EFFECTS OF INTEGRATED SOIL FERTILITY MANAGEMENT ON SOIL MICROBIAL BIOMASS, NITROGEN MINERALIZATION, PHOSPHORUS DYNAMICS, AND MAIZE PRODUCTIVITY IN HUMIC NITISOLS OF KENYA

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Effects of Integrated Soil Fertility Management on Soil Microbial Biomass, Nitrogen Mineralization, Phosphorus Dynamics, and Maize Productivity in Humic Nitisols of Kenya

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DECLARATION

This thesis is my original work and has not been presented for a degree in any other University.

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This thesis has been submitted for examination with our approval as the University Supervisors.

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DEDICATION

I dedicate this work to my father, Mr. Peterlis Otieno Opiyo; my stepmother Mrs. Susan Atieno Otieno; my later mother Mrs. Dorine Auma Otieno and my late grandmother. It is also dedicated to my siblings; Evelyne Akinyi, Edwin Odhiambo, Halivan Omondi, Maurine Akinyi, Nancy Atieno, Phelix Onyango, and Irene Anyango. Lastly, I dedicate this work to all people who aspire to be better persons and all the PhD candidates.

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ACRONYMS AND ABBREVIATIONS

ANR	Apparent nitrogen recovery
APSIM	Agricultural Production Systems sIMulator Model
CHK	Central Highlands of Kenya
CT	Conservation tillage
DPS	The degree of phosphorus saturation
FAO	Food and Agriculture Organization
GDP	Gross domestic product
ISFM	Integrated soil fertility management
$KMnO_4$	Potassium permanganate
MBC	Microbial biomass carbon
MBN	Microbial biomass nitrogen
MBP	Microbial biomass phosphorus
MT	Minimum tillage
NPFP	Nitrogen partial factor productivity
$NaHCO_3$	Sodium bicarbonate
NaOH	Sodium hydroxide
NT	No tillage

OC	Organic carbon
PPPF	Phosphorus partial productivity factor
RP	Rock phosphate
S_{max}	Phosphorus maximum sorption capacity
SMB	Soil microbial biomass
SOC	Soil organic carbon
SOM	Soil organic matter
SSA	Sub-Sahara Africa
USAID	The United States Agency for International Development
WUE	Water use efficiency

ABSTRACT

Nitrogen and phosphorus are the two most important macronutrients, often limiting crop production. Their responses to diverse integrated soil fertility technologies are still poorly understood in acidic Nitisols. A randomized complete block design was laid out in an acidic Nitisols at Kangutu Primary School in Chuka subcounty to investigate the effects of selected integrated soil fertility management technologies on; 1) soil microbial biomass carbon, nitrogen, and phosphorus, 2) nitrogen mineralization, partial factor productivity, and apparent recovery, 3) soil phosphorus fractions, degrees of saturation, maximum sorption, legacy and phosphorus use efficiency, and 4) maize productivity. The study used the Agricultural Production Systems sIMulator Model (APSIM) to simulate nitrogen mineralization under the technologies. Integrating: conventional tillage + maize residue + goat manure + *Dolichos lablab* intercrop; minimum tillage + maize residue + *Tithonia diversifolia* + goat manure; and minimum tillage + maize residue + goat manure + *Dolichos lablab* intercrop recorded the highest increase in microbial carbon, nitrogen, and phosphorus by 78%, 48%, and 41%, respectively. Nitrogen mineralization under the technologies was significantly ($p < 0.0001$) variable in certain sampling dates. Conventional tillage + maize residue + goat manure + *Dolichos lablab* intercrop had 5.11 and 52.80 kg N ha^{-1} significantly higher apparent nitrogen recovery and partial factor productivity, respectively. Similarly, minimum tillage + maize residue + goat manure + *Dolichos lablab* intercrop greatly increased apparent nitrogen recovery by 5.75 relative to control. Generally, APSIM poorly simulated nitrate and ammonia nitrogen based on the lowest root means square error and the highest d-index. Resin phosphorus, sodium bicarbonate-extractable inorganic phosphorus, and maximum phosphorus sorption increased by 182, 76, and 52 mg P kg^{-1} under minimum tillage + maize residue + inorganic fertilizer + goat manure. Sodium hydroxide-extractable inorganic phosphorus and maximum phosphorus sorption significantly increased by 216 mg P kg^{-1} and 49 mg P kg^{-1} under conventional tillage + maize residue + inorganic fertilizer + goat manure. The same technology had the highest phosphorus partial factor productivity of 0.093 and 0.140 kg biomass kg^{-1} P and phosphorus agronomic efficiency of 0.080 and 0.073 kg biomass kg^{-1} P during the short and long rains cropping seasons. The findings of this study underpin the importance of integrated soil fertility management technologies in managing soil nitrogen and phosphorus in a maize-based cropping system. The study, therefore, recommends integrated technologies as alternatives or complementary to the sole use of inorganic fertilizers. It also recommends minimal use of model default (inbuilt) values for improved APSIM performance in N mineralization estimation.

CHAPTER ONE

INTRODUCTION

1.1 Background of the Study

Soil is the primary crop growth medium, particularly among smallholder farmers who account for 80% of the universe's population (Gaffney *et al.*, 2016). The persistent declining soil fertility affects the living standards of a majority of these farmers and greatly accounts for the low yields of major crops. For instance, cereal yields in sub-Saharan Africa (SSA) trail that in Asia and Latin America by over 3.5 and 6.5 tons per hectare, respectively (Li *et al*., 2018). Soil fertility depletion is partly due to the soil nutrient mining rate, which is greater than most tropical soils' capacity to self-rejuvenate (Zhang *et al*., 2019). This interference with soil nutrients directly and diversely impacts soil microbial biomass, nitrogen (N), and phosphorus (P) dynamics that need further investigation.

Soil microbial biomass (SMB) is an essential source of soil nutrients, specifically carbon (C), N, and P. It is a crucial soil quality indicator that rapidly responds to soil management practices (Yan *et al*., 2022). The ratios of microbial C (MBC) to microbial N (MBN) and MBC to microbial P (MBP) are better pointers to C dynamics and soil microbial nutrient deficiency (Luo *et al*., 2022). However, the prevailing literature has limited data on MBC: MBP ratio. Various soil manipulations, such as fertilization and tillage, affect SMB (Oliveira *et al*., 2022). Fertilization by either inorganic fertilizer, organic amendments, or a combination of inorganic and organic amendments has previously been demonstrated to influence SMB under varying conditions (Zhu *et al*., 2020). Song *et al*. (2022) reported significantly higher microbial biomass C (MBC; 17.65–40.86%) and microbial biomass N (MBN, 18.63–50.76%) under a combination of inorganic fertilizer and organic amendment in a cropping system that rotated maize-wheat and wheat-soybean. Ren *et al*. (2019) showed a 40% and 55% increase in MBC and MBN under manure and NPK fertilizer, respectively. Additionally, microbial biomass P (MBP) increased while MBC: MBP ratio variability reduced by 10.8% when straw was retained (Wang *et al*., 2022).

Variations in soil nutrient ratios, plant rhizosphere characteristics and soil properties influence how SMB respond to management practices. A decline in SBM has been reported by Guo *et al*. (2022) under *Cunninghamia lanceolata* monoculture. A past study also showed that SMB content varied with soil type (Wei *et al*., 2022). Therefore, assessing SMB C, N, and P under different integrated soil fertility management (ISFM) technologies could improve our understanding of how they respond under maize-based cropping system in Humic Nitisols.

The effect of the conservation tillage system on SMB is weighty in the current literature than the conventional tillage system (Bolo *et al*., 2021). Conventional tillage has been shown to decrease MBC and MBN (Li *et al*., 2018). A meta-analysis revealed a higher total SMB under reduced tillage systems than under zero and conventional tillage systems (Morugán-Coronado *et al*., 2022). Evaluating the effect of tillage frequencies from no-tillage (NT) and semi-annual tillage to conventional tillage (CT) after every 4, 2, and 1 month, Xiao *et al*. (2019) found that MBC gradually declined with the increasing tillage frequency, but MBN declined rapidly under all the tillage frequencies. This could be because soil microbial biomass is a function of diverse microbial communities that may be affected differently by tillage systems. Therefore, it is still unclear whether MBC, MBN, and MBP respond similarly to a particular tillage system. Assessing these parameters under conventional and minimum tillage, especially when treated with soil fertility amendments, provides crucial information on the response of SMB properties to different tillage systems in Humic Nitisols.

The application of fertilizers and tillage methods influence nitrogen mineralization and immobilization processes. Fertilization amendments such as inorganic fertilizers and organic inputs contain substantial amounts of inorganic, organic, and mineralizable N that can hinder or enhance the mineralization process. Sole inorganic fertilizer and a combination with manure increased N mineralization in a study by Wu *et al*. (2021). There is also an indication that chronic N addition may negatively affect N mineralization (Song *et al*., 2022). Ashraf *et al*. (2022) observed rapid N mineralization under long-term manure treatment. Higher N mineralization has also been reported under crop residue retention

(Gao *et al*., 2021). On the other hand, previous researchers have reported increased and decreased N mineralization under reduced tillage and conventional tillage systems, respectively (Pecci *et al*., 2021; Vazquez *et al*., 2019). In contrast, Raiesi & Kabiri (2017) reported decreased N mineralization under a reduced tillage system. Because of these contradicting findings, further study on the impact of the tillage system on N mineralization is imperative to better understand and manage N dynamics in the soil already low in plant-available N.

Nitrogen mineralization studies provide important N fertilization management information (Akponikpè *et al*., 2010). However, these studies are complex, time-consuming and often confounded by interactions among environmental, management, and litter biochemical characteristics. Consequently, process-based models are gaining prominence in understanding N mineralization process. The Agricultural Production Systems sIMulator Model (APSIM) is one such model that, through a simple mineralization module (SMM), permits appropriate parameterization of N mineralization and provides vital information for effective nutrient management. The Model has been employed in supporting N management decision-making regarding cattle manure, millet residue and inorganic fertilizer application (Akponikpè *et al*., 2010). It also accurately predicted N mineralization from *Brassica* catch crop residues (Vogeler *et al*., 2019). Additionally, APSIM has been shown to adequately simulate conservation and conventional tillage practices under different N rates (Chaki *et al*., 2022). One striking strength of APSIM is that it has a user interface that enables the parameterization of complex soil processes (Cichota *et al*., 2021). Despite this potential to simulate N mineralization and reduce experimental cost, APSIM has not been extensively applied in maize-based cropping systems that integrate different fertility amendments under various tillage methods in the Central Highlands of Kenya (CHK).

The addition of inorganic fertilizers, animal manure, or a combination of inorganic fertilizers and animal manure are some common approaches farmers adopt to improve P in cultivated soils (Bhattacharyya *et al*., 2015; Wei *et al*., 2022). Cereal-legume intercrop, rock phosphate (RP), and *Tithonia diversifolia* are additional technologies utilized to improve CHK soil P (Soltangheisi *et al*., 2018; Somavilla *et al*., 2021). These fertilization technologies may affect P dynamics like P fractions, maximum sorption capacity (S_{max}), degrees of saturation (DPS), and P use efficiency (PUE). However, Arruda *et al*. (2019) opined that organic amendments significantly impact P sorption characteristics more than inorganic fertilizers. On the other hand, Pradhan *et al*. (2021) reported contradicting results of organic amendments on DPS. Understanding the effects of different fertilization sources on P fractions, S_{max}, DPS, and PUE is vital for better comprehension and management of P under CT and minimum tillage (MT) systems in acidic Nitisols.

1.2 Problem Statement

Nitrogen and P are the two most crucial limiting nutrients in Humic Nitisols in tropical and subtropical agricultural soils (Wanjiku *et al*., 2019). About 80% of the global population depends on agriculture. Humic Nitisols are the most cultivated soil globally, thus the low levels of these nutrients in the soil could have far-reaching consequences. Nitisols is the predominant type of soil in Chuka Subcounty, Tharaka-Nithi County of Central Highlands of Kenya (CHK), and is often characterized by high acidity, low N, and P. The decline in soil N and P is caused by poor agricultural activities, such as unsuitable tillage methods and exhaustion of nutrient reserves without adequate replenishment. Moreover, it is a serious concern that despite the crucial role played by SMB in replenishing soil nutrients, available studies in Nitisols remain scanty (Zhu *et al*., 2020). Since there are controversies on soil microbial studies associated with; the duration of the experiment, cropping systems, and substrate type and rates, it is imperative that selected ISFM technologies are evaluated against microbial biomass in a maize-based cropping system in the region.

