leaching or gaseous losses via denitrification under moist conditions. In contrast, fertilizer rate 75,25, and 100,0 (FYM-dominant treatments) demonstrated moderate and more stable NO_3^- curves**.** This slower release pattern reflects the mineralization of organic N from FYM**,** which improves nitrogen synchrony with plant demand and minimizes losses. The control (0 0)**,** which received no fertilizer, maintained the lowest NO_3^- concentrations, consistent with nutrient limitation and limited N turnover. The 50,50 combination, balanced both rapid mineral N supply and a steady release from FYM, showing intermediate nitrate trends. These findings align with (Sahoo *et al.,* 2022), who reported that mineral fertilizers such as urea drive nitrate surges early in the season, often exceeding crop demand, while FYM buffers this release over time.

The sole maize system showed the highest NO_3^--N concentrations, especially at 0–20 cm and during DAP 30–90. The most pronounced peaks occurred under 0,100 and 25,75 fertilizer rates, reflecting high external N input and intense early demand by the fast-growing maize crop. However, where FYM was limited, the nitrate spike was not efficiently buffered, increasing the risk of nitrate leaching and gaseous losses. In FYM-rich treatments, notably 50,50 and 75,25, maize plots still recorded high nitrate levels though with a more gradual decline. Desmodium plots consistently had lower NO_3^- levels, with smaller fluctuations throughout the season. These patterns suggest efficient nitrate uptake, likely aided by symbiotic nitrogen fixation, which may reduce the plant's reliance on mineral N from soil pools. The peak under desmodium often occurred later reflecting a delayed mineralization effect under lower microbial turnover or slower N demand. At 20–40 cm, NO_3^- was consistently lower, further supporting the idea that desmodium helps retain nitrogen in the upper soil layers, potentially via denser root mats or reduced leaching. Intercrop systems exhibited intermediate nitrate concentrations, particularly under the 50,50 and 75,25 combinations. The presence of desmodium likely contributed to a buffered N dynamic, reducing NO_3^- accumulation compared to sole maize. This may reflect a complementarity in nutrient use: maize capitalizes on quick-release N while desmodium relies on symbiotic N or slower-release FYM N. This observation supports work by (Giller & Cadisch, 1995), who demonstrated that legume-cereal intercrops can improve nutrient-use efficiency and reduce nitrate loss.

Nitrate accumulation is controlled by the oxidation of ammonium (NH_4^+) through nitrifying bacteria, a process that is quick in aerated, warm soils with enough substrate (urea, FYM). In this experiment, the rapid increase in 0,100 and 25,75 under maize confirms effective nitrification but also raises concerns about leaching and denitrification, especially in wet conditions with high NO_3^- loads. As observed, desmodium and intercrop systems exhibited better nitrate regulation, likely due to slower N turnover and biological nitrogen fixation (BNF) that matched plant demand.

5.2 NH_4^+-N Concentration

The cropping system had a highly significant effect on NH_4^+, indicating that the type of cropping system (maize, desmodium, or intercrop) significantly influenced ammonium levels, with desmodium and intercrop systems often showing higher residual NH_4^+ than maize due to moderated nitrification and improved nitrogen retention. These findings align with (Li *et al.,* 2019)who reported increased NH_4^+ retention in legume-intercropped systems.

Ammonium-N levels fluctuated over time as shown in figure 7 and 8, with peaks observed between DAP 60 and 90. These peaks aligned with periods immediately after basal fertilizer application and the first topdressing, both of which involved urea. The surface soils showed values were generally lower, indicating limited vertical movement and more microbial activity in the upper layer. After DAP 120, a gradual decrease in NH_4^+ concentrations were observed across all cropping systems and sites. This suggests increased nitrification, where ammonium is converted to nitrate (NO_3^-), along with greater root uptake during mid- to late-vegetative and reproductive crop stages. This pattern is typical of upland soils with urea-based fertilizers, where NH_4^+ is a temporary nitrogen form, quickly converted under aerobic conditions (Subbarao *et al.,* 2007).

Treatment 100,0 (FYM-only) and 75,25 (75% FYM + 25% inorganic) combinations consistently recorded the highest NH_4^+ concentrations. This was attributed to the slow mineralization of organic N compounds in FYM, which provides a continuous and regulated release of NH_4^+. In addition, urea applied in smaller doses in 75,25 would contribute to short-term spikes, followed by mineralization-derived NH_4^+ from FYM decomposition. Fertilizer treatments 0,100 (100% inorganic) and 0,0 (no fertilizer) had the lowest NH_4^+ levels throughout the season. The rapid hydrolysis of urea in 0,100 may have contributed to a short-lived NH_4^+ pulse, with quick conversion to NO_3^-, while 0,0 lacked any external N inputs altogether. The 25,75 and 50,50 fertilizer rates demonstrated intermediate values, highlighting the balance between fast-release urea and the gradual mineralization of FYM. These observations are consistent with the findings of (Aboyeji *et al.,* 2019), who reported elevated NH_4^+ levels under organic amendments due to continuous mineralization and microbial biomass turnover.

Maize plots showed early peaks in NH_4^+ followed by a sharp decline by at later dates, especially in the 0 100, 100 0, 25 75, and 75 25 fertilizer combinations. The decline was more noticeable at Site 2, indicating either more efficient plant uptake or faster nitrification rates. Maize's quick early biomass growth contributed to this pattern, as roots rapidly deplete available nitrogen in the upper soil layer. This trend underscores a risk of nitrification-driven N loss, particularly under high urea application with limited organic matter buffering.

Desmodium systems maintained higher NH_4^+ concentrations for a longer period into the season, especially under 25,75, 75,25, and 100,0 fertilizer rates. The NH_4^+ concentrations peaks indicates reduced nitrification rates, due to the presence of biological nitrification inhibitors released by legumes, as suggested by (Subbarao *et al.,* 2007). Desmodium's ability to fix atmospheric nitrogen may decrease competition for soil NH_4^+, allowing it to persist longer.

The maize-desmodium intercrop showed intermediate NH_4^+ levels. The dynamics demonstrate complementary nitrogen use, with maize utilizing rapid-release urea-derived N and Desmodium maintaining N availability through slow mineralization and symbiotic fixation. The result is stabilized NH_4^+ concentrations, preventing extremes seen in either monoculture. Additionally, this cropping system showed sustained NH_4^+ availability beyond DAP 120, which may have contributed to reduced nitrate leaching and improved nitrogen-use efficiency.

The NH_4^+ concentrations were consistently higher in the 0–20 cm soil layer, where most fertilizer was applied and microbial activity is focused. At 20–40 cm, levels were generally lower, with limited evidence of vertical NH_4^+ movement. This is attributable to NH_4^+ being strongly adsorbed onto soil colloids thereby limiting leaching.

5.3 Soil pH

Fertilizer treatment significantly affected soil pH with FYM-based treatments maintaining higher pH levels, while plots receiving 100% inorganic N (urea) showed lower pH, consistent with urea-induced acidification during nitrification (Zhou *et al.,* 2017). A significant interaction between fertilization regime (rate) and cropping system, suggests that desmodium-based systems better buffered soil acidity than sole maize under similar fertilization, likely due to rhizobial activity. Soil pH was slightly lower in deeper layers, consistent with leaching of acidic ions and less buffering by organic residues concentrated in surface layers. These findings align with (Girma *et al.*, 2020), who observed that organic amendments improved pH buffering in acid-prone tropical soils. The application of urea and TSP raises H^+ concentration through nitrification and phosphate fixation, contributing to soil acidification. In contrast, FYM increases soil pH by adding base cations (Ca^{2+},

Mg^{2+}), enhancing cation exchange capacity (CEC), and stimulating microbial CO_2 release and carbonate buffering.

Soil pH values across all cropping systems ranged from 5.0 to 6.5, placing the soils in the slightly acidic to near-neutral range. These values fall within the tolerable range for most crops grown in tropical and sub-tropical soils, including maize and desmodium. Throughout the cropping season, a trend of pH increase was observed around DAP 90 and DAP 180, coinciding with topdressing fertilizer applications. These increases reflect the alkaline buffering capacity of organic inputs, particularly FYM, and the potential lime-equivalent effect of certain microbial processes following organic carbon addition. Among the fertilizer treatments, plots amended with higher FYM to inorganic combinations (75,25 and 100,0) consistently maintained higher soil pH, especially in desmodium and intercrop systems. This pH increase is linked to the addition of basic cations (Ca^{2+}, Mg^{2+}, K^+, and Na^+) through organic matter, which neutralize H^+ ions and reduce soil acidity (Girma *et al.*, 2020).