Soil microorganisms and enzymes drive the mineralization process and are responsive to soil management practices and different soil types. Assessing this process under the selected ISFM technologies is critical in deepening our understanding of N mineralization in a Humic Nitisol. Soil biological processes are highly variable and difficult to predict, a problem exacerbated by climatic variabilities and unpredictability. Studies of such complex processes can greatly benefit from robust simulation models such as APSIM for N management decision-making (Gaydon *et al*., 2017; Soufizadeh *et al*., 2018). Nevertheless, N mineralization simulation studies in Humic Nitisols are generally very scarce, especially in Chuka Subcounty. Deploying APSIM in studying N mineralization enhances knowledge on the N mineralization process in such soil types under divergent tillage systems treated with various soil fertility amendments.

Phosphorus fractionation and sorption characteristics greatly influence soil P status and PUE. Very few past studies have investigated how different ISFM technologies impact P dynamics in the Humic Nitisols of Chuka Subcounty (Bhattacharyya *et al*., 2015; Wei *et al*., 2022). Thus, assessing the status of various P fractions and PUE in response to long-term fertilization on contrasting tillage systems is vital to improve our knowledge of P behaviour in Humic Nitisols. Furthermore, P sorption characteristics are critical factors in risk assessment systems that control P release and are positively related to P fractions (Bai *et al*. 2019). However, sorption parameters have been shown to react differently to the same treatments executed in different studies. This revelation strongly supports the need for additional information on P fractions and sorption characteristics to advance the understanding of P changes and mobility. It is, thus, essential to investigate P fractionation, sorption characteristics, and use efficiencies in Humic Nitisols in response to ISFM technologies, as this information is currently limited in the study area.

1.3 Justification

Agricultural production is mainly limited by the soil's low N and P, leading to food insecurities. The deficiencies of N and P will significantly contribute to the projected 25-110% food gap between the current agricultural production and the future production levels (Hunter *et al*., 2017) if not corrected. Improving soil N and P through sustainable technologies is core to tackling socio-economic problems in developing economies that depend on agriculture. For instance, Kenya incurred an estimated US$38 billion loss in the gross domestic product due to reduced labour productivity caused by malnutrition (USAID, 2014). The low food production in Chuka Subcounty is because the farmers practice agricultural intensification systems without adequately replacing the lost nutrients due to high cost and sometimes unavailability of inorganic fertilizers within the locality.

Integrated soil fertility management is an approach that has been proposed to sustainably improve soil fertility and agricultural productivity among smallholder farmers in Chuka Subcounty. The components of the ISFM technologies in this study are abundant and readily available in the region. The approach harnesses locally available resources and can reduce or eliminate expensive inorganic fertilizers. The advantage of ISFM technologies is that they are adaptable to heterogenous local farm conditions. Because of this, the components of ISFM are vast and variable. Therefore, understanding the effects of emerging ISFM technologies on soil N and P dynamics is crucial in enhancing crop productivity through improved soil fertility. Soil microbial C, N, P, N mineralization, P factions, and sorption characteristics contribute to plant soil health and nutrition. The information on how the selected ISFM technologies influence these parameters can benefit farmers in the region, researchers, and other stakeholders wanting to upscale the technologies. Modelling scientists can also benefit from the results of APSIM as a decision support tool in N management by seeking to improve the model or replace it with other process-based models.

1.4 Objectives

This sub-section covers the main and specific objectives of the study.

1.4.1 Main Objective

The main objective was to evaluate the effects of selected ISFM technologies on soil microbial biomass, N mineralization and simulation, P dynamics, and soil moisture for enhanced crop productivity in Humic Nitisols.

1.4.2 Specific Objectives

The specific objectives of the study were to:

1. Determine the effects of selected ISFM technologies on soil microbial biomass N, C, and P.
2. Evaluate the effects of selected ISFM technologies on N mineralization, partial factor productivity, and apparent N recovery.
3. Simulate soil N mineralization under selected ISFM technologies.
4. Assess the response of soil phosphorus fractions, degree of saturation, maximum sorption capacity, use efficiency, and legacy to selected ISFM technologies and,
5. Evaluate the effects of the selected ISFM technologies on maize yield,soil moisture content, and water productivity.

1.5 Research hypotheses

Four research hypotheses were identified, namely:

1. Selected ISFM technologies do not significantly affect soil microbial biomass N, C, and P.
2. The selected ISFM technologies have no significant effect on N mineralization, partial factor productivity, and apparent N recovery.
3. The APSIM is not the best suited to simulate soil N mineralization under the selected ISFM, and
4. Selected ISFM technologies have no significant effect on soil phosphorus fractions, degree of saturation, maximum sorption capacity, use efficiency, and legacy.
5. The selected ISFM technologies have no significant effects on maize yield, soil moisture content, and water productivity.

1.6 Scope of the study

This study investigated the effects of selected ISFM technologies on MBC, MBN, MBP, N mineralization, P fractions, P sorption characteristics and PUE in the Humic Nitisols of Chuka Subcounty. The study also validated the use of APSIM in simulating N mineralization under the selected ISFM technologies. The data on the parameters of interest were collected during short rains in 2020 (SR20) and long rains in 2021 (LR21) from an experiment established in March 2016 during the long rains (LR16) season. The study adopted maize (*Zea mays* L.) H516 variety as the test crop to understand the influence of the selected ISFM technologies on crop productivity

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

Among other aspirations, the Sustainable Development Goals (SDGs) aim is to eradicate poverty, safeguard the planet and guarantee the prosperity of every person by 2030. Improving and maintaining soil quality could be vital in achieving these SDGs. Currently, soil fertility decline is one of the root causes of food insecurity worldwide and could derail the attainment of the SDGs. The bulk of SSA agriculture is rain-fed, occasioned with low soil fertility investment making the region one of the poorest and experiencing stagnated or declining crop productivity (Kiboi *et al*., 2019). Sub-Saharan Africa produces 1.5 t of cereal crops ha^{-1}, representing only 30% of its potential (Epule & Bryant, 2015). This low production is attained from arable land, where 65% is already degraded and relied upon by over 2 million people (Wanjiku *et al*., 2019). These statistics indicate the need for prompt interventions to improve soil fertility which can have a multiplier effect on agricultural production in the SSA region.

Though it is projected that maize will continue to play a major role in global and regional food and fodder dynamics, its production in the Central Highlands of Kenya (CHK) has constantly remained low. Maize productivity is less than 2.0 t ha^{-1} against the region's potential of 6.0 t ha^{-1} (Kiboi *et al*., 2017). The meagre maize productivity is, to a larger extent, attributable to low soil N, P, and water use efficiency. Water is a key limiting factor in the rainfed agricultural production system as Fang et al. (2010) emphasised a reduction in maize yield by 20 - 85% due to water scarcity. The recent prediction that farmers under rainfed agriculture risk experiencing a decrease in crop yields of approximately 50% in the next 30-35 years if the soil fertility issue is not urgently addressed is more problematic and needs urgent action.

Soil fertility is a challenge in SSA because land is under pressure to support the rapid population growth. Under just 50 years, agricultural land use has caused the depletion of total organic carbon and total N by 72% and 15%, respectively (Willy *et al*., 2019). Together with overreliance on rainfed agriculture by smallholder farmers, the degraded soil fertility significantly contributes to low agricultural productivity. Low soil moisture is also a critical challenge in rainfed agricultural production systems that further decreases crop yield. With the increasing rainfall water scarcity due to climate change (Cook *et al*., 2018), there is an urgent need for technologies that both replenish soil fertility and enhance crop water productivity (WP) and nutrient use efficiency. Previous studies have not comprehensively evaluated the long-term impact of ISFM technologies on WP to understand rain water performance in the Humic Nitisol despite being arguably the most agriculturally cultivated soil type worldwide, especially in the Chuka Subcounty.

Humic Nitisol covers approximately 1.6% of the global land surface and is the most agriculturally utilised type of soil according to FAO soil classification (https://www.fao.org/3/Y1899E/y1899e06.htm). As the predominant soil type in the CHK (Jaetzold *et al*., 2006), the main agricultural limitations are intrinsic low N, P and high acidity. Considerable nutrients are also lost through leaching, crop mining, runoff, and soil loss due to erosion (Musyoka *et al*., 2018). Rejuvenating the N and P status of these soils is thus crucial for sustainable agricultural productivity.

2.1.1 Drivers of Soil Fertility Decline

Drivers of soil fertility decline vary from farm to farm, region to region, and country to country because of variable socio-economic, biophysical, and land use conditions. Lack of adequate soil fertility replenishment through external inputs application has been extensively cited by researchers as one of the leading causes of soil fertility decline (Okeyo *et al*., 2014). Even with the prevailing yield gap, soil fertility management at the farm level is still challenging because of the high cost and unavailability of soil fertility amendments, both inorganic and organic sources.

Plant nutrient mining through harvesting, nutrient loss via erosion, and run-off at rates greater than replenishment by weathering of primary rock minerals also contribute to declining soil fertility (Eger *et al*., 2018). Without soil conservation measures, the amount of soil and nutrients lost through erosion was approximately 41.5 t ha^{-1} annually. Moreover, as much as 57% and 31% of organic carbon (OC) and available P, respectively, were quantified to be lost from the eroded but cultivated soils in Rwanda (Kagabo *et al*., 2013). It is estimated that more than 80% of agricultural activities are practised under rain-fed conditions and influenced by climatic variations associated with low soil moisture and nutrient content (Okeyo *et al*., 2014).

The tillage system affects soil fertility in terms of distribution and exposure to depletion agents. Wyngaard *et al*. (2012) intimated that conventional tillage changes the distribution of soil properties within the soil profile and also affects biochemical activities in the soil mass. Soil aggregate stability, soil organic carbon (SOC), and water retention capacity have been found to reduce under conventional tillage systems (Ordoñez-morales *et al*., 2019). On the other hand, it has been reported that a conservation tillage system can reverse the effects of CT. For instance, it is opined that the conservation tillage; i) alters organic C profile and concentrates it in the soil surface layer, ii) protects soil organic matter (SOM) from rapid decomposition, iii) increases water retention, iv) boosts soil fertility amendments responsiveness, and v) increases N mineralization and restores biological processes thus increasing crop productivity (Kiboi *et al*., 2017). Therefore, the need to understand the response of soil biological and chemical properties to different agronomic practices under an appropriate tillage system is of great importance.

Frantic attempts to use inorganic amendments as a source of nutrients have failed because these fertilizers are expensive, sometimes not available to smallholder farmers, (Kiboi *et al*., 2019). Use of the wrong type of fertilizer at times, is another factor that affects crop growth. Deliberate efforts have been made in Chuka Subcounty to promote the integration of amendments that meet smallholder farmers' financial needs for the enhancement of agricultural production (Musyoka *et al*., 2017). These interventions have mainly concentrated on assessing the effects of the integration of various amendments on crop productivity without giving much attention to soil biological quality and P dynamics.

2.1.2 Potential Soil Fertility Solutions

Integrated soil fertility management could be the best bet to improve soil biological quality and chemical fertility. Integrating inorganic fertilizers and organic amendments could prevent N loss and increase agricultural productivity due to improved agronomic use efficiency of the applied amendments. Sole application of organic amendments (organics) or in combination with inorganic fertilizers affects soil's physical and chemical properties (Brunetti *et al*., 2019). This may affect SMB, N mineralization, and P dynamics. Nitrogen and P inputs from ISFM may alter nutrient cycles, affecting microbial communities, soil enzymatic activities, and thus, N mineralization and P fractions. Also, there are indications that ISFM influences the amount and distribution of P fractions within the soil profile (Soltangheisi *et al*., 2018).

Researchers have recommended one or more components of ISFM as a means of addressing soil fertility decline. For example, the co-application of crop residues and inorganic fertilizer has been proposed by Zhang *et al*. (2021), while the sole application of inorganic fertilizer has also been advocated for. Organic inputs such as manure and *T. diversifolia* have also been tested successfully. Additionally, combined inorganic fertilizer and organic amendments are well-documented concepts in soil fertility management (Lian *et al*., 2022). Rock phosphate and cereal-legume intercropping with common beans, cowpeas, and *Dolichos lablab* (Costa *et al*., 2021) have also been promoted. Therefore, assessing an array of ISFM technologies, as opposed to one-for-all recommendations for diverse farms, can solve soil fertility issues.

Tillage affects aggregate-size classes (Nyawade *et al*., 2019), which influences various microbial accessibility to aggregate-linked SOM affecting N mineralization. But limited consensus exists on the pattern of aggregate-associated nutrient mineralization as affected by tillage. The contention is partly attributed to different types of crop residues (Tian *et* *al*., 2016). For instance, N mineralization patterns differed between canola and wheat residues. Jha *et al*. (2020) reported about a 5%, 25 %, and 30% increase in SOC, total N, and MBC in a Vertisol under conservation tillage with crop residue retention. Still, Minimum tillage (MT) may replace labile P fractions and enhance the availability of residual P to crops. However, the effect of tillage on soil physicochemical properties can have a comparable influence on soil microbial biomass. Soil microbial community and functions were redundant in both MT and CT tillage systems in Kaolitic soil (Lopes & Fernandes, 2020).

Generally, the impact of the tillage system on soil fertility remains inconsistent. This can be attributed to treating the tillage systems with different soil fertility amendments. Perhaps, such practices greatly affect soil organic matter (SOM), thereby influencing SMB, N mineralization, and P fractions. Past studies blamed CT for the waning soil fertility in the CHK (Kiboi *et al*., 2017, 2019). However, this is not sufficiently justified due to the inconstancies associated with the effect of the tillage system on soil quality parameters. Most ISFM technologies under various tillage methods promoted in CHK have been evaluated against soil chemical and physical parameters (Kiboi *et al*., 2019). However, there is a need to complement this traditional assessment approach with the biological evaluation of the performance of ISFM under different tillage systems.

2.2 Conceptual Framework

The relationship between the independent and dependent variables of the study is shown in **Figure 2.1**. Independent variables are the various ISFM technologies which included; 1) Inorganic fertilizer, 2) maize residues + mineral fertilizer, 3) maize residues + mineral fertilizer + goat manure, 4) maize residues + *Tithonia diversifolia* + rock phosphate, 5) maize residues+ goat manure + *Dolichos lablab*, and 6) maize residues + *Tithonia diversifolia* + goat manure, combined with either conventional (CT) or minimum (MT) tillage systems. The variables of objective 1 included; SMB C, N, and P. The dependent variables in objective 2 were; N mineralization, partial factor productivity (PFP) of N, and N recovery. In objective 3, APSIM was validated to predict N mineralization under the independent variables. The dependent variables in objective 4 included; labile and non-labile (recalcitrant) fractions of P, maximum sorption capacity, degree of saturation, legacy, and agronomic use efficiency.

Lack of implementation of the independent variables is associated with the depletion of dependent variables, denoted by odd number arrows 1 to 7, pointing away from the variables. Therefore, the execution of the independent variables significantly affected the dependent variables, denoted by the even numbered arrow 2 pointing towards the variables. Hypotheses 1, 2, and 4 were rejected because independent variables caused significant effects on dependent variables of the associated objectives. Hypothesis 3 associated with objective 3 was also rejected since the prediction of N mineralization by APSIM was validated.

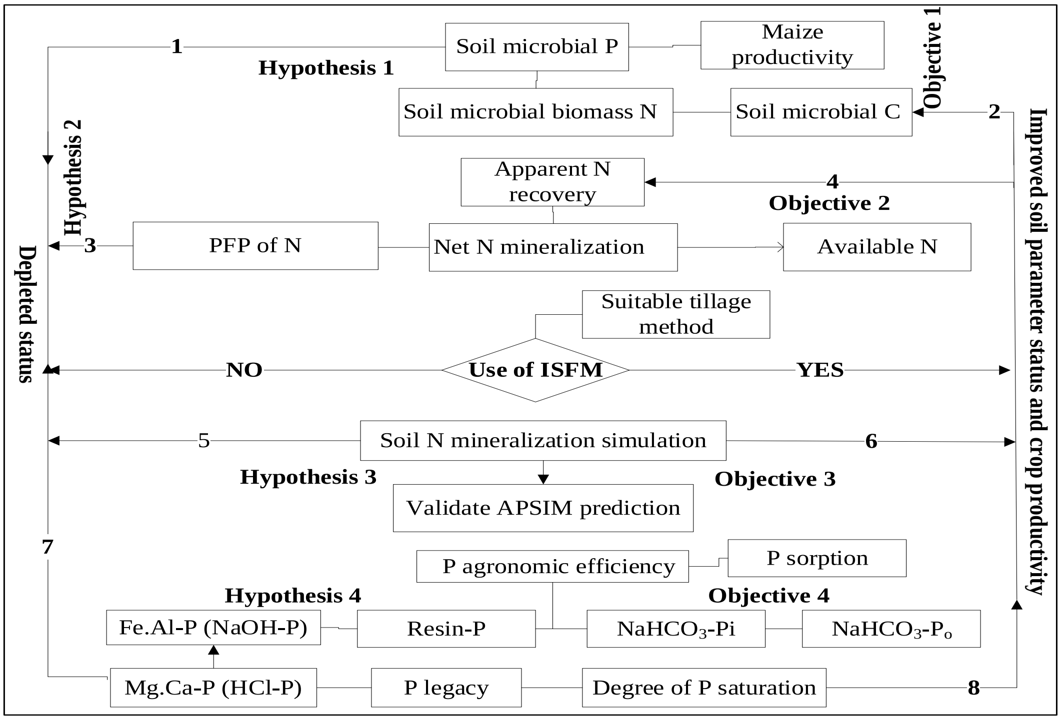


Figure 2.1: Conceptual Framework

2.3 Soil Microbial Biomass Dynamics

Soil microbial biomass is an important emergent soil property that is primarily regulated by soil pH and Al^{3+} (Jones *et al.*, 2019). Soil microbes play a crucial role in ecosystem processes like nutrient and C cycling and are influenced by field management and soil health (Jia *et al.*, 2020). Globally, it is estimated that MBC, MBN, and MBP storage on the 0-30 cm top soil is 23.13 Pg, 3.93 Pg, and 2.16 Pg, respectively (Wang *et al.*, 2022). Fungi and bacteria account for more than 90% of the total SMB and mainly drive the decomposition of SOM, which controls the fate of the nutrient cycle in the soil.

Soil microbial C contributes to SOC through the transformation of organic labile C to more tenacious anabolic forms (Zhu *et al*., 2020), explaining the strong correlation between SOC and MBC (Wang *et al*., 2020). On the other hand, MBN contains the largest fraction of biologically active soil N which is particularly crucial in soil N cycling. This is because SMB adapts to changes in the soil ecosystem by two mechanisms; i) maintaining stable stoichiometric homeostasis and/or ii) changing the soil elemental balance (Asada *et al*., 2022). Soil MBP is a crucial soil P fertility indicator and relates perfectly with P uptake and crop yield (Peng *et al*., 2021). However, its turnover depends on soil P availability.

Soil microbial biomass dynamics are strongly linked to soil physicochemical properties. Therefore, technologies that affect soil physicochemical properties, such as fertilization and tillage, may impact SMB, impacting MBC, MBN, and MBP. A previous study by Jia *et al*. (2020) reported increased MBC and MBN and attributed the increment to the effect of N fertilization on soil property. Ludwig (2019) similarly linked the improved soil aggregate size distribution and SMB to N intensification in a semi-arid ecosystem under different types of crops. A meta-analysis revealed a decrease in SMB under N fertilization (Wang *et al*., 2018). The Uptake of P associated with MBP exhibited temporal variations under varying P stocks in forested soil (Spohn *et al*., 2018), while MBP was significantly higher under inorganic P fertilization in grassland soil (Shi *et al*., 2020). SMB responds differently to nutrient availability and amendments with different C/N/P/S ratios (Fujita *et al*., 2019). Assessing the response of SMB C, N, and P to varying fertility amendments is, thus, imperative in advancing the understanding of the impact of ISFM technologies on SMB, C, N, and P.

2.3.1 Effects of ISFM on Microbial Biomass Dynamics

Soil fertility amendments and tillage can change the composition of the microbial community by altering soil chemical properties; C content, availability of N, soil pH, and soil moisture, and soil physical parameters; aggregate formation and soil structure (Ordoñez-morales *et al*., 2019; Vazquez *et al*., 2019). Nitrogen fertilization may affect the distribution and abundance of specific soil microfauna. Bacteria require higher soil N compared to fungi; thus bacteria to fungi ratio may increase following N addition. However, in the situation that N addition results in low soil pH, the ratio is reversed because acidity inhibits bacterial growth, while fungi are more adaptable to acidic environments compared to bacteria, which eventually affects microbial C, N, and P.

Soil fertility amendments of organic origin impact soil microbe communities, influencing SMB C, N, and P. Microbial C, N, and microbiome enzyme activity increased with farmyard manure application (Luo *et al*., 2018). Israr *et al*. (2019) found higher MBC on green manure-treated plots than the control. Available P and manure C significantly increased MBP by 330 and 3.7 μg P kg^{-1} soil, respectively, in acidic soil where MBP critical level was found to be 140 kg ha^{-1} (Peng *et al*., 2021). These findings illustrate the greater effects of different types of manure on SMB nutrients, particularly MBC. Despite the variant responses of SMB C, N, and P to different fertilizations, microbial resource studies in CHK are few and with varying outcomes (e.g., Kiboi *et al*., 2018). It is, thus, essential to study the three SMB resources under multiple soil nutrient supplementations in the Humic Nitisols in the study area.

Inorganic fertilization has been shown to influence SMB resources. Applying inorganic P was found to have significantly increased MBP but did not affect MBC and MBN in grassland (Shi *et al*., 2020). Also, substantially higher MBC and MBP were reported in a Vertisol under wheat cultivation fertilized with inorganic P (Mahmoud *et al*., 2018). Contrary, MBC and MBP negatively correlated with available soil P in a study conducted by Fujita *et al*. (2019). In a bean-wheat cropping system, NPK (23:45:25) increased MBC and MBP but had the lowest MBN (Azeem *et al*., 2019). But, Zheng *et al*. (2020) found that SMB resources were co-limited by N but not C and P. Moreover, the same authors found high MBC limitations under the sole application of inorganic fertilizer. In contrast, sole NPK, NPK plus a low amount of straw, and NPK combined with a low amount of manure eliminated MBP limitation. In paddy soil, reduced levels of NPK plus a low amount of rice straw and sole NPK significantly increased MBC and MBN (Ding & Su, 2018). Studying the response of SMB resources to sole NPK (23:23:0) and Triple

Superphosphate (TSP) or in combination with organic amendments would enhance our understanding on SMB dynamics in a Humic Nitisol under maize cropping system.

A global meta-analysis study epitomises the crucial impact of tillage on SMB dynamics (Li *et al*., 2018). A reduction in MBC and MBN was observed under the CT system in calcareous soil (Xiao *et al*., 2019). While Kiboi *et al*. (2018) did not find a significant effect of tillage on SMB C and N in a short-term study, Xiao *et al*. (2019) reported a sharp decline in MBN under CT and MT systems. Conversely, from the global meta-analysis results, MBC increased by 33% under MT with residue removal treatment, while MT with residue retention increased MBC and MBN by 25% and 64%, respectively (Li *et al*., 2018). Given the varying results, it was important to study the impact of treating CT and MT systems with multiple amendments on microbial elements under the maize cropping system.