Plots with 100% inorganic fertilization (0,100), especially in maize monoculture, showed acidification, with pH values nearing the lower limit of 5.0 at greater depths. This acidification is a known result of urea hydrolysis and subsequent nitrification, which releases hydrogen ions (H^+) during the oxidation of NH_4^+ to NO_3^- (Zhou *et al.*, 2017). When inorganic fertilizers are applied alone and without organic buffers, they contribute to long-term pH decreases, increasing the risk of aluminum toxicity and reduced phosphorus availability in highly weathered tropical soils.

Desmodium plots consistently exhibited the highest pH values**,** especially in surface soils, regardless of fertilizer treatment. It´s dense canopy and organic root exudates may buffer pH fluctuations through enhanced microbial and rhizosphere processes. Maize plots**,** particularly under fertilization rates like 0,100 and 25,75, exhibited the lowest pH values, likely due to high N uptake and strong acidification effects of urea**.** The intercrop system consistently maintained intermediate pH values**,** suggesting functional complementarity between maize and desmodium. Several studies support these findings. For instance, (Zhou *et al.,* 2017) found significant pH reductions in maize systems under sole urea application, while (Haynes & Mokolobate., 2001), observed long-term buffering benefits of organic amendments on pH in acid tropical soils.

5.4 Available Phosphorus

Fertilizer treatments had a statistically significant effect on available phosphorus at 0–20 cm in Site 1, where FYM-rich plots (75,25 and 50,50) exhibited higher P levels. This suggests improved P solubilization from FYM, which supports microbial phosphate mobilization (Richardson & Simpson, 2011). At deeper depths and in Site 2, differences were not significant, indicating that P dynamics are localized at the surface as shown in Figure 11. The most notable increases occurred in the 0–20 cm depth, indicating surface enrichment from fertilizer application and organic matter decomposition. P values are within or above the critical threshold of approximately 10 mg/kg Bray I-P, which is generally required for optimal crop growth in tropical soils (Nziguheba *et al.*, 2016).

Soils under 50,50 and 75,25 fertilizer regimes consistently recorded the highest available P, in Site 1 and slightly lower in Site 2. This increase is scientifically attributed to the organic matter content in FYM, which releases organic acids during decomposition. These acids solubilize bound phosphorus, especially in acidic and weathered soils (Bolan et al., 1994), and also enhance microbial activity, which mineralizes organic P compounds. FYM only; 100,0 also improved P levels but showed slower increases, while 0,100 (Inorganic only) had lower P values at all stages and depths. This is due to rapid phosphate fixation and the lack of organic chelating agents. In 0,0 control, P remained lowest, confirming that nutrient depletion occurs rapidly without supplementation.

Desmodium plots consistently maintained higher available P, especially at the 0–20 cm depth. Peak values in 75,25 and 50,50 at DAP 150, declining slightly to at harvest. This trend is explained by rhizosphere acidification, a known trait in legumes, which releases root exudates (e.g., citrate, malate) that mobilize phosphorus (Bhuyan *et al.*, 2020). In addition, biological nitrogen fixation enhances overall microbial biomass, further promoting mineralization of organic P. The intercrop exhibited intermediate but stable P concentrations. The shared root systems and complementary nutrient uptake between the two species likely minimized competitive depletion. Desmodium's root activity may have created localized phosphorus hotspots that maize could access. This is supported by (Zhang & Li., 2003), who found that intercropping legumes with cereals improves P acquisition via rhizosphere interactions. Sole maize systems showed greater variability and faster P decline, particularly by DAP 180–210, even under 50,50 and 75,25, suggesting higher uptake and less P recycling. Deeper layers (20–40 cm) under maize often remained low. This trend aligns with maize’s high P demand during grain filling, coupled with a more limited root exudate capacity for solubilizing bound P.

5.5 Soil Total Nitrogen

There were no statistically significant differences in total soil nitrogen across treatments at either depth or site. However, numerical means suggested that the 75,25 and 50,50 fertilizer rates consistently maintained higher nitrogen values across depths. Although these differences were not statistically significant, the observed trends align with findings by (Getaneh *et al.*, 2024), who reported that balanced FYM-inorganic combinations enhance N retention due to gradual mineralization. The significant effect of replication indicates environmental heterogeneity across blocks, which is common in field experiments and highlights the importance of randomization and replication.

Total nitrogen (%) exhibited a clear temporal pattern across all cropping systems and treatments as shown in (Figure 12). The initial values at DAP 0 were relatively consistent and low, reflecting the pre-fertilization condition. Nitrogen concentrations rose by DAP 90, aligning with fertilizer topdressing and peak vegetative growth. A peak in total N was consistently observed around DAP 150, likely indicating active nitrogen cycling, root exudation, and microbial activity. Subsequently, N levels declined toward DAP 210 (harvest), suggesting nitrogen uptake by crops, immobilization, or losses through leaching or gaseous emissions. The 0–20 cm depth consistently showed higher nitrogen percentages than the 20–40 cm layer across all treatments, cropping systems, and sites. This pattern reflects fertilizer application at the surface, heightened microbial activity, and increased root biomass in the upper horizon, all influencing nutrient dynamics (Singh *et al.*, 2006).

The 50,50 (50% FYM + 50% inorganic) and 75,25 fertilizer combinations maintained the highest total N concentrations throughout the season. This trend was observed across both depths and both sites**,** indicating a consistent response to balanced organic–inorganic fertilization. The superior performance of 50,50 and 75,25 can be attributed to synchronized nutrient release**,** where FYM provides sustained mineralization of organic N, while inorganic N offers readily available ammonium or nitrate forms during critical growth stages (Palm *et al.*, 2001). In contrast, 0,0 (no fertilizer) and 0,100 (sole inorganic) plots consistently had lower total nitrogen values across the season. In the 0,0 treatment**,** the lack of N input likely limited mineral availability. Meanwhile, 0,100 exhibited sharp declines post-DAP 90, especially in maize systems, likely due to leaching losses or rapid plant uptake outpacing replenishment, a common issue with sole urea application in tropical soils (Aulakh & Bijay-Singh, 1997).

Desmodium plots consistently recorded higher nitrogen concentrations, especially in the surface layer (0–20 cm) as shown in Figure 12. This is due to symbiotic nitrogen fixation via rhizobia, which is supported by FYM application, enhancing microbial biomass and nodulation. The gradual N buildup from DAP 0 to 150 reflects active fixation, as previously reported by (Freyer & Bingen, 2021) mirrors the slow-release nature of FYM. Even the 0,0 desmodium plots maintained relatively stable N levels compared to maize, emphasizing the self-fertilizing benefit of legumes. The intercrop system exhibited intermediate but stable nitrogen levels, closer to desmodium than maize. Total N increased steadily with DAP, particularly under the 50,50 and 75,25 fertilizer rates. The legume component likely enhanced N retention through reduced leaching and complementary uptake, where desmodium fixed N_2 and maize accessed mineral N. These trends are supported by previous findings by (Giller & Cadisch, 1995) on legume-cereal complementarity in improving soil N status and cycling. Maize plots had lower total N, especially under 0,0 and 0,100 rates, with a sharper decline after DAP 150. Without a slow-release source like FYM or support from symbiotic fixation, N was rapidly depleted or lost via leaching, as seen in similar upland maize systems. Only the 50,50 and 75,25 fertilizer combinations buffered against this decline, reinforcing the benefit of organic input.

Site-level comparisons showed similar trends in both locations, although Site 1 often had slightly higher total N, possibly due to better organic matter content and baseline fertility. The combined use of FYM and Inorganic fertilizers, provides a synchrony of release and uptake**,** improving nitrogen recovery efficiency. Desmodium's role in biological N fixation (BNF)**,** as documented by Jin *et al. (*2024), adds to the available N pool and reduces dependency on external inputs. The sole application of inorganic N (urea) is known to result in acidification, volatilization, and leaching losses (Zhou *et al.,* 2017), which explains the lower residual N in the 0 and 100 treatments.

5.6 Soil Total Organic Carbon

Soil organic carbon was minimally impacted by fertilizer treatments at both depths. Treatments with higher FYM clearly supported carbon buildup, in line with (Congreves *et al.,* 2014), who found that FYM promotes stable carbon pools in agroecosystems. Site 1 generally exhibited slightly higher SOC than Site 2 across treatments and cropping systems, especially at DAP 90 and 150, suggesting better baseline fertility or a stronger organic matter response to FYM at that site. In both locations, the 0–20 cm layer contained more carbon than the 20–40 cm layer, primarily due to surface-focused FYM application and limited carbon leaching. Subsoil organic matter buildup was limited by microbial activity and slower FYM infiltration.

Soil organic carbon (SOC) values exhibited temporal fluctuations throughout the cropping season, with notable spatial differentiation by depth and site. Across all cropping systems and treatments, SOC was consistently higher at 0–20 cm than at 20–40 cm, indicating surface dominance of organic matter from applied FYM and plant residues. Fertilizer treatments had a pronounced influence on soil carbon levels. Plots receiving high FYM inputs, 75,25 (75% FYM) and 100,0 (100% FYM)**,** recorded the highest SOC concentrations, in topsoil by DAP 150, particularly under Desmodium and intercrop systems.

FYM contributes to both labile carbon pools**,** which drive microbial activity, and recalcitrant fractions, which support long-term C sequestration and soil structure. This is consistent with findings by (Palm *et al.,* 2001), who emphasized the role of FYM in enhancing SOC and soil aggregation. Conversely, plots under 0,0 (no fertilizer) and 0,100 (100% inorganic fertilizer) had the lowest SOC values across all sites and depths, generally remaining very low. These treatments lacked organic inputs, and the microbial stimulation from urea alone was insufficient to sustain carbon accrual. The 25,75 and 50,50 fertilizer rates, which combined FYM with mineral fertilizers, showed intermediate SOC levels reflecting balanced organic matter input and mineralization**.**

The Desmodium cropping system consistently exhibited the highest SOC values, especially at the 0–20 cm depth and during the mid-season (DAP 90–150). Peak SOC levels in desmodium plots with 75,25 and 100,0 which was significantly higher than maize or intercrop. This is likely due to the legume's root network, biological nitrogen fixation, and rhizo-deposition of organic compounds into the rhizosphere (Drinkwater *et al.,* 1998). Additionally, Desmodium typically has slower decomposition rates and high carbon-to-nitrogen ratios, contributing to prolonged carbon retention in the soil. The intercrop system showed moderate SOC values, in surface soils. Intercrop plots benefited from root complementarity, with Desmodium adding extra organic matter and slowing decomposition. The FYM-rich combinations under intercropping (50,50 and 75,25) maintained stable SOC levels throughout the season. This finding aligns with those of (F.

Zhang & Li, 2003), who reported improved carbon dynamics in cereal-legume intercrops due to enhanced nutrient efficiency and increased belowground carbon input. Sole maize plots had the lowest SOC content, especially under 0,0 and 0,100 fertilizer rates. Maximum values were rarely exceeded at DAP 150, and subsoil values dropped. Maize's high nutrient uptake, faster residue decomposition, and lower biomass returned to the soil (especially when stover is removed) result in lower organic carbon retention. In FYM-treated plots (50,50 and 75,25), SOC levels improved, but remained lower than desmodium because of differences in root exudation and residue quality.

5.7 Greenhouse Gas Emissions

5.7.1 Methane, Carbon Dioxide and Nitrous Oxide emissions

Across all treatments, cumulative CH_4 emissions were very low, confirming that both desmodium and maize crops are effectively methane-neutral. Desmodium crop showed slight positive seasonal totals of about 1 kg CO_2-C ha^{-1} under the control and 50,50 (50% FYM, 50% inorganic) treatments, whereas maize crop acted largely as a CH_4 sink, particularly at 50,50 substitutions. These findings agree with upland agriculture studies in Kenya that reported near-zero or negative CH_4 fluxes under well-drained soils (Maaz et al., 2021) showing that legume-based systems typically act as small CH_4 sinks due to active methanotrophy (Raji & Dörsch, 2020). The consistency of low CH_4 flux across the fertilizer gradient underscores that organic–inorganic substitutions, including the 25,75 (25% FYM, 75% inorganic), 50,50 (50% FYM, 50% Inorganic), and 75,25 (75% FYM, 25% Inorganic), ratios, do not appreciably alter methane dynamics in these aerobic soils.

Desmodium plots emitted more total CO_2, of 4200 to 5200 kg C ha^{-1} than maize which had 3800 to 5000 kg CO_2-C ha^{-1}, with the highest emissions recorded at the 25,75 and 50,50

FYM-inorganic treatments. These treatments, which supply 25 % and 50 % of N as organic FYM, respectively, provided readily decomposable substrates that stimulated microbial respiration and root activity, explaining the elevated CO_2 release (Zhang et al., 2022) who reported emissions up to 5000 kg CO_2-C ha^{-1} in leguminous and FYM amended systems. CO_2 emissions declined at the 75,25 fertilizer rate, where FYM supplied 75 % of total N, even though this treatment contained more organic matter. This pattern suggests that a higher proportion of FYM may lower respiration rates once mineral N becomes limiting, or that slower FYM mineralization moderate's microbial turnover. When emissions are considered alongside yields, desmodium maintained higher biomass and lower greenhouse-gas intensity at the 75,25 (75% FYM, 25% Inorganic), while maize yields peaked at 50,50. This supports the argument that higher organic substitution can achieve lower CO_2 emissions without necessarily reducing desmodium productivity, whereas maize requires more balanced organic-inorganic ratios to sustain yield. Similar trade-offs between organic inputs, soil respiration, and crop yield have been reported in legume-FYM systems in East Africa.

Peak N_2O fluxes in desmodium crop occurred early in the season, with plots receiving 25,75 and 50,50 FYM–inorganic ratios, likely driven by rapid urea hydrolysis, nitrification, and denitrification stimulated by increased soil NO_3^- and labile C from FYM mineralization (Wang et al., 2021). Total cumulative N_2O emissions were higher under desmodium compared to maize which had emissions. Soil moisture and NO_3^-–N levels are key drivers influencing N_2O emissions in aerobic soils (Butterbach-Bahl et al., 2013; Wang et al., 2021). The early N_2O pulse observed immediately after fertilizer application corresponds to peaks in soil nitrate concentration and optimal water-filled pore space

(WFPS), which together favor microbial processes (Zhou et al., 2017). Correlation analysis supported this pattern, showing that N_2O fluxes were positively related to soil NO_3^-–N and WFPS, confirming that nitrate availability and higher moisture contents enhanced denitrification rates. N_2O fluxes were weakly negatively correlated with soil pH, indicating that lower pH likely limited complete reduction of N_2O to N_2, resulting in greater N_2O accumulation (X. Liu et al., 2020; Wang et al., 2021). These results highlight the interactive influence of moisture, nitrate availability, and pH on N_2O production dynamics and underscore the importance of synchronizing fertilizer application with periods of moderate WFPS (<60%) to minimize denitrification-related N losses.

5.7.2 Greenhouse Gas Emissions Intensities under the different crops

Desmodium biomass yield increased from control to treatment 75,25 (75% FYM, 25% Inorganic), with moderate gains under 25,75 (25% FYM, 75% Inorganic), and 50,50 (50% FYM, 75% Inorganic), Emission factors (EFs) and yield-scaled emissions (YSE) also remained low across treatments, indicating that Desmodium's symbiotic N fixation and efficient nutrient uptake moderated N_2O losses despite increased biomass. This is consistent with reports that leguminous forages maintain low EF values (<0.3 %) even under moderate fertilization (Wang et al., 2021). Desmodium's ability to sustain stable emissions while increasing biomass demonstrates its potential as a low-emission forage, with yield improvements directly enhancing emission efficiency. Net-GWP remained stable across all treatments, suggesting fertilizer type and substitution rate had little influence on overall emissions. This reflects Desmodium's N-fixing ability which buffers soil N dynamics and limits N_2O production even when external N inputs rise (Macharia al., 2020; Yao et al., 2024). Greenhouse-gas intensity (GHGI), which normalizes emissions per unit of biomass, sharply declined from control to 75,25, about 70% reduction, reflecting higher biomass with stable emissions.