2.4 Soil Nitrogen Mineralization

Nitrogen availability is vital for plant growth and microfauna functionality. However, it is the most frequently deficient in agricultural fields. Both natural and anthropogenic processes cause the decrease in available N. Generally, global N is low because output exceeds soil N input (Wang *et al*., 2018), but the availability of N may increase through the mineralization of organic N into inorganic forms.

Organic amendments contain appreciable amounts of C, N, P, and K that can promote N mineralization. A previous study established about 49% association between MBN and net N mineralization (Wu *et al*., 2021), while MBC affected N mineralization with a path coefficient of 0.405 (Yang *et al*., 2020). Worldwide N demand is estimated to rise soon. Therefore, the mineralization of organic N could play a crucial role in balancing the demand while safeguarding environmental integrity. Nevertheless, effective management of mineralized N is challenging because it is susceptible to losses through; denitrification, erosion, volatilisation, leaching, and microbial immobilization (Musyoka *et al*., 2018). N mineralization studies may crucially enhance the management of N in agricultural fields.

2.4.1 Effect of Integrated Soil Fertility Management on Soil Nitrogen

Integrated soil fertility management leads to both inorganic and organic N increase in the soil. Despite this, there is still a profound knowledge gap in understanding the impact of this double input on N transformations in acidic soils under maize-based cropping systems. Soil N transformation processes are driven primarily by soil microbial communities. It was documented in China that combining inorganic and organic fertilizers affected soil fungal and bacterial community compositions, attributed to the effect of the rate and type of N on soil respiration (Chen *et al*., 2018). Ma *et al*. (2018) reported that integrating inorganic and organic fertilizers changed the competitive uptake of organic N between wheat crops and soil microorganisms and noted a positive correlation between N uptake and inorganic N. These could have a remarked impact on soil N mineralization in maize-based cropping systems under acidic soil. Therefore, it is imperative to understand N mineralization as affected by various ISFM technologies under acidic soils for adequate soil N fertilization and management decisions.

Inorganic fertilizers are important N addition to the soil, profoundly influencing microfauna functions and N mineralization potential (Wyngaard *et al*., 2018). Combining manure with inorganic fertilizer improves N mineralization by enhancing the accumulation of aggregate-protected and unprotected C (Ashraf *et al*., 2022). Nitrogen mineralization would otherwise decrease in conditions with low C (Song *et al*., 2022). Inorganic P combined with a low inorganic N fertilizer improved gross and net N mineralization in a wheat cropping system (Bicharanloo *et al*., 2022). NPK fertilizer enhances N mineralization by regulating bacterial community and SMB (Wu *et al*., 2021). Nevertheless, N mineralization is transient and very dynamic; hence, assessing the effect of inorganic fertilizers (NPK 17:17:17 and TSP topped with calcium ammonium nitrate, CAN) provides crucial N management information in an N and P-deficient acidic soil of CHK.

Rock phosphate (RP) is a natural source of P which affects N mineralization. For instance Moharana & Biswas (2018) found the highest N mineralization under RP-enriched rice straw compost than under normal compost. Furthermore, enriching compost with RP can promote rapid N mineralization. Additionally, treating cow and pig manures with RP resulted in rapid N mineralization in a laboratory study conducted in South Africa (Ajibade *et al*., 2020). A short-term study showed a varying effect of combining RP with *T. diversifolia* on NH_4^+-N and NO_3^--N across sampling dates under conventional and minimum tillage methods (Kiboi *et al*., 2020). Few past mineralization studies demonstrate the effect of RP on N mineralization, but the majority are short-term experiments conducted in controlled environments such as laboratory incubation studies. Therefore, field incubation under a long-term trial is critical to validate or invalidate the findings of laboratory studies.

Mixing organic amendments of different qualities (e,g., C: N ratio) may influence N mineralization. The ratio (C: N) may either lead to N chemically binding to lignin and phenolic compounds or result in well-decomposed and recalcitrant organic matter, resulting from the initial rapid litter decomposition rate. The latter scenario enhances N mineralization that can adapt to low soil pH, especially when there is an increase in the availability of ammonia (Månsson & Falkengren-Grerup, 2003). The addition of litter to the soil system could, therefore, impact the soil N mineralization process. Rothé *et al*. (2019) found 18.4 % synergetic nitrogen mineralization when *Lablab purpureus* was co-applied with composted manures in a pineapple plantation. Elsewhere under sandy loam soil, organic inputs increased net mineralization by 10% to 55% (Cassity-Duffey *et al*., 2020). Moreover, organic fertilization affected ammonia-oxidizing archaea and bacteria community structure and abundance in paddy soil (Dai *et al*., 2021), which may impact the overall N mineralization process. These examples reveal that N mineralization from different organic amendments (animal manure and litter) is variable (Lazicki *et al*., 2020) and show no clear trend in different soils. It is, therefore, important to study the interactive effect of multiple organic amendments on N mineralization, particularly in Humic Nitisols, which are acidic.

The tillage method modifies the soil fertility dynamics and can either favour a build-up or loss of N, depending on the type of tillage practised (Nyawade, 2019). It affects soil microbial biomass, which in turn influences N transformations. Vazquez *et al*. (2019) reported that the tillage method affects microbial activities which are reflected in N cycling. Minimum tillage enhanced microbial activities in degraded acidic soils in Spain, increased soil moisture, and improved resistance of microbial activities to drought stress in a Mediterranean climate (León *et al*., 2017). While Vazquez *et al*. (2019) reported that no-tillage increased net mineralization, Raiesi & Kabiri (2017) recorded a decreased rate of N mineralization under conservation tillage. The contradictions could be a result of other management practices performed under the tillage methods. It is, therefore, vital to understand N mineralization under conservation and conventional tillage systems managed under ISFM strategies.

2.4.2 Modelling Nitrogen Mineralization

Uncertainties that characterize climate change and the high cost of trial experimentations within the realm of the changing climate have continued to force a paradigm shift to simulation studies. Process-based crop growth and cropping system models have been widely deployed to perform valuable studies on a wide range of topics, such as: assessing the impact of climate change; yield gaps and trends; evaluating the effect of sowing dates, nitrogen, soil moisture, crop varieties; cropping densities and sequence; and fertilizer management (Gaydon *et al*., 2017; Soufizadeh *et al*., 2018), among others. These models include; DSSAT, ORYZA (Radanielson *et al*., 2018), CSM-CERES-Maize (Hammad *et al*., 2018), and others. Nevertheless, different models, parameterized with the same parameters/inputs, can differ in their representation of the variable of concern. Therefore, there is a need for a specific, best-fit system-based model to simulate N mineralization, which is a very dynamic process affected by farmers' management practices (Gaydon *et al*., 2017).

Nitrogen mineralization is a complex process that requires accurate decision-support tools for effective management and prediction. Evidence of modelling N dynamics exists in the current literature, such as; Cold Regions Hydrological Modelling Platform (CRHM; Costa *et al*., 2021), DNDC model (Li *et al*., 2014), STICS soil-crop model, 2*SN* model (Venterea *et al*., 2021), Microbial-ENzyme Decomposition (MEND) model (Wang *et al*., 2020). Nitrogen dynamics has also been modelled using; Environmental Policy Integrated Climate (EPIC) model, HYDRUS-2D, SWB-Sci computer model (Ogbazghi *et al*., 2016), NCSOIL model (Noirot-Cosson *et al*., 2017). Additionally, N dynamics have been modelled under the maize-common bean intercrop system using the MOMOS model. Also, the PASTIS model was utilized to study N mineralization under repeated compost manure application (Chalhoub *et al*., 2013). These models have limited capability to model real farmers' soil fertility management decision trees, which is often complicated and changes from time to time depending on resource(s) availability.

The Agricultural Production Systems sIMulator Model (APSIM) has been improved to simulate complex interactions between crop genotype, climatic conditions, and management practices across varied environments (Brown *et al*., 2018). The APSIM is an even more powerful decision-support tool (Holzworth *et al*., 2018). It is a robust, efficient, and simple technique that can simulate various agricultural production scenarios. The sIMulator has successfully been used to study cropping systems, the effects of disease on crop yield, the salinity effect on sunflower yield, and the effect of conservation agriculture on wheat yield within the climate change context (Gaydon *et al*., 2017). The APSIM cropping systems modules (Holzworth *et al*., 2014) and soil module (SoilOrganicMatter) (Cichota *et al*., 2021) make APSIM a suitable candidate model to study N mineralization under contrasting tillage systems treated with diverse soil fertility amendments and residue retention in a maize cropping systems.

The robustness of APSIM allows the simulation of N mineralization in cropping systems. Recently, the model was used in modelling N mineralization from Brassica catch crop residues (Vogeler *et al*., 2019). The Model has also been validated under different cropping systems in Asia (Gaydon *et al*., 2017) and modelling N mineralization in maize crops (Soufizadeh *et al*., 2018). Furthermore, the crop module flexibility makes it possible to model intercrop systems (Wu *et al*., 2021). The few studies adopting APSIM in N mineralization have given attention to partitioning C pools from organic N based on first-order decay (e.g. Luo *et al*., 2014; Vogeler *et al*., 2019). The APSIM has also been applied in assessing the effect of inorganic fertilizer on N mineralization (Khaembah *et al*., 2021) and the estimated effect of P fertilization in Vertisols (Raymond *et al*., 2021). It is, therefore, important to evaluate the capability of APSIM to model N mineralization under a combination of inorganic and organic fertilizers. Parameterization of just one source of fertilization can lead to over- or underestimation of a parameter (Mohanty *et al*., 2012). A previous study intimated that APSIM accurately predicted NO_3^--N but poorly estimated NH_4^+-N and suggested improvement in mineralization processes in APSIM (Smith *et al*., 2019).

The tillage effect on soil parameters has been reliably modelled using APSIM. Yang *et al*. (2018) accurately modelled the effects of conservation tillage practices on evapotranspiration, soil water dynamics, and crop WP under maize-winter and wheat-soybean rotation systems. Ram *et al*. (2018) studied the effect of the tillage system on organic matter decomposition and recommended an improvement in the tillage component in crop models. The effect of N application rates, tillage, and residue management on N dynamics was later successfully modelled in a rice-wheat system using APSIM (Chaki *et al*., 2022). The application of APSIM on understanding N mineralization under minimum tillage treated with diverse amendments remains scarce, especially in CHK.

2.4.3 Nitrogen Use Efficiency

Low soil N, the high cost of N fertilizers, and their low use efficiencies have shifted attention to improving nitrogen use efficiency (NUE) for sustainable crop production. Nitrogen is one of the most important macronutrients for crop growth and development, yet its net use efficiency is just 30-35% (Umar *et al*., 2020). The global average NUE is 38% which varies with the type of crops in response to soil property changes (Yu *et al*., 2022). Several studies have found improved NUE in different crops under low soil N conditions (e.g., Liang *et al*., 2022). However, it differs among different crops even when treated with the same fertility amendments (Musyoka *et al*., 2017). Moreover, fertilizer response and NUE by maize are often spatially variable. Inorganic fertilizers, organic inputs, and residues of previous crops are important sources of N in soils experiencing N deficiency like Humic Nitisols.

Slow-releasing N fertilizers like urea were reported to have enhanced maize NUE in Nepal (Gautam *et al*., 2022). Liang *et al*. (2022) proposed the co-application of N as NH_4^+-N with P and K fertilizers for sustained NUE. Organic amendments are sources of NH_4^+-N through the mineralization process, while enhanced NUE has been reported under organic amendments in various crops (Hua *et al*., 2020). A global meta-analysis found low maize and wheat NUE under organic fertilizers (Yu *et al*., 2022). This finding was nevertheless contradicted by the results of Afreh *et al*. (2018), who found higher NUE under manure application. These differences in findings could be attributed to the type and quality of organic amendments applied. Moreover, a study intimated that ammonia nutrition cause an NUE decline (Chen *et al*., 2023). Also, residue retention with or without inorganic fertilizer (Yang *et al*., 2022) and RP (Cheptoek *et al*., 2022) have demonstrated their ability to improve the NUE of various crops in different locations. A study conducted by Biswas *et al*. (2019) found improved NUE in wheat when farm yard manure was treated with RP. However, further information on how integrating inorganic and organic fertilizations influence NUE is still needed for the effective management of N in a maize-based system.