The highest maize grain yield was achieved under the 50,50 (50% FYM, 50% Inorganic) closely followed by 25,75. Both exceeded the unfertilized plot control (0,0). Yield declined under 75,25, despite the same total P application across fertilizer treatments. This reduction can be attributed to the high proportion of FYM, which likely slowed nutrient mineralization and reduced the synchronization of nitrogen (N) availability with maize demand during critical growth stages. The inorganic N fraction in 25,75 and 50,50 treatments was likely more readily available, supporting early vegetative growth, whereas in 75,25, a greater share of N was organically bound within FYM and thus released more gradually through microbial mineralization (Macharia, et al., 2020) in Kenyan maize systems and confirmed in broader meta-analyses (Yao et al., 2024). Emission Factors (EFs) showed a 20%-fold increase from treatment 50,50, which had the lowest followed by 25,75, then 75,25 had the highest. Studies from (Macharia et al., 2020; Wang et al., 2021) show typical EFs of 0.2-0.5% under high N loads. Application of N via high FYM rates substantially increases emission losses, emphasizing the need to match fertilizer to crop demand to minimize environmental impact. Net-GWP increased from 3,700 in control to 5,200 under the 75,25 treatment, an approximately 40.7% increase. Moderate treatments (25,75 and 50,50) produced intermediate values of 4,300 and 4,300, respectively. This indicates that high organic substitution can elevate microbial respiration and N_2O emissions without corresponding yield benefits. This aligns with (Macharia et al., 2020), who reported net-GWP values (scaled per season) rise significantly with higher organic N loads, especially when FYM was applied in excess without corresponding yield gains, suggesting elevated microbial respiration and N_2O emissions.

The increase GHGI (Green House Gas Intensity) under 75,25 (75% FYM, 75% Inorganic) in maize crop reflects cumulative microbial and N_2O-driven emissions worsened by suboptimal yield. While fertilization enhances crop performance, excessive organic input without yield response can harm emission balance, indicating that, it reached its lowest under 50,50, then increased again in 75,25 (Li et al., 2019). This pattern reflects typical trade-offs; moderately fertilized treatments improve emission efficiency by increasing yield without proportional emission increasing. A global meta-analysis by (Yao et al., 2024), supports this, showing GHGI values for maize averaging 211 kg CO_2-eq Mg^{-1} at yields above 10 t ha^{-1}, with lower GHGI linked to higher yield efficiency. GHGI peaked under 75,25 due to both reduced yield and increased net-GWP. Balanced fertilization of 50,50 treatment achieved both high yield and low emissions, giving the lowest GHGI and EF among maize plots. This demonstrates that balanced organic–inorganic nutrient management maximizes yield per unit greenhouse gas emitted, the core goal of sustainable intensification (Yao et al., 2024).

YSE values were lowest under 25,75, and 50,50 treatments, slightly higher in the control, and peaked under 75,25, about three times higher than both the control and more efficient treatments. This pattern aligns with meta-analytical results showing typical maize YSE values around 0.2 g N_2O-N kg^{-1} at yields above 10 t ha^{-1} (meta-analysis of over 6,000 observations; global mean 211 g CO_2-eq Mg^{-1}), implying a similar scale. The sharp increase at 75,25 again indicates inefficiency, high emissions, but lower yield, making this treatment less favorable agronomically and environmentally. YSE shows that treatments must produce yields proportional to emissions; optimal systems (25,75, and 50,50) maintained low emission intensity, while imbalanced ones do not.

5.7.3 Correlation between GHGs & Soil Properties

CH_4 emissions in our study showed weak, correlations with NO_3^-–N, NH_4^+-N, or soil moisture, and remained consistently low across all treatments. This aligns with expectations in upland aerobic soils, where CH_4 oxidation outweighs production. These results agree with (Zhao et al., 2016), who found minimal CH_4 emissions (<20 μg m^{-2} h^{-1}) in non-flooded maize-wheat rotations. CH_4 dynamics are mainly driven by water saturation and redox potential, which were absent in our well-drained plots. Likewise, (Butterbach-Bahl et al., 2013) noted that upland cropping systems often act as net CH_4 sinks, especially in medium-textured soils with good aeration. This means that CH_4 emissions in such systems are minor and not significantly affected by nutrient additions or common soil parameters. The weak correlations confirm that in aerobic upland conditions, CH_4 emissions are negligible and less responsive to fertilization or moisture variations, highlighting its limited role here. Soil moisture showed a negative correlation with NO_3^-–N but a positive one with total C and total N, reflecting its dual influence on nutrient transformations. In this study, moist plots had lower NO_3^- <12 mg kg^{-1} and higher total N >0.2 %, suggesting reduced nitrification and possible microbial immobilization. These patterns align with microbial preferences for anaerobic processes in moist conditions and slower organic N mineralization in drier soils. (Cao et al., 2024) reported that increased soil moisture inhibits nitrification, decreasing NO_3^-–N accumulation, while enhancing N retention through microbial assimilation. Similarly, (Wang et al., 2021), observed that soils at 70-80 % WFPS had higher microbial biomass and immobilized N, but lower NO_3^- levels, affecting plant uptake and emissions. High moisture also promotes short-term C stabilization, potentially explaining the positive link between soil moisture and %C. Overall, soil moisture's influence on nitrogen forms and organic carbon emphasizes its central role in microbial activity and greenhouse gas production, highlighting the importance of water management in climate-smart agriculture.

Correlation between CO_2 emissions, %C, and total N increased, reflecting increased biological activity. This is consistent with long-term system trials reporting increased CO_2 emissions under organic and integrated nutrient management due to better substrate availability. (J. Liu et al., 2021) demonstrated that plots amended with FYM and crop residues had CO_2 fluxes up to 600 μg m^{-2} s^{-1}, versus less than 300 μg m^{-2} s^{-1} in unfertilized plots, attributing the increase to higher microbial respiration supported by larger total C and N pools. Similarly, (Congreves et al., 2017) identified soil organic carbon as the strongest predictor of cumulative CO_2 emissions in maize systems. Elevated microbial biomass and enzyme activity are key drivers. The correlation between CO_2 and soil organic C/N underscores organic matter's role in fueling respiration and highlights how integrated nutrient management boosts soil biological processes.

Nitrous oxide (N_2O) emissions were positively correlated with soil NO_3^-–N and negatively with NH_4^+–N and soil moisture, indicating that nitrate-driven denitrification was the dominant source of N_2O. When viewed with temporal mineral N trends, emission peaks coincided with high NO_3^- levels following fertilizer application, particularly under moderate soil moisture (55–65% WFPS), conditions that favor incomplete denitrification (Baggs et al., 2003 ; Senbayram et al., 2022). As mineral N declined later in the season due to plant uptake, N_2O fluxes dropped correspondingly. (Cao, 2024) observed a similar exponential relationship between soil NO_3^-–N and N_2O emissions in temperate cropping systems, reporting that increasing NO_3^- from 10 to 30 mg kg^{-1} tripled N_2O emissions, while high soil moisture (>80 % WFPS) reduced emissions by limiting oxygen diffusion. Additionally, (Yang et al., 2017) found N_2O fluxes to be positively associated with NO_3^- concentrations and negatively with NH_4^+ in a wheat-maize rotation under controlled irrigation. This further supports the literature documented that denitrification is the key microbial process under the studied conditions.

5.8 Maize & Desmodium Biomass Yield

The high performance of 25,75 suggests that high proportions of readily available inorganic N (urea), combined with organic carbon from FYM, enhanced reproductive grain filling. This supports the findings of (Ndirangu *et al.*,2022), who observed that moderate organic additions synergize well with mineral inputs for maize yield, due to improved nutrient synchronization and microbial activation. The poor performance of 0,0 highlights a nutrient limitation, while the moderate yields under 0,100 indicate that mineral fertilizers applied meets short-term N demand; however, the absence of organic matter may hinder microbial function and long-term sustainability. The relatively lower performance of 100,0 (FYM only) emphasizes the slow-release of organic N, which may not match maize's early demand spike, as noted by (Muriuki *et al.*, 2017).

Grain yields in the intercrop system at Site 1 were more consistent, producing the highest yield, significantly exceeding 0,0 and 75,25. Fertilizer rates (25,75, 50,50, 100,0) yielded statistically similar results (Fig. 16 b)

The lower variability in the intercrop system indicates that biological nitrogen fixation (BNF) by desmodium, combined with below-ground complementarity, helps buffer against nutrient imbalances caused by different fertilizer combinations. Similar yield stabilization has been reported by (Kihara & Bolo., 2021), who demonstrated that legume intercrops boost nitrogen-use efficiency and decrease reliance on external inputs. Interestingly, 0,100 performed best in this system, probably because desmodium compensates for the nitrogen balance by fixing nitrogen, allowing maize to benefit from the rapid nitrogen release of urea fully. However, this may raise long-term sustainability concerns, as systems relying solely on inorganic inputs are vulnerable to soil acidification and depletion of soil organic carbon (SOC)(Macharia *et al.,* 2020).