Nearly 50% of total N in cropped soils is from the biological fixation under legume-diazotrophic bacteria association (Mahmud *et al*., 2020), while cereal-legume intercrops contribute 15% (Kakraliya *et al*., 2018). Maize is intercropped with diverse legumes globally and in Kenya by smallholder farmers (Yang *et al*., 2017). Besides increasing maize yields per unit area of cropped land, maize-legume intercrop also enhances NUE (Xu *et al*., 2020). Intercropping maize with peanut (*Arachis hypogaea*) and soybean (*Glycine max*) resulted in 8–29%, 28–49%, and 8–29% increase in maize yield, NUE, and partial productivity factor (PPF), respectively (Wang *et al*., 2022). Dolichos bean (*Dolichos lablab*) has an underexploited potential to fix N and improve NUE. Because N legume fixation varies among and within species (Mugi-Ngenga *et al*., 2022), the capacity of Dolichos beans to influence NUE should be investigated. The effect of treating Dolichos beans with manure under two contrasting tillage systems on maize NUE is a grey area for research.

Tillage modulates conditions for NUE amidst varying and often contradicting outcomes, probably due to differences in soil and crop types. Nitrogen use efficiency differed across five tillage systems (conventional (CT), subsoiling, chiselling, disk-harrowing, and no-tillage) under maize and wheat pure stands grown in two different soil types (Jug *et al*., 2019). Fern *et al*. (2021) reported improved NUE in wheat and barley treated with inorganic N and poultry manure under a no-tillage system. Additionally, no-tillage combined with maize straw retention recorded higher NUE in wheat in a dry ecosystem (Yang *et al*., 2020). But, CT combined with residue retention and N addition had higher winter wheat NUE than reduced tillage in a cooler ecosystem (Brennan *et al*., 2014). A study reported that contour ridge tillage combined with residue retention had higher N recovery (NR; 29.4%), agronomic efficiency (NAE; 25.8%), and N PPF (1.7%) of maize than reduced tillage in Lixisol (Nafi *et al*., 2019). A global meta-analysis of 767 observations for conservation tillage systems, nevertheless, reported a 15% average decrease in maize NUE (Zhang *et al*., 2022). In another study, deep vertical rotary tillage combined with the same N fertilizer as in a no-tillage system had significantly higher NR (82.1 %), NAE (36.2 %), and PPF (20.1 %) for summer maize (Zhai *et al*., 2019). Despite the varying NUE responses to tillage systems, there is a limited understanding of the effect of MT on maize NUE. Moreover, tillage system studies that integrate smallholder farmers' complex (multiple) fertilization management are currently unavailable.

2.5 Soil P Fractionation

Soil P is one of the most important plant nutrients, second only to N. Its availability or lack of it to plants is affected by soil management practices such as fertilization and tillage.

These two agronomic practices have an influence on P fractions, sorption characteristics, and use efficiency.

2.5.1 Soil Phosphorus

Phosphorus is one of the three essential plant nutrients usually accumulated on the agricultural soil surface and is estimated to be 1412 kg ha^{-1} (Moe *et al*., 2019). The majority of agricultural soils worldwide have large total P reserves, but only a small fraction is often available for plant uptake. For agricultural optimization, P has to be added into the soil through inorganic and/or organic forms and legume intercrops. World over, P input from inorganic fertilizers and manure is estimated to be 14.2 and 9.6 million t year^{-1}, respectively, but 12.3 million t year^{-1} P is lost through harvested crops (Macdonald *et al*., 2011).

Phosphorus regulates crop root development and forms part of adenosine diphosphate and triphosphate, which drive critical metabolic processes in plants. Yet, it is one of the most limiting essential nutrients in acidic soils such as Humic Nitisols (Bai *et al*. 2019). Phosphorus challenges are mainly linked to; low solubility, low concentrations in soil solution, and high fixation. Humic Nitisols are deep and highly weathered thus, contain substantial amounts of hydrogen (H^+), aluminium (Al^{3+}), and iron (Fe^{3+}) ions which are responsible for P fixation (Mahmood *et al*., 2021). Therefore, the need to understand technologies that could improve soil P in such soils is critical for optimal crop production.

Clay inorganic P is one of the sources of soil P, but its disadvantage is that it depletes with increasing soil residence time (Eger *et al*., 2018). Soil is often considered a P sink which is converted into a P-releasing source usually in response to changing external conditions, mostly decreasing exogenous P load (Bai *et al*., 2019). The P conversion process (mineralization) is instigated by the soil microbial need for C. Soil texture and mineralogy influence the chemical reaction that P undergoes after fertilization and the intensity of the accumulation of distinct fractions (Nunes *et al*., 2020). Nonetheless, a study in China feared that over-dependence on soil-sourced organic P could have severe implications for

P management (Li *et al*., 2019). Therefore, alternative P sources are crucial in P management in agricultural soils.

Phosphorus management greatly depends on external additions from fertilizers and organic amendments, which may lead to P build-up in the soil. Panagos *et al*. (2022) reckon equal contributions of inorganic fertilizers and manure as P inputs. Organic P (Po) can be as high as 80% of total soil P in some soils (Xu & Arai, 2022). The transformations, mobility, and availability of P are affected not only by P and N additions but also by tillage, type of crop grown, P-solubilizing microbes, and enzyme activities (Tayyab *et al*., 2018). A recent study reported that inorganic P fertilization moderates associations between arbuscular mycorrhiza, rhizosphere yeasts, and maize (Sarabia *et al*., 2017). Other P sources include RP, organic inputs such as compost, and cover crops (Soltangheisi *et al*., 2018). Additionally, P can be added to the soil by incorporating crop residues. But, adding crop residues low in P to soils that are also low in P can lead to net assimilation of organic P. Legume residues increased soil P as opposed to cereal residues which are low in P (Damon *et al*., 2014).

2.5.2 Response of Soil P Fractions to Fertility Management Technologies

Fertilization technologies can influence the distribution or amounts of P fractions. Previous studies have reported P's response to inorganic fertilizers (Bhattacharyya *et al*., 2015) and animal manure (Wei *et al*., 2022). A study has found significantly higher P under the co-application of inorganic fertilizer and animal manure (Mi *et al*., 2018). Pizzeghello *et al*. (2016) state that inorganic fertilizer and farmyard manure affected extractable P forms.

Also, RP has been reported to improve P fractions in different soil types (Soltangheisi *et al*., 2018; Somavilla *et al*., 2021). The contribution of inorganic phosphoric fertilizers to soil residual P pool was reported by Shafqat and Pierzynski (2013). It was found that large proportions of added inorganic P promoted the accumulation of moderately labile P on the topsoil layer (Pavinato *et al*., 2009). On the contrary, Tiecher et al. (2018) reported a lack of association between inorganic fertilizers and inorganic and residual P fractions. Further, Soltangheisi *et al*. (2018) reported increased fractions of labile P under cover crops treated with single superphosphate fertilizer. Several studies in CHK have promoted cereal-legume intercrop (Arb *et al*., 2020) and *T. diversifolia* (Kiboi *et al*., 2020) in managing soil fertility. Thus, in addition to RP, it is imperative to evaluate the contribution of ISFM on P fractions in Humic Nitisols of the CHK.

The effect of cereal-legume intercrop on P dynamics may be caused by interaction between non-mycorrhizal, mycorrhizal plants, and Mycorrhizosphere bacteria (Song *et al*., 2021). Soil microbial processes drive transformations of P as the legume crop grows (Joan *et al*., 2017). Maize-faba bean intercrop had a lower HCl-Po fraction in calcareous soil (Liao *et al*., 2020). When there was no P input, maize-faba bean intercrop depleted hydrochloric acid-extractable inorganic P (HCl-Pi), sodium hydroxide- extractable organic and inorganic P (NaOH-Po and NaOH-Pi)but increased NaOH-Pi when under long-term P fertilization (Liao *et al*., 2021). Root residues with an intermediate C/P ratio of intercropped maize-faba beans could lead to a reduction in sodium bicarbonate-extractable organic P ($NaHCO_3$-Po) and hydrochloric acid-extractable organic P (HCl-Po) fractions (Liao *et al*., 2022).

Additionally, relative to monocropping, intercropping maize with either peanut or soybeans had significantly higher labile-P (3.1-7.8%), stable-P (18.7-63.2%), soluble-P (8.4-35.5%), hydrolysable-P (0.2-28.3%), and exchangeable-P (38.6-637.1%) (Yang *et al*., 2022). Organic amendment (multi-nutrient compost) increased labile Pi by 62–93% than the control (no fertilizer addition). Still, it reduced recalcitrant Pi by 29% over inorganic fertilizations in a maize-cowpeas intercrop system (Roohi *et al*., 2020). It was found that microbial processes mobilized large amounts of Pi during legume crop growth stages (Joan *et al*., 2017). It has also been reported that intercropping leguminous and non-leguminous crops did not affect P fractions (Tariq *et al*., 2022) which could be attributed to divergent legume species. Therefore, assessing P fractions under maize-*Dolichos lablab* intercrop would contribute immensely to our understanding of the effect of such a unique intercrop system on different P fractions.

Conventional and conservation tillage affect P fractions and offer an indirect path to P management. Modification of reduced tillage with crop residue retention increased labile and organic P in acidic soil in Western Kenya (Margenot *et al*., 2016). Nunes *et al*. (2020) found a higher accumulation of labile inorganic P (P_i) fractions, calcium-bound P (HCl-P), and physically protected organic P (P_o) under no-tillage (NT) than in CT in a clayey Rhodic Ferralsol. Additionally, there were higher labile and moderately labile P fractions but lower recalcitrant P fractions under NT than in CT in two paddy soils (Ahmed *et al*., 2020). In two Brazilian Ferralsols, Thomas *et al*. (2022) found only a slight increase in recalcitrant P_i and P_o and just small remains of labile fractions in addition to massive amounts of legacy P after long-term cultivation of soybean/cotton with varying cover crops rotations.

Moreover, the tillage system did not significantly affect labile P_o in a maize-based system, but NT had higher amounts of soluble and loosely bound P fractions. In contrast, CT had higher iron-bound P (Fe-P), calcium-bound P (Ca-P), aluminium-bound P (Al-P), and reductant soluble P (Anil *et al*., 2022). However, concentrations of different P fractions, as demonstrated by Pradhan *et al*. (2021), can be dictated by the crop growth stage under fertilization. Therefore, it is important to assess the impact of CT and MT on the quantities of different P fractions for effective P management in a maize-based cropping system.

Moreover, the tillage system indirectly influences soil P dynamics by modifying the soil ecosystem favouring P-solubilizing microorganisms and enzymes and aggregate protection (Oliveira *et al*., 2022). The tillage method could affect the vertical distribution of P fractions (Obour *et al*., 2017). Yang *et al*. (2017) found a significant increase in total phosphorus in 20-40 cm depth under CT with maize straw mulching, while the P content remarkably increased in the topsoil under NT with grass mulch. It was also recorded in Brazil that NT did not significantly affect quantities of available P (Pavinato *et al*., 2009). However, Tiecher *et al*. (2018) reported a direct relationship between moderate inorganic P and resin P under NT. The direct impact of NT on the positive correlation between moderate inorganic P and resin P could have resulted because of the improved microbial diversity and stability (Yi *et al*., 2017). On the other hand, it was reported that CT indirectly influenced resin-P through contribution to moderately labile organic P input. Though the direct effect of tillage on soil microbes and the consequent P bioavailability is well known, little is still known about how it affects different P fractions under ISFM practices under different tillage methods.

2.5.3 Response of P Sorption Characteristics to Fertility Management Technologies

Some of P sorption characteristics include; maximum sorption capacity (S_{max}), degrees of P saturation (DPS), and bonding energy (*k*). Maximum sorption capacity is the sum of the P sorption index and oxalate-extractable P, estimated by fitting empirical models like the Langmuir isotherm using laboratory experiment data (Campos *et al*., 2016). Degrees of P saturation is a simple risk assessment index developed to estimate the potentiality of P loss from soils (Rechberger *et al*., 2021). The DPS is the ratio of P already sorbed and the soil sorption capacity or the percentage of sites saturated by P in relation to soil adsorption capacity. It is possible to derive *k*, energy with which P is sorbed on the binding sites, from the Langmuir isotherm equation (Yan *et al*., 2017). Though P sorption parameters have been used in many countries, they are yet to be fully exploited in Kenya, especially in CHK, where farmers use diverse ISFM technologies that may affect the parameters.

Amorphous Al^{3+} and Fe^{3+} greatly contribute to P sorption in acidic soils (Arruda *et al*., 2019; Mahmood *et al*., 2021), but fertilization can also impact it. The effect of sorption and desorption of mineral P on bioavailability is well documented (Zhang *et al*., 2019), while organic P is now drawing research interest (Sun *et al*., 2019). There are indications that inorganic fertilizers and organic amendments influence P sorption characteristics (Debicka *et al*., 2016; Thomas *et al*., 2022). But these characteristics have differed in response to the same fertility inputs in previous studies. Both increase and decrease in P sorption under organic amendments have been reported in different soils (Nobile *et al*., 2020). Moreover, inorganic and organic fertility amendments are thought to affect different P fractions (Pizzeghello *et al*., 2016), which could affect P sorption characteristics. Arruda *et al*. (2019) alluded that organic amendments have a greater impact on P dynamics than inorganic fertilizers, while Pradhan *et al*. (2021) reported contradicting impacts of organic amendments on DPS.

The tillage system modifies P sorption characteristics as demonstrated in the various studies investigating its effect on P sorption characteristics. For example, Shafqat & Pierzynski (2010) found higher S_{max} and lower k when NT was amended with manure compared to CT. Similarly, a study carried out in Brazil found that NT improved S_{max} and DPS in the near soil surface layer in an incubation trial using Oxisols under maize–radish–cotton–soybean rotation system (Pavinato *et al*., 2010). A 9-year (18 cropping seasons) long-term study established on acidic weathered soil in western Kenya found increased S_{max} under reduced tillage (RT) system with or without residue retention (Margenot *et al*., 2016). But, the effect of direct drilling on P sorption was insignificant to CT in a calcareous Vertisol (Bravo *et al*., 2006). Though organic matter (OM) increased under NT, the tillage did not significantly affect maximum P adsorption capacity in a study by Fink *et al*. (2014). A combination of MT and organic fertilization decreased P maximum adsorption capacity and the bonding energy, *k*, while DPS increased (Pradhan *et al*., 2021). The clay content of soil can also influence P sorption parameters under different tillage systems. Phosphorus adsorption was higher in Ferralsol (high clay content) than in Nitisols (low clay content) under NT relative to CT (Fink *et al*., 2016). Despite being widely promoted, the effect of MT on P sorption characteristics has not been vastly exploited. Therefore, it is important to investigate the long-term effect of the tillage system on P sorption parameters at the field level.

2.5.4 Phosphorus Use Efficiency

Phosphorus worldwide is deficient in 43% of 1.37 billion ha of agricultural land (Wang *et al*., 2021). Because of this, future projections have suggested an increase in the use of P fertilizers from 34.3 Tg to 83.7 Tg annually by the year 2050 to meet the growing food demand (Hinsinger *et al*., 2011). Many agrarian nations are transitioning to middle-income economies with a resultant increase in gross domestic product. Thus, it is estimated that there will be about 145% growth in the national P inflow by the year 2030

(Tasmeea *et al*., 2021). Further, it is estimated that 10 to 23 Tg P yearly will accumulate in the soil, out of which 3 to 5 Tg P will be lost through erosion annually by the year 2050 (Bouwman *et al*., 2009). The current and future surge in consumption of P fertilizers in croplands and the goal to increase crop productivity demand for ISFM strategies that improve P use efficiencies (PUE) to avoid wastage and potential environmental pollution. On average, global grain and aboveground PUE are low at 9.1% and 12.4% in cereals (Yu *et al*., 2021).

Previous studies have illustrated the effect of the application of fertilizers on PUE. Management practices that affect soil N, P, and community turnover influence PUE (Zhang *et al*., 2023). The application of TSP increased three soybean cultivars' agronomic PUE, while NPK 20:20:20 recorded the lowest values (Pakhshan *et al*., 2013). In sugarcane plantations, the P fertilization rate of 28–50 mg kg^{-1} had the highest PUE, beyond which it declined (Wu *et al*., 2020). Also, applying sole NPK and compost improved PUE by 53.7% and 59.9% in a maize-wheat system (Xin *et al*., 2017). Furthermore, Zafar *et al*. (2013) recorded 17% higher PUE in maize under integrated inorganic fertilizer and poultry manure application than sole inorganic fertilizer. Also, a study conducted in Ethiopia reported an increase in P agronomic use efficiency (PAE) from 26.3 to 163 and P partial productivity factor (PPF) from 169.1 to 324.8 under the sole application of TSP when TSP was integrated with *T. diversifolia* (Endris, 2019). Similarly, maize PUE was higher under a combination of P fertilizer and residues of cover crops (Pavinato *et al*., 2017). Therefore, assessing the effect of diverse soil fertilization amendments on maize PAE and PPF in acidic Nitisols of CHK could be vital in P management.

Rock phosphate is an important source of soil P in cultivated land and may improve PUE in different crops. A study in Western Kenya reported improved PUE under RP (Cheptoek *et al*., 2021). Pavinato *et al*. (2017) revealed that over time, RP greatly improved PUE (the highest recorded value was 30 kg grain per kg P) than the soluble sources of P. Combining RP and acidulated PR with organic amendments improved PUE in maize-based cropping system in calcareous soil (Mussarat *et al*., 2021). Organic fertilization increases the activity of phosphate-solubilizing bacteria to solubilize RP, resulting in improved PUE (Liang *et al*., 2022). Additionally, maize PUE of RP has been enhanced by combining it with TSP and/or N fertilizer (Mohanty *et al*., 2021). Therefore, it is also vital to investigate the effect of combining RP with *T. diversifolia* on maize PUE in CHK.

Interspecific interactions and complementarity between intercropped crops may increase PUE in acidic soils (Wang *et al*., 2020). Root morphology, carboxylate exudation, and mycorrhizae associations are some important mechanisms that legume crops use to increase P acquisition and PUE (Pang *et al*., 2018). The interaction effect of fertilization and intercropping on PUE is primarily controlled by rhizosphere-microbial processes (Roohi *et al*., 2020). Dwivedi *et al*. (2019) recorded increased microbial activities under P fertilization correlated with higher P availability and PUE in a maize-wheat system. Furthermore, a meta-analysis study indicated that cereal-legume intercrop increases PUE (Tang *et al*., 2020). Several other studies have also reported improved PUE under different cereal-legume intercrop systems (Wang *et al*., 2017; Yang *et al*., 2022). However, PUE varies with the type of cereal-legume intercrop. It is, thus, essential to assess the influence of maize-Dolichos intercrop on PUE.

Different factors explain variations in PUE. For instance, it tends to be higher under low soil P status and varies with the stage of crop growth and cultivar. Variations in maize PUE can be attributed to varietal differences. It is thought that plants recover about 10-15% of P fertilizer applied, but this value could be affected by the experimental period and source of P (Zafar *et al*., 2013). As high as 50-70% P recovery has been reported in a long-term experiment (Roberts & Johnston, 2015). It is, therefore, crucial to understand the effect of ISFM technologies on PUE in acidic Nitisols characterized by low available P.

2.6 Summary of the Literature Review

Nitrogen and P, in different forms, are deficient in most cultivated soils globally and in the CHK. This status explains the observed reduction in yields of major crops. Soil microbial biomass C, N, and P contributes to the general soil fertility and sources of nutrients to crops. Additionally, N mineralization from fertility amendments adds nutrients to the soil. Though there are substantial amounts of P in most soils, it remains one of the most problematic nutrients to manage, especially in highly weathered soils like Humic Nitisols. Different technologies have been proposed and utilized to manage either N, P or both. These include sole inorganic fertilizers, animal manure, combined inorganic fertilizers and animal manure, legume intercrop or rotation, RP, and various green manures. The ISFM concept has been expensively promoted as the best strategy to improve soil fertility in smallholder farms. However, studies have shown varying responses of soil fertility indicators to different ISFM technologies.

Soil microbial biomass C, N, and P can be affected by N and P fertilization, soil aggregate size distribution, and crop types. The changes of MBC, MBN, and MBP to soil fertility amendments and tillage may be in response to the change in the composition of the microbial community by altering soil chemical and physical properties. Significant MBC has been reported under green manure-treated plots, while farmyard manure also increased MBC and MBN. Additionally, inorganic fertilizers can enhance MBC and MBP but reduced MBN.

Nitrogen mineralization is also affected by soil fertility amendments and respond variably. Positive correlations between N mineralization with MBN and MBC exist in the current literature. The ISFM influences N mineralization through the addition of inorganic and organic N. Soil N transformation processes are driven mainly by soil microbial communities, responding to practices that affect the soil fauna. Combining inorganic and organic fertilizers affect soil fungal and bacterial community compositions. Combining manure with inorganic fertilizers can also improve N mineralization by enhancing the accumulation of physically-protected and unprotected N. empirical evidence showed that integrating inorganic P fertilizer and a low inorganic N fertilizer improves gross and net N mineralization in a wheat cropping system. The application of NPK and RP may also promote N mineralization by regulating bacterial community and SMB. High amounts of on $\mathrm{NH_4^+}$-N and $\mathrm{NH_3^-}$-N has been reported when RP was combined with *T. diversifolia.* It is generally agreed that tillage influences n mineralization by modulating soil fertility dynamics but with contradicting outcomes.

Nitrogen mineralization is a complex process that requires accurate decision-support tools. There is evidence that illustrates that this process can be accurately simulated using process-based models. Most of the available models cannot simulate real farmers' soil fertility management decision trees and the complex integrated fertility amendments. The APSIM can simulate complex integrated amendments under CT and MT systems. The Model has been adopted in simulating N mineralization in maize crops, assessing the effect of inorganic fertilizer on N mineralization. Moreover, a study intimated that APSIM accurately predicted $\mathrm{NO_3^-}$-N but poorly estimated $\mathrm{NH_4^+}$-N. The model has also been found to simulate tillage's effect on soil parameters reliably.

Phosphorus fractionation and sorption characteristics are essential in understanding the P conversion processes and PUE. These parameters are affected by fertilization technologies. The contribution of inorganic phosphoric fertilizers to soil residual P pool has been reported. Application of inorganic fertilizers promoted the accumulation of moderately labile P, while RP improved P fractions in different soil types. However, there was no association between inorganic fertilizers to both inorganic and residual P fractions. Higher fractions of labile P have been recorded under cover crops treated with single superphosphate fertilizer. Maize-faba bean intercrop resulted in a lower HCl-Po fraction, while HCl-Pi, NaOH-Po, and NaOH-Pi were depleted without P input. Phosphorus fractions are influenced differently by the tillage system. For instance, some studies have found a higher accumulation of labile inorganic Pi fractions, calcium-bound P HCl-P, and physically protected Po under NT than in CT. Elsewhere, NT had higher amounts of soluble and loosely bound P fractions, while CT had higher Fe-P, Ca-P, Al-P, and reductant soluble P. Previous studies show that inorganic fertilizers and organic amendments influence P sorption characteristics. Both increase and decrease in P sorption have been reported under organic amendments. Nevertheless, it has been alluded that organic amendments have a greater impact on P dynamics than inorganic fertilizers but other studies have also found contradicting impacts of organic amendments on DPS. Other studies have found higher S_{max} and lower k when NT was amended with manure compared to CT. Also, NT improved S_{max} and DPS in the near soil surface layer in an incubation trial using Oxisols under maize–radish–cotton–soybean rotation system. A combination of MT and organic fertilization exhibited a decrease in P maximum adsorption capacity and the bonding energy, while DPS increased in another study.