At Site 2, grain yields were generally lower than at Site 1, possibly due to reduced soil fertility. The highest yields were observed under 50,50, 75,25, and 100,0 fertilizer rates, all of which were statistically similar, indicating that FYM-rich plots performed better in this context than at Site 1 (Fig. 16 c). This suggests that organic matter helps improve soil moisture retention, which is important given the potential dryness of Site 2. The lowest yield in the 0,0 treatment confirms that nutrient limitations exist. In comparison, the moderate yield under 0,100 again reflects the immediate availability of N, though without the moisture-retentive and structural benefits of FYM. The results support (Kamau *et al.*, 2022), who reported that organic inputs help buffer crops against climatic stress, especially under low-input or semi-arid conditions.

In the intercrop system at Site 2, the improved performance of blended FYM-inorganic treatments indicates better nutrient synchrony and possibly enhanced microbial interactions in the rhizosphere. As seen at Site 1, BNF by Desmodium likely played a stabilizing role; however, unlike at Site 1, 0,100 did not produce the highest yield, suggesting reduced inorganic N efficiency due to site limitations or moisture stress. These findings are supported by (Wanyama *et al.*, 2023), who emphasized that FYM integration improves intercrop resilience and maximizes land equivalent ratios (LER) under variable rainfall.

Above ground biomass yield followed a pattern similar to grain yield, with the highest values observed under a 25,75, significantly higher than the control (0,0). Fertilizer rates 50,50; 75,25; and 0,100 all had the lowest values again seen in the control and FYM-only (100,0) plots (Fig.17 a). The results suggest that vegetative growth is influenced not only by N availability but also by improved soil structure and microbial activity, both of which are enhanced by FYM. The trend matches grain yield patterns, indicating a minimal trade-off between vegetative and reproductive growth under optimal conditions (Otieno *et al.*, 2021).

Biomass in the intercrop system ranged from**,** with the highest values observed under 0,100 and 25,75. Unlike in grain yield, where 0,100 topped the chart, biomass was more evenly distributed across all fertilizer regimes (Fig. 17 b). The elevated biomass in FYM-containing treatments (especially 25,75, and 100,0) could be due to higher total aboveground growth from both maize and desmodium**,** particularly if desmodium contributed significantly to the biomass pool. These findings are consistent with (Nyawade *et al.,* 2020)**,** who observed increased biomass accumulation in maize-legume intercrops with integrated fertility management.

Biomass yields in 25,75 showed the highest accumulation, significantly outperforming 0,0 and 50,50 (Fig.17 c). This suggests that early inorganic N supply**,** complemented by FYM's moisture retention, favored vegetative growth at this site. The lower biomass under 100,0 suggests that FYM alone may have released nutrients too slowly to support early vegetative expansion. The trend confirms site-specific responsiveness to input combinations, supporting (Mucheru-Muna *et al.*, 2021), who reported that FYM must be combined with fast-acting fertilizers for maximum benefit.

Biomass yields, reflected grain yield patterns and confirms that balanced nutrient input improves both vegetative and reproductive performance, especially in intercrops. The lower biomass in the 0,100 and 0,0 conditions suggests a lack of buffering or synergistic growth support. Performance under FYM-rich combinations again shows better water retention and microbial support, which are crucial in semi-arid zones (Ng'etich *et al*., 2022).

Nitrogen Uptake (kg N ha^{1})

The leading performance of 50,50 highlights the synergistic effect of combining fast-release urea and slow-mineralizing FYM, which provides a steady nitrogen supply throughout the season. This finding aligns with (Breure *et al.*, 2023), who demonstrated that partially replacing urea with FYM enhances nitrogen use efficiency and uptake in maize. The lower uptake in the 100,0 treatment likely results from delayed nitrogen mineralization that cannot meet maize's early nitrogen demand peak. The poor uptake under 0,0 confirms nutrient limitations.

The increased uptake in intercrop systems suggests improved biological nitrogen fixation (BNF) by Desmodium and rhizospheric interactions that enhance N availability and uptake by maize. The intercrop system may also improve root distribution and decrease N losses through leaching, consistent with findings by(J. M. Kihara & Bolo, 2021). This underscores the buffering effect of intercrops on nutrient dynamics.

Interestingly, unlike Site 1, 50,50 did not significantly outperform 100,0 or 0,100, at site 2 possibly due to lower mineralization rates or water limitations at this site, which reduced urea efficiency and allowed FYM-treated soils to catch up in performance. This supports the idea that site-specific factors, such as moisture availability, microbial activity, and soil texture, strongly influence N mineralization and uptake, as highlighted in (Wanyonyi *et al.,* 2023). The role of FYM in buffering nutrient supply during dry period is particularly evident at this site.

The intercrop system mitigated treatment variation, likely due to BNF from desmodium, improved soil N retention, and reduced competition. These findings support the role of intercrops in enhancing nutrient acquisition and recycling, consistent with (Mucheru-Muna *et al.*, 2021), who demonstrated that intercrops increase root N uptake by improving soil biological quality and decreasing N losses through better synchronization between supply and demand.

Phosphorus Uptake (kg P ha^{1})

Phosphorus uptake was significantly influenced by treatment. The higher P uptake in FYM-inclusive treatments is attributed to improved P solubility through FYM-mediated pH buffering, enhanced microbial activity, and organic acid production that facilitates inorganic phosphate dissolution. This aligns with findings by (Nziguheba *et al.,* 2016), who demonstrated that FYM increases P availability, especially in acidic or P-fixing soils.

Phosphorus uptake in the intercrop system showed less variation between treatments, with the 0,100 (inorganic only) treatment having the highest uptake, significantly exceeding the 50,50 and 75,25 fertilizer rates (Figure 19 b). This could be due to the increased root surface area and mycorrhizal associations in the intercrop system, which enhance P scavenging from less available pools. The unexpectedly high P uptake under 0,100 may reflect TSP immediate P availability, though this does not ensure long-term sustainability. These patterns align with (Chivenge *et al.,* 2022), who observed rapid but short-lived P uptake with mineral inputs alone.

P uptake ranged from about 16 kg/ha (0,0) to 27 kg/ha (75,25) (Figure 19 c), with all treatments, including FYM (50,50, 75,25, 100,0), performing well. Similar to Site 1, this study demonstrates FYM's role in mobilizing occluded P, especially in P-deficient soils, and supports findings from (Jairus *et al.,* 2021), that indicate increased P uptake when FYM is combined with inorganic P fertilizers. The consistent results across different FYM ratios also suggest that even moderate levels (25,75, 50,50) are sufficient to significantly increase P uptake, especially when FYM improves soil structure and microbial phosphorus cycling. In Site 2 intercrop, P uptake was highest under the 75,25 and 50,50 fertilizer rates, significantly greater than under the 0,0 and 100,0 treatments (Figure 19 d). This shows a synergistic effect of organic P release from FYM and better root-P interactions from the intercrop. The increased uptake at a 75,25 combinations in this system confirms that a balanced organic-inorganic input not only boosts availability but also improves acquisition, especially when combined with legume-mediated rhizosphere acidification and P mobilization, as suggested by (Arruda *et al.,* 2019).

5.8 Desmodium Biomass Yield

At Site 1, Desmodium yield varied significantly across treatments and cropping systems. The highest yield under intercrop was observed with 0,100 (FYM) followed by 25,75 and 50,50 (Figure 20 A)**.** Notably, intercropped Desmodium in the control (0,0) recorded the lowest yield (0.77 t/ha), indicating the necessity of nutrient input.

The significant interaction between Treatment × Cropping System and fertilizer Treatment × Site further confirms variability in Desmodium response due to cropping arrangements and edaphic conditions. The highest yield under sole cropping with 50,50 fertilization regime can be attributed to improved nutrient synchronization, as intermediate organic-inorganic blends enhance nutrient availability while improving soil structure and microbial activity (Mango *et al.*, 2019). Conversely, in the intercrop, nutrient competition with maize may explain the lower Desmodium yields, especially under low input.

These results suggest that at Site 2, organic nutrient sources more effectively support Desmodium growth. Similarly, (Kassaw & Alemu, 2022) found that Desmodium yields in intercropping systems improve under balanced nutrient applications and suitable microclimates. However, they (J. M. Kihara & Bolo, 2021) reported limited biomass under full FYM application due to delayed nutrient release in cool zones, indicating site-specific responses.

Nitrogen Uptake (% N)

In site 1 (Figure 20 b), Nitrogen uptake was statistically not significant across treatments or systems**,** suggesting relatively uniform %N in Desmodium tissues. However, numerically, sole Desmodium under 50,50 had the highest %N followed closely by 0,0 and 75,25. Though the values are not significantly different, the trend indicates that blended fertilizers might enhance N concentration in Desmodium biomass, likely due to improved nitrogen use efficiency (NUE), consistent with (Mucheru-Muna *et al.*, 2021).

In Site 2 (Figure 21 e), a statistically significant site effect was observed with generally higher N content in intercrops compared to sole crops. The highest N uptake was observed under intercrop with 50,50 and 75,25, whereas the lowest was under sole cropping at 0,100.

This pattern could be linked to increased root nodulation and BNF in intercropping systems under conducive soil conditions (Ndung'u *et al., 2021)*.

Phosphorus Uptake (% P)

Phosphorus uptake was significantly affected by treatment reflecting the sensitivity of Desmodium P content to both nutrient inputs and environment. At site 1 (Figure 20 c & f), the highest P uptake in sole Desmodium was under 0,0**,** with slightly lower values under 50,50 and 75,25. In intercrops, 0,0 and 0,100 had the highest P uptake suggesting that Desmodium benefits from residual or slowly available P forms, especially under organic systems. Despite being the lowest yield treatment, control (0,0) had relatively high P %, possibly due to a dilution effect in high-yielding treatments or due to microbial mineralization of native P in the absence of fertilizer.

At Site 2 (Figure 21 c & f), both sole and intercropped Desmodium showed high P uptake across the fertilizer regimes, ranging between. Notably, 0,0 still exhibited the highest %P in monocrop and intercrop further reinforcing the hypothesis that Desmodium is efficient in P uptake from low-input soils, possibly via root exudates or mycorrhizal associations (Macharia *et al.*, 2020). However, P uptake in yield terms was higher under 0,100 and 25,75, aligning with trends observed in biomass production.

5.9 Nutrient Use Efficiency

5.9.1 Agronomic efficiency (AE)

The highest N agronomic efficient (AE) observed at 25,75 outperformed both 100,0 and 0,100. Sole FYM (100,0) had the lowest AE, likely due to slow N mineralization and poor synchronization with crop demand during early growth. The 0,100 and 50,50 treatments showed similar intermediate AE indicating that partial substitution of FYM improved nutrient synchronization. In the intercrop, fertilization regime 0,100 had the highest AE followed by 25,75 and 50,50. Intercrop AE decreased under FYM-rich treatments (75,25, 100,0), possibly due to nutrient competition between maize and desmodium or delayed mineralization in cooler microsites (Figure 22).

Integrated nutrient strategies (especially 25,75) enhanced AE by balancing the rapid release of N from urea and microbial mineralization from FYM. This aligns with findings from (Ghosh *et al.*, 2020), who reported that partial organic substitution (25–50%) maximized yield per unit N.

The higher AE at 0,100 for the intercrop may reflect the legume's contribution to soil fertility through biological nitrogen fixation (BNF), reducing reliance on external N. This aligns with (Mucheru-Muna *et al.,* 2021), who noted improved fertilizer use efficiency in cereal-legume intercrops under N-only treatments.

At site 2 for maize monocrop, (Figure 22), AE was highest in the 25,75 and 75,25 combinations followed by the 50,50 ratios. The 100,0 ratio had the lowest AE (around 15), again showing poor N availability from organic matter alone. All AE values were within or above the critical benchmark recommended for smallholder systems (W. Zhang *et al.*, 2016). The performance of the 25,75 and 75,25 ratios confirms that combining fast-acting N with a slower, buffered organic source is effective. This balance reduces leaching while maintaining supply, a principle supported by (C. Zhou *et al*., 2021).

At site 2 intercrop (Figure 22 D)**,** the 75,25 fertilizer combinations showed the highest AE while the 25,75 and 50,50 and 0,100 had poor AE, confirming nutrient mismatch and/or legume N competition in low N treatments. Intercrops benefit from root diversity, which improves soil nutrient exploration and uptake efficiency. However, intercropping with high FYM can reduce maize's access to mineral N, as Desmodium may suppress nitrifiers or take up more N in the early phases (J. M. Kihara & Bolo, 2021).

The highest RE in maize monocrop (Figure 23 a)**,** occurred under a 25,75 substitution, followed closely by 50,50 and 0,100, 100,0 had the lowest RE, reinforcing that FYM alone does not support quick N uptake. Treatments combining FYM and urea achieved better N synchrony, resulting in increased uptake. This supports (Bhardwaj *et al.*, 2021), who documented increased RE with integrated nutrient management under tropical conditions. RE in maize intercrop (Figure 23 b)**,** peaked at 50,50 (around 55%), followed by 25,75 and 0,100 (about 45%). 100,0 and 75,25 showed the lowest RE, again indicating mineralization lag and nutrient competition. The intercrop system had RE greater than 0.5 under three treatments, suggesting high biological efficiency. Intercropping improves rhizosphere microbial diversity and N cycling, a process well explained by (Gugissa *et al.*, 2022).

In site 2 maize monocrop (Figure 23 c)**,** 0,100 and 25,75 fertilizer combinations had the highest RE, making them statistically superior to other treatments. RE under 100,0 and 75,25 was again the lowest, similar to trends at Site 1. In drier or cooler conditions (Site 2), urea provided more immediate N than FYM. This aligns with (Dawuda *et al.*, 2021), who reported low RE under sole FYM in semi-arid environments due to delayed decomposition. Maize intercrop in site 2 (Figure 23 d)**,** RE peaked at 0,100, followed by 50,50 and 75,25**.** 100,0 had the lowest RE**,** while 25,75 was also lower. In intercrops, BNF from desmodium supplements N**,** possibly reducing the need for mineral N, which explains the strong performance of the urea-only and 50,50 treatments.

CHAPTER SIX

SUMMARY, CONCLUSION AND RECOMMENDATION

6.1 Findings

Nitrous Oxide (N_2O) emissions increased with soil moisture and nitrate levels, especially under sole maize systems, consistent with nitrification–denitrification processes. In contrast, CH_4 emissions remained low and showed a weak relationship with soil moisture, indicating minimal methanogenic activity likely due to well-aerated soils. The CO_2 emissions were positively correlated with soil moisture and NO_3^--N, indicating enhanced microbial respiration and organic matter decomposition in moist soils. Desmodium-based systems demonstrated improved nitrogen recovery and use efficiency, indicating that legumes enhance soil N dynamics through biological nitrogen fixation and improved rhizosphere interactions. The relationships between GHG emissions and soil parameters revealed different emission drivers among cropping systems. For example, CO_2 and N_2O were positively correlated with NO_3^--N and negatively correlated with pH, implying acidification-related emission pathways. Yield-scaled N_2O emissions (intensity) were lowest in the 50,50 and 75,25 fertilizer combinations, highlighting the benefits of integrated nutrient management. Besides, organic-inorganic fertilizer regimes, particularly the 50,50 and 25,75 FYM: inorganic combinations, significantly enhanced N and P uptake, crop yields, and GHG-use efficiencies compared to sole applications of FYM or inorganic N. Specifically, maize monocrop systems with a 50,50 fertilization regime recorded the highest N and P uptake at Site 1. Conversely, intercropping systems at Site 2 benefited most from 75,25 and 0,100 (pure inorganic) fertilization regime, indicating site-specific treatment effects. The CO_2 fluxes were moderately negatively correlated with soil pH and moisture, reflecting their influence on microbial respiration. Meanwhile, N_2O emissions demonstrated significant positive relationships with NO_3^--N and moisture, consistent with denitrification processes under higher water-filled pore space. The correlation analyses also identified contrasting relationships between GHGs and soil parameters across cropping systems. Sole maize showed stronger positive relationships between N_2O and NO_3^-, while sole desmodium exhibited stronger links between CO_2 and soil moisture, underscoring the influence of plant type and rhizosphere activity on emissions. Emission intensity (g N_2O-N per kg of yield) was lowest in treatments with higher yield efficiency, such as the 25,75 and 50,50 substitutions, supporting the GHG mitigation benefits of integrated fertilization. These findings emphasize the synergistic effects of FYM and inorganic N in enhancing soil fertility while reducing GHG emissions.