The application of TSP increased three soybean cultivars' agronomic PUE, while the application of NPK 20:20:20 recorded the lowest values. The application of NPK and compost improved PUE in a maize-wheat system. A higher maize PUE has been reported under integrated inorganic fertilizer and poultry manure. Also, a study conducted in Ethiopia reported an increase in PAE and PPF under the sole application of TSP and when integrated with *T. diversifolia*.

2.7 Research Gap

Soil microbial biomass C, N, P, N mineralization and P fractions play important roles in soil fertility and crop nutrition. However, despite ISFM technologies being promoted in CHK and generally among smallholder farmers, little is known about how these soil parameters respond to different ISFM technologies, which could explain why crop yields are still low. It was unclear how integrating maize residue with; 1) goat manure and Dolichos, 2) manure and NPK 17:17:17, 3) manure and *T. diversifolia*, and 4) *T. diversifolia* and RP and sole inorganic fertilizer under CT and MT systems affect C, N, P, N mineralization, P fractions, and P sorption characteristics in Humic Nitisols. Furthermore, APSIM is an important decision-support tool widely utilized in simulating different facets of agricultural production systems globally. However, it has not been validated as the best model to accurately simulate N mineralization under the selected ISFM technologies in the current study.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Introduction

This Chapter describes the study area where the experiment was established, putting more emphasis on the predominant soil type. It also covers the research design and treatments adopted, and soil sampling procedure. Furthermore, the Chapter describes how data addressing each objective was collected and the laboratory analyzes carried out. Lastly, it details how the collected data was statistically analyzed and presented.

3.2 Study Site

The experiment was established in the Humic Nitisols of Chuka Subcounty at Kangutu Primary School (00° 98'S, 37° 08'E) in Tharaka-Nithi County situated within the Central Highlands of Kenya **(Figure 3.1)**, under Organic Resource for Soil Fertility Management (ORM4Soil) Project in March 2016 (long rains) and ran for eleven (11) cropping seasons. The last season was the long rains of 2021. Maize (*Zea mays* L.), H516 variety was planted throughout the experimental period as the test crop. Several components of the research were undertaken by various postgraduate students. This study focuses on the 2020 short rains (SR20) to 2021 long rains (LR21).

Initial soil properties of the study area are shown in **Table 3.1.** The soil is typically deep and highly weathered, with moderate to high inherent fertility. The annual rainfall in the County is bimodal and ranges between 1200 to 1400 mm. The long rains (LR) fall from March–June, and short rains (SR) are experienced between October– December thus, there are two cropping seasons in a calendar year.

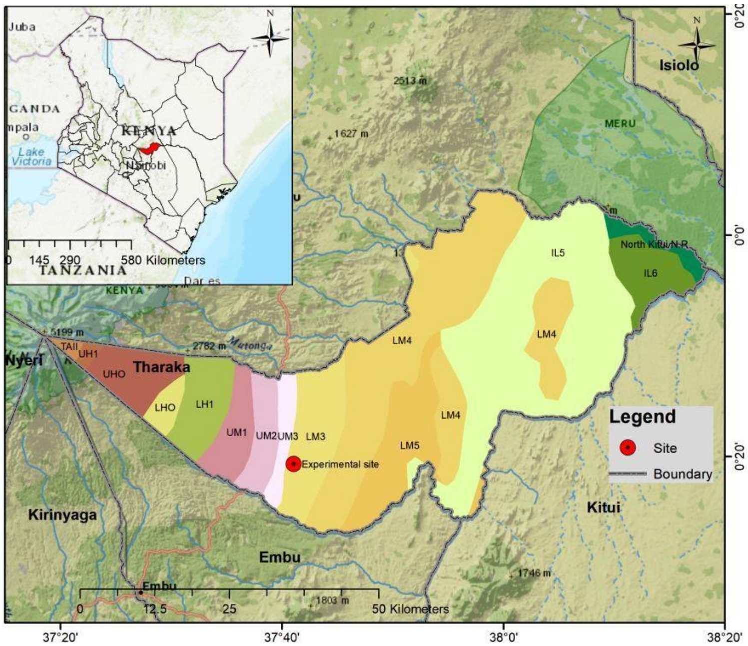


Figure 3.1: Study Map of Kenya's Administrative Boundaries, Tharaka-Nithi County, Experimental Site and Agroecological Zones

Figure 3.1 legend: IL5, IL6, LH0, LH1, LM3, LM4, LM5, UH0, UH1, UM1, UM2, and UM3 represent agroecological zones and denote inner lowland zones 5 and 6, low highland zones 0, 1, 3, 4, and 5, upper highlands 0 and 1, and upper midland zones 1, 2, and 3, respectively.

Table 3.1: Initial Soil Physicochemical Properties before the Start of the Experiment in March 2016 Long Rain Season (LR16)

Soil parameter	**Value**
Total N (%)	0.14
Total carbon, C (%)	1.48
Soil organic matter (%)	2.55
Total P (g kg^{-1})	29.35
Available P (g kg^{-1})	0.02
Iron, Fe^{3+} (ppm)	32.53
pH (1:1 H_2O)	4.85
Clay (%)	70
Sand (%)	16
Silt (%)	14
Textural class	Clay

Source: Kiboi *et al*. (2017)

Mean annual temperatures range from 19 to 21 °C. Daily rainfall and radiation in the site for the experimental period are shown in **Figure 3.2**. Kangutu rests at 1,458 m above sea level and is situated within UM 2 agroecological zone (main coffee growing zone) (Jaetzold et al., 2007). Smallholder farmers mainly practice mixed farming for subsistence purposes, where maize is the dominant food crop among the farmers who keep livestock and grow cash crops.

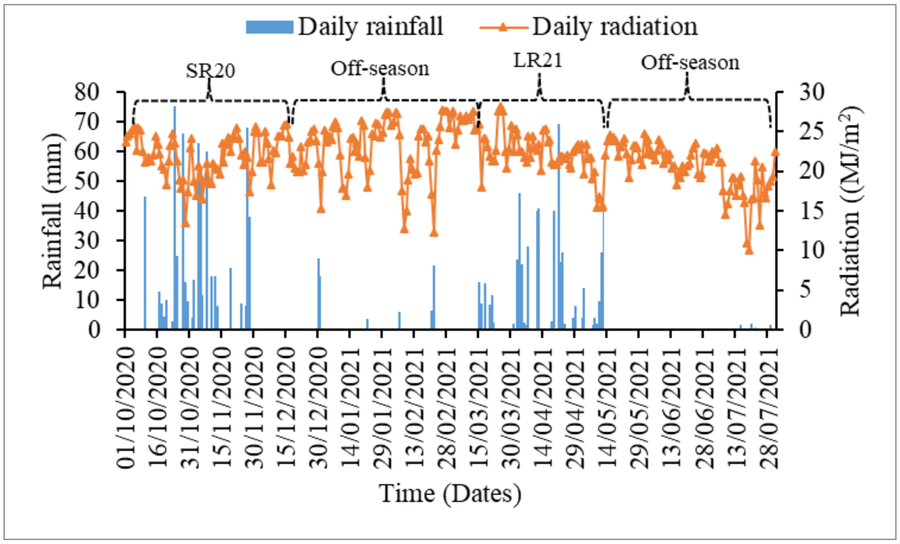


Figure 3.2: Daily Rainfall Amount and Radiation Received During SR20 and LR21 Seasons

3.3 Experimental Design and Management

The experiment was laid out in a randomized complete block design for a period of 11 cropping seasons. A preliminary household survey was conducted in Chuka to inform the selection of the treatments. Tillage system and soil fertility amendments were integrated, and considered combined treatments as shown in **Table 3.2.** The treatments were replicated four times in plots measuring 6 m x 4.5 m. Maize (*Zea mays* L.) H516 variety was the test crop in the experiment since the establishment of the project in in March 2016 long rains (LR16). However, data for this study was collected during short and long rains in 2020 (SR20) and 2021 (LR21), respectively.

Table 3.2: Treatments Implemented During the Trial

Tillage system	Soil fertility amendments (SFAs)	Combined treatment
Conventional	No amendments (Control)	C
Conventional	Inorganic fertilizer	CTF
Conventional	Crop residue + Inorganic fertilizer	CTCrF
Conventional	Crop residue + Inorganic fertilizer + Goat manure	CTCrGF
Conventional	Crop residue + Goat manure + Dolichos intercrop	CTCrGL
Conventional	Crop residue + *Tithonia diversifolia* + Goat manure	CTCrTiG
Conventional	Crop residue + *Tithonia diversifolia* + Rock phosphate	CTCrTiR
Minimum	No fertility amendments	MT
Minimum	Inorganic fertilizer	MTF
Minimum	Crop residue + Inorganic fertilizer	MTCrF
Minimum	Crop residue + Inorganic fertilizer + Goat manure	MTCrGF
Minimum	Crop residue + Goat manure + Dolichos intercrop	MTCrGL
Minimum	Crop residue + *Tithonia diversifolia* + Goat manure	MTCrTiG
Minimum	Crop residue + *Tithonia diversifolia* + Rock phosphate	MTCrTiR

Soil management involved ploughing to 20 cm depth using a hand hoe in CT, while MT involved surface scrabbing using a machete to clear the plant residue and digging 20 cm deep planting holes. Two weeks before planting, organic amendments were placed in planting holes under the MT system but applied uniformly under the CT system and incorporated into the soil by ploughing. Care was taken to ensure uniform distribution of the organic amendments during application. Inorganic fertilizers were applied at planting. Nitrogen was applied at 60 kg N ha^{-1} based on the maize N requirement for the soil type (Kiboi *et al*., 2018). Sources of N were NPK 17:17:17, goat manure and *T. diversifolia*. An amount equivalent to 60 kg N ha^{-1} by dry weight from goat manure (3.4 t ha^{-1}) and *T. diversifolia* (1.7 t ha^{-1}) that contained 1.75% and 3.80% N, and 0.39% and 0.30% P, respectively, were applied. *T. diversifolia* was cut at active vegetative stage before flowering where leaves and tender twigs were chopped into smaller pieces before application. Similarly, P was applied at the recommended maize rate of 90 kg P as P_2O_5 from the NPK and RP (27:29% total P_2O_5, 36:38% CaO). Triple Superphosphate (0:46:0) was applied alongside NPK to attain a 90 kg P ha^{-1} rate. Treatments with sole inorganic fertilizer (NPK) were top-dressed using Calcium Ammonium Nitrate (CAN) when the crop was at knee height. Nutrient application rates were halved in plots that received a combination of inorganic-organic, while full rates were applied in sole inorganic fertilizer and sole organics plots.

Maize was planted at 0.75 m and 0.50 m, inter- and intra-spacing, respectively. Three (3) seeds were placed per hole and thinned back to two (2) seedlings after full emergence. *Dolichos lablab* was planted in the middle of the inter-rows of maize on the same day as maize under the intercrop treatments (CTCrGL and MTCrGL). Five (5) t ha^{-1} of maize residue was surface-applied after thinning (Kiboi *et al*., 2019). Weeding was done twice a season by roguing and hand hoe under MT and CT, respectively. The plots were kept free from diseases and pests by constant surveillance and the application of pesticides.

3.4 Data Collection and Laboratory Analyses

The sub-section describes soil sampling and laboratory analysis procedures. It presents how soil microbial C, N, and P, mineralized N, P fractions, and sorption characteristics were determined in the laboratory.

3.4.1 Soil Sampling and Rainfall Measurement

Soil samples were collected from within-rows at the end of the experimental period from 0-20 cm depth using a soil auger for N, P, MBC, MBN, MBP, P fractionation, and P sorption characteristic determination. About 100 g samples were collected and divided into 75 g to determine N, P, and P fractions and sorption characteristics. The remaining 25 g samples were transported to the laboratory on a cool box filled with ice cubes and stored in a deep freezer at -20 °C awaiting extraction. Bulk density determination samples were collected using core rings from the 0-20 cm soil depth. Daily rainfall readings were obtained from a manual rain gauge installed approximately 20m from the experimental site. The rainfall readings were recorded daily at 0900 h. Radiation was obtained from the National Aeronautics and Space Administration (NASA) website (https://power.larc. nasa .gov/data-access-viewer/). Longitude (37.6833) and latitude (-0.33849) coordinates were used to specify the exact location. The ‘All Sky Surface Shortwave Downward’ file was downloaded from the ‘Solar fluxes and related’ folder.