6.2 Conclusion

From this study, it can be concluded that:

1. Combining inorganic N with FYM, especially at 50,50 or 25,75, improved nutrient uptake, maize and desmodium biomass yield, and GHG-use efficiency across different cropping systems and sites.
2. Intercropping maize with desmodium increased N uptake compared to sole maize, due to better root interactions and nitrogen fixation.
3. Integrated fertilizer management (especially 50,50 and 75,25 FYM-inorganic combinations) effectively balances yield improvements and environmental sustainability by increasing nutrient absorption and lowering GHG emission intensity.

4. Soil moisture and Nitrate-N were key factors influencing N_2O and CO_2 emissions, confirming their essential roles in microbial nitrogen transformations and respiration processes.

6.3 Recommendations

Based on the above findings, the following recommendations are made:

- Implement integrated nutrient management strategies, by combining 50,50, 75,25 and for maize and desmodium cropping systems they reliably enhance yields, nutrient use efficiencies, and lower emission intensities.
- Promote maize-desmodium intercropping in ASALs and other smallholder systems, especially where nitrogen fixation and erosion control are important.
- Apply fertilizer at the right times to prevent peak rainfall from causing denitrification, and use FYM well before planting to ensure that mineralization matches the crop's needs.
- Further research should examine the long-term impacts of these integrated treatments on soil organic carbon, microbial communities, and their resilience to climate variability.
- Policy and extension efforts should prioritize educating farmers about FYM preparation, handling, and efficient application methods to maximize its benefits and decrease reliance on chemical fertilizers.

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APPENDICES

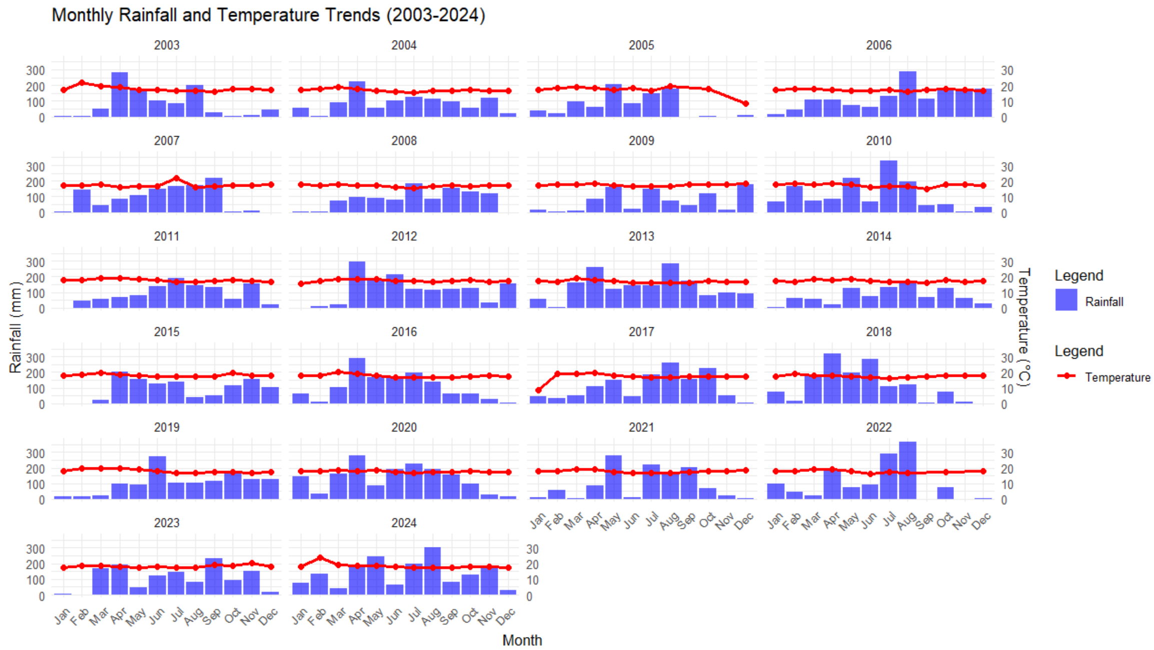
Appendix I: A summary of ANOVA on the effect of P substitution on maize yields (t ha^{-1})

	Yield (t/ha^{-1})				TotalBiomass (t/ha^{-1}				HI				N (%)				P (%)			
	Monocrop(Maize)		**Intercrop**		**Monocrop(Maize)**		**Intercrop**		**Monocrop(Maize)**		**Intercrop**		**Monocrop(Maize)**		**Intercrop**		**Monocrop(Maize)**		**Intercrop**	
Treatment	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
0,0	6.21 ^{e}	4.39 ^{c}	7.96 ^{c}	4.18 ^{d}	14.52 ^{d}	6.51 ^{c}	18.49 ^{c}	6.95 ^{c}	0.43 ^{ab}	0.68 ^{a}	0.44 ^{ab}	0.60 ^{a}	46.32 ^{e}	39.65 ^{c}	67.77 ^{b}	39.52 ^{c}	12.69 ^{e}	16.58 ^{c}	19.17 ^{b}	16.34 ^{c}
25,75	11.22 ^{a}	5.49 ^{b}	9.84 ^{b}	4.96 ^{c}	27.26 ^{a}	18.83 ^{a}	25.85 ^{a}	9.87 ^{b}	0.42 ^{ab}	0.29 ^{c}	0.38 ^{b}	0.51 ^{b}	85.9 ^{b}	49.06 ^{b}	100 ^{a}	50.79 ^{b}	20.38 ^{bc}	22.78 ^{b}	19.72 ^{b}	20.71 ^{b}
50,50	10.17 ^{b}	6.32 ^{a}	8.57 ^{c}	6.46 ^{ab}	24.22 ^{b}	11.62 ^{b}	21.86 ^{b}	11.37 ^{a}	0.42 ^{ab}	0.55 ^{b}	0.39 ^{ab}	0.57 ^{ab}	100 ^{a}	59.94 ^{a}	69.18 ^{b}	65.37 ^{a}	24.51 ^{a}	23.50 ^{b}	16.12 ^{c}	25.90 ^{a}
75,25	10.41 ^{ab}	6.60 ^{a}	8.46 ^{c}	7.16 ^{a}	23.38 ^{b}	12.81 ^{b}	18.94 ^{c}	11.55 ^{a}	0.45 ^{a}	0.52 ^{b}	0.45 ^{a}	0.62 ^{a}	86.23 ^{a}	63.59 ^{a}	76.24 ^{b}	68.23 ^{a}	22.25 ^{ab}	25.58 ^{ab}	16.77 ^{bc}	28.93 ^{a}
100,0	8.04 ^{d}	6.59 ^{a}	7.97 ^{c}	3.99 ^{d}	20.70 ^{c}	12.81 ^{b}	19.78 ^{bc}	7.09 ^{c}	0.39 ^{b}	0.52 ^{b}	0.40 ^{ab}	0.57 ^{ab}	59.64 ^{d}	67.51 ^{a}	69.54 ^{b}	40.14 ^{c}	16.69 ^{d}	26.73 ^{a}	16.77 ^{bc}	15.69 ^{c}
0,100	9.15 ^{c}	6.72 ^{a}	11.23 ^{a}	6.21 ^{b}	24.55 ^{b}	13.34 ^{b}	27.18 ^{a}	12.41 ^{a}	0.38 ^{b}	0.51 ^{b}	0.42 ^{ab}	0.50 ^{b}	75.60 ^{c}	60.74 ^{a}	100 ^{a}	64.04 ^{a}	17.95 ^{cd}	24.41 ^{ab}	26.22 ^{a}	22.72 ^{ab}
Mean	9.2	6.02	8.95	5.49	22.44	12.65	22.02	9.87	0.42	0.51	0.41	0.56	75.62	56.75	80.46	54.68	19.08	23.26	19.13	21.76
Cropping System																				
Monocrop				7.61 ^{a}				17.54 ^{a}				0.462 ^{b}				66.55 ^{a}				21.17 ^{a}
Intercrop				7.25 ^{a}				15.94 ^{b}				0.487 ^{a}				67.60 ^{a}				20.42 ^{a}
Mean				7.43				16.74				0.475				67.08				20.79
Site 1				9.10 ^{a}				22.23 ^{a}				0.41 ^{b}				78.44 ^{a}				19.10 ^{b}
Site 2				5.75 ^{b}				11.26 ^{b}				0.53 ^{a}				55.71 ^{b}				22.49 ^{a}
Mean				7.43				16.75				0.47				67.08				20.8
Source of Variation																				2
T				<0.0001***				<0.0001***				<0.0001***				<0.0001***				<0.0001***
CS				0.0261*				<0.0001***				0.041*				0.593				0.259
S				<0.0001***				<0.0001***				<0.0001***				<0.0001***				<0.0001***
T*CS				0.00026***				<0.0001***				0.0489*				0.00014***				0.0011**
T*S				<0.0001***				0.023*				0.00023***				0.000199***				0.024*
Sem +-				2.309				3.39				0.0035				93.7				10
CV (%)				20				11				12				14				15

Appendix II: A summary of ANOVA on the effect of P substitution on desmodium yields (t ha^{-1})

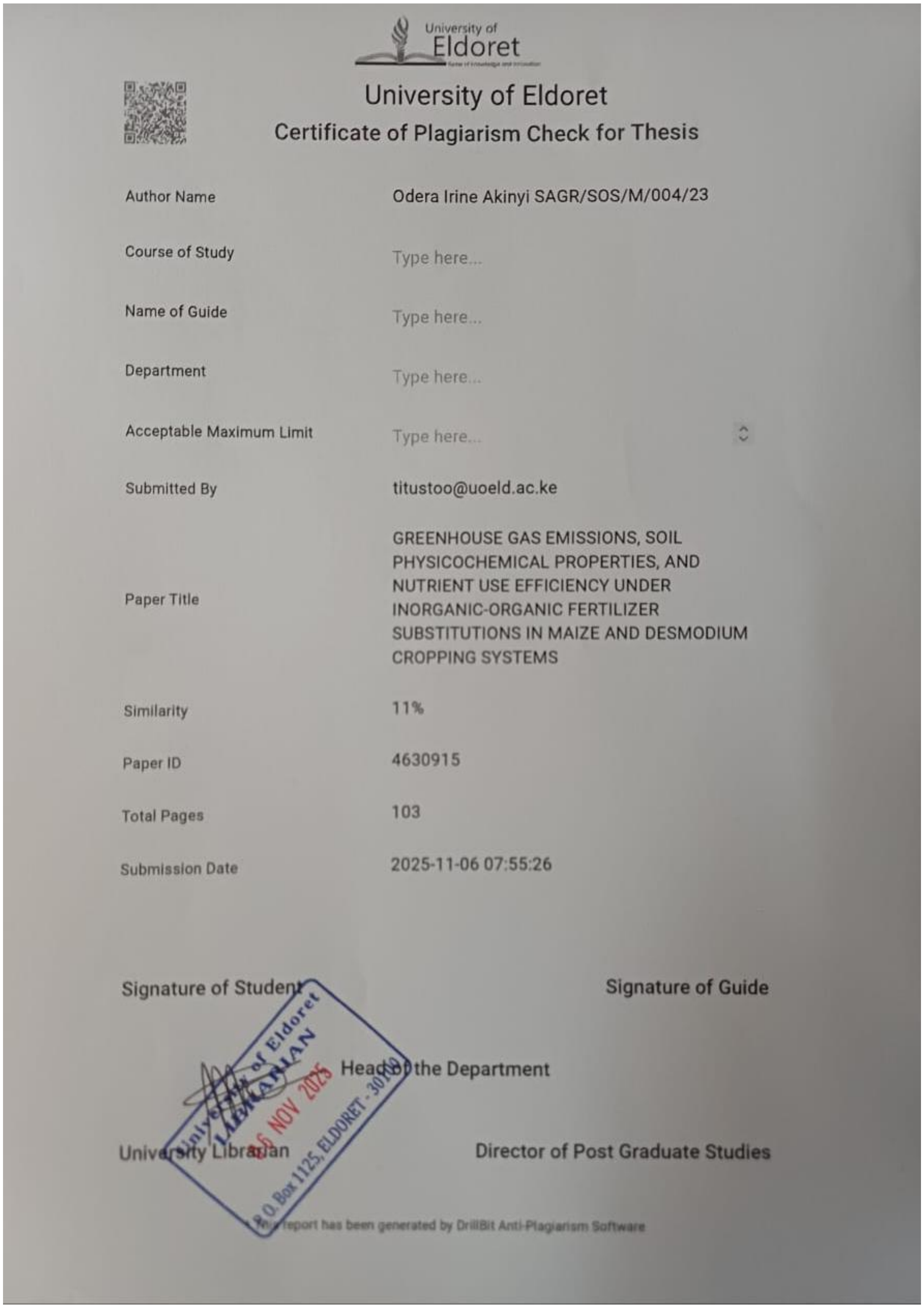
	Yield(t/ha^{-1})				**N (%)**				**P (%)**			
	Monocrop(Desmodium)		**Intercrop**		**Monocrop(Desmodium)**		**Intercrop**		**Monocrop(Desmodium)**		**Intercrop**	
Treatment	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
0,0	1.46 ^{d}	1.85 ^{d}	0.77 ^{d}	1.46 ^{d}	0.17 ^{a}	0.20 ^{a}	0.25 ^{a}	1.07 ^{a}	0.87 ^{a}	1.04 ^{a}	0.99 ^{a}	0.23 ^{a}
25,75	4.30 ^{bc}	4.04 ^{c}	2.51 ^{b}	5.81 ^{ab}	0.15 ^{a}	0.22 ^{a}	0.14 ^{c}	0.96 ^{b}	0.92 ^{a}	1.07 ^{a}	0.87 ^{ab}	0.20 ^{b}
50,50	5.39 ^{a}	1.62 ^{d}	2.34 ^{b}	2.85 ^{c}	0.18 ^{a}	0.21 ^{a}	0.19 ^{b}	1.06 ^{a}	0.84 ^{a}	0.98 ^{a}	0.84 ^{b}	0.20 ^{b}
75,25	3.81 ^{c}	6.04 ^{a}	1.65 ^{c}	5.12 ^{b}	0.17 ^{a}	0.21 ^{a}	0.19 ^{b}	1.04 ^{ab}	0.86 ^{a}	0.98 ^{a}	0.95 ^{ab}	0.20 ^{b}
100,0	5.05 ^{ab}	5.14 ^{b}	0.79 ^{d}	3.27 ^{c}	0.14 ^{a}	0.24 ^{a}	0.15 ^{c}	0.99 ^{ab}	0.97 ^{a}	0.92 ^{a}	0.87 ^{ab}	0.22 ^{ab}
0,100	4.34 ^{abc}	6.25 ^{a}	3.52 ^{a}	6.74 ^{a}	0.14 ^{a}	0.22 ^{a}	0.14 ^{c}	0.99 ^{ab}	0.87 ^{a}	1.03 ^{a}	0.86 ^{ab}	0.20 ^{b}
Mean	4.06	4.15	1.93	4.16	0.16	0.22	0.18	1.02	0.89	1	0.9	0.21
Cropping System												
Monocrop				4.11 ^{a}				0.94 ^{a}				0.19 ^{a}
Intercrop				1.63 ^{b}				0.96 ^{a}				0.19 ^{a}
Mean				4.93								0.19
Site 1				2.99 ^{a}				0.89 ^{b}				0.17 ^{b}
Site 2				2.75 ^{a}				1.01 ^{a}				0.21 ^{a}
Mean				2.87				0.95				0.19
Source of Variation				P Value				P Value				P Value
T				<0.0001***				0.233				<0.0001***
CS				<0.0001***				0.333				0.131
S				0.0994				<0.0001***				<0.0001***
T*CS				<0.0001***				0.0545				<0.0001***
T*S				<0.0001***				0.269				<0.0001***
Sem +-				0.52				0.00849				0.000459
CV (%)				25				9				11

Appendix III: Monthly Rainfall & Temperature Trends (2003-2024)



Appendix IV: Sequence of activities carried out throughout the evaluation period from land preparation, crop growth, harvesting, sampling and soil sample preparation

Appendix V: Similarity Report



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