3.4.2 Determination of Available N, P, Legacy P, and SMB C, N, and P

The samples were air-dried, ground, and passed through a 2-mm mesh. Available soil N and P were extracted following Kjeldahl and Bray 2 methods, respectively (Ryan *et al*., 2001). For N determination, 0.3 g of oven-dry was digested using 2.5 ml of digestion mixture at 110 °C for 60 minutes. One (1) mm hydrogen peroxide was added successively to accelerate the digestion. A colourless solution from the digestion was left to cool then 25 ml of distilled water added and left to further cool. The mixture was made up to 50 ml using water. A clear solution from the top of the mixture was taken for N determinisation using distillation-titration method. Sample from the clear solution was used to determine P using colometric method. Phosphorus was determined using UV Spectrophotometer at 400 nm wavelength. Soil pH was determined using pH meter (2.5:1 H_2O). Nitrogen was determined using the Distillation-Titration method **(Plate 3.1),** while the extracted P was determined colorimetrically using a spectrophotometer, as Okalebo et al. (2002) outlined. Legacy P was calculated as the difference between available soil P at the end of the study and initial soil P at the start of the experiment.

Plate 3.1: Soil Digestion and Kjeldahl Process for N Determination

Microbial biomass C, N, and P were determined by the chloroform fumigation-extraction method (Sun *et al.*, 2018). Briefly, 15 g of wet soil samples were emptied into 50 ml beakers and placed in two sets of desiccators (**Plate 3.2**). The moisture content of the samples was determined so that the final results were expressed on a dry weight basis. One desiccator containing the samples was fumigated with ethanol-free chloroform at 25 °C for 72 h in a dark room. The other desiccator containing an equal weight of samples was not fumigated but was similarly placed at 25 °C for 72 h in a dark room. Both fumigated and non-fumigated samples were extracted using 40 ml 0.5 M K_2SO_4, KCl, and 0.5 M $NaHCO_3$ solutions for C, ammonia-bound N (NH^+_4-N), and inorganic soil P, respectively. The solutions were shaken for 30 min at 200 rpm on an end-to-end shaker, after which the extracts were filtered through No 42 filter papers. The filtrates were measured using a spectrophotometer at 600 nm, 655 nm and 882 nm for MBC, MBN and MBP, respectively.

Plate 3.2: Soil Samples Placed in Desiccators for Incubation and Extraction

Biomass C, N, and P were then converted using Equations **3.1, 3.2**, and **3.3** (Sun *et al*., 2018):

$$\mathrm{MBC} = {}^{\mathrm{E_C}}/_{\mathrm{K_{EC}}} \tag{3.1}$$

$$\mathrm{MBN} = {}^{\mathrm{E_N}}/_{\mathrm{K_N}} \tag{3.2}$$

$$\mathrm{MBP} = {}^{\mathrm{E_P}}/_{\mathrm{K_P}} \tag{3.3}$$

Where E_C = (organic C extracted from fumigated soil – organic C extracted from non-fumigated soil) and K_{EC} = 0.45, which is the scalar factor to convert E_C to soil MBC; E_N = (flush of NH^{+}_{4}-N due to fumigation – NH^{+}_{4}-N produced in the non-fumigated control); K_N = 0.57 (proportionality conversion to MBN; E_P = (Total P_i extracted from fumigated soil – Total P_i extracted from non-fumigated soil) and K_P = 0.40 (conversion factor to MBP).

3.4.3 Determination of Mineral N

Nitrogen mineralization was determined by the field incubation method (*in situ*) (Arslan *et al*., 2010). The field incubation study was conducted during SR20 and LR21 cropping seasons. Soil samples were collected fortnightly from the 0-20 cm depth using Eijkelkamp Gouge Auger. At the onset of the incubation study, the samples were randomly collected from three points in every plot and thoroughly mixed to form composite samples. Plant debris was manually removed, and each composite was divided into two equal portions. The first portion was taken to the laboratory for the determination of initial mineral N (NH_4^+-N and NO_3 -N). The other portion was placed in a polythene bag wrapped in a second bag and tightly tied and buried in one of the three sampling points, at the same depth of sampling until the next sampling interval. This procedure was repeated after every two weeks from the planting date. The samples were transported to the laboratory in cool boxes filled with ice packs and kept in a deep freezer at -20 °C awaiting analysis. At the same time, 10 g soil samples were weighed *in-situ* and placed in sampling bags. These samples were used for the gravimetric determination of soil moisture content (SMC) by oven-drying at 105 °C for 24 h. Gravimetric SMC (%) was converted to volumetric SMC ($m^3\ m^{-3}$) using Equations **3.4** to **3.7**. Volumetric SMC was used to calculate water productivity (WP) in equation **Error! Reference source not found.**.

$$\text{Bulk density } (\text{g } cm^{-3}) = \frac{\text{Soil Solids (Ms)}}{\text{Total Volume of Soil (Vt)}} \qquad \textbf{(3.4)}$$

$$\text{Gravimetric SMC } (\%) = \frac{(\text{Total soil mass(Mt)} - \text{Soil solids(Ms)})}{\text{Soil Solids (Ms)}} \text{x100} \qquad \textbf{(3.5)}$$

Volumetric SMC (%) = Gravimetric SMC (%) x bulk density **(3.6)**

Equivalent water depth (De) = % Volumetric SMC x soil depth **(3.7)**

Moist soil samples were passed through 8 mm sieves, and roughly 10 g were taken and separated into 5 g each. The first 5 g was oven-dried at 105 °C for 24 h for moisture correction **(Plate 3.3).** Then the other 5 g sample was analyzed for mineral (N_{min}) N, according to Gomez-Munoz *et al*. (2017). Briefly, 5 g (oven-dry equivalent) of soil samples were weighed into 100 ml plastic shaking bottles into which 50 ml 0.5 M K_2SO_4 was added. The mixtures were shaken on a reciprocal shaker at 200 rmp for 30 min and then filtered using Whatman no. 42 filter papers. The extracts were analyzed for NH_4^+-N and NO_3 –N via UV spectrophotometer at 655 nm and 419 nm, respectively.

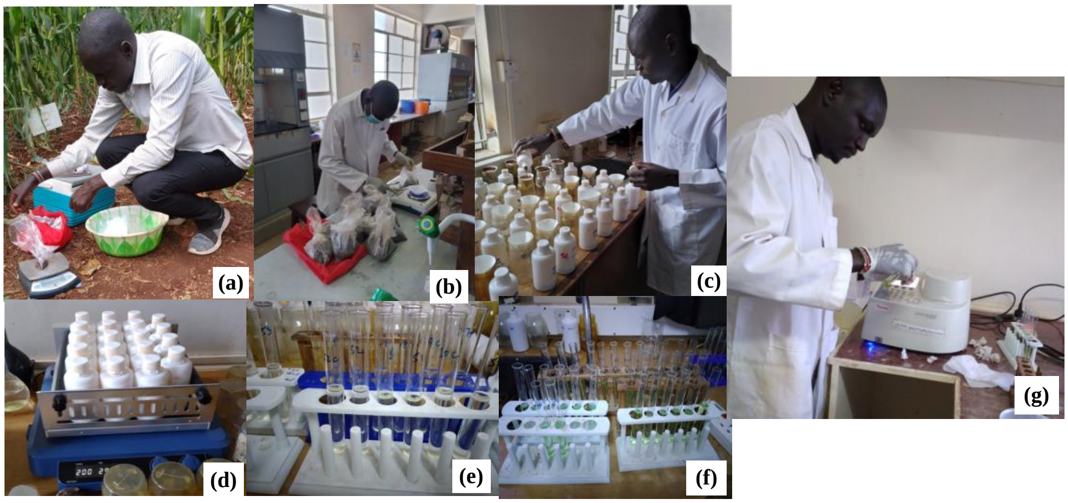


Plate 3.3: Determination of N Mineralization from (a) Sampling, (b) Weighing, (c) Filtering, (d) Extraction through Shaking, (e & f) Colour Development, to (g) Reading of the Absorbance

Net N mineralization was calculated by subtracting N_{min} at the beginning of incubation from N_{min} obtained at each sampling (incubation) time. Apparent N recovery (ANR) was determined by the difference method (Rao *et al.*, 1992), while N partial productivity factor (PPF) was determined using equations **3.8** to **3.10**:

$$\text{Net N mineralization} = \mathrm{N_t} - \mathrm{N_{in}} \qquad \textbf{(3.8)}$$

$$\mathrm{ANR} = \frac{\text{N in fertilized plants} - \text{N in unfertilized plants}}{\text{N applied}} \qquad \textbf{(3.9)}$$

$$\mathrm{PFP\ (kg\ biomass\ kg^{-1}N\ )} = \frac{\mathrm{Y_C} + \Delta\mathrm{Y_N}}{\mathrm{N_{input}}} \qquad \textbf{(3.10)}$$

Where ANR = Apparent N recovery; N_t= Mineral N at time t; N_{in}= initial mineral; Y_C denotes crop yield biomass in control plots, ΔY_N is the increment in biomass yield as a result of N application; N_{input} is the amount of N applied (kg N ha^{-1}).

3.4.4 APSIM Soil Nitrogen Mineralization Simulation

The study used APSIM 7.10 Classic version (Holzworth *et al*., 2018). It is a robust, process-based simulator consisting of a modular simulation framework. There are seven modules within the APSIM; climate data module (metfile.apsim), crop module (Maize Bimodal.aspim), soil water module (SOILWAT), fertilizer module (FERT), manure module (MAN), soil N module (SOILN), and surface organic matter module (Surface Organic Matter) (Holzworth *et al*., 2014). The modules permit navigation of the model to simulate the effect of the integration of genotype, environment, and management practices (Brown *et al*., 2018; Holzworth *et al*., 2018). These modules require data inputs relating to; daily climatic data, crop genotype, soil characteristics, and management practices.

3.4.5 Model Parameterization, Calibration, and Validation

The APSIM was parameterized for bimodal continuous maize production. Soil parameters included; soil depth, soil water content, bulk density, and soil initial N, C, NH_4- and NO_3-N. Measured and model default (inbuilt model values) initial soil physical and chemical properties used to calibrate APSIM are given in **Table 3.3** and **Table 4.3.** Fresh organic matter (FOM), soil microbial biomass (FBiom), NH_4-N, NO_3-N, and urea were maintained as default values. The FOM C: N was maintained at 40. SOILN module was used to parameterise N mineralised from organic sources, namely, maize stover, Tithonia, and goat manure (Cichota *et al*., 2021).

Table 3.3: Soil Initial physical and Chemical Properties Used in APSIM Initialization

Soil depth	Sand	Silt	Clay	[1]Maize LL	[2]DUL	pH	Total C	C:N
mm	%			mm/mm		Water	%	Ratio
0-150	14.00	16.00	70.00	0.26	0.20	4.85	1.48	10.57
150-250	14.00	16.00	70.00	0.25	0.24	4.85	1.48	10.57
250-350	14.00	16.00	70.00	0.28	0.26	4.85	1.48	10.57
350-450	14.00	16.00	70.00	0.31	0.27	4.85	1.48	10.57
450-550	14.00	16.00	70.00	0.36	0.29	4.85	1.48	10.57
550-650	14.00	16.00	70.00	0.39	0.29	4.85	1.48	10.57
650-750	14.00	16.00	70.00	0.45	0.30	4.85	1.48	10.57
750-850	14.00	16.00	70.00	0.45	0.45	4.85	1.48	10.57

[1] Maize lower limit (default values).

[2] Drained Upper Limit adopted from Mupangwa *et al*. (2011)

Table 3.4: Treatment Initial Parameterization Values for SR20 and LR21 Cropping Seasons

	SR20 season				LR21 season		
Treatment	**Bulk Density**	**NO$_3$-N**	**NH$_4$-N**	**Initial soil water**	**NO$_3$-N**	**NH$_4$-N**	**Initial soil water**
	kg m^{-3}	**kg ha^{-1}**		**%**	**kg ha^{-1}**		**%**
C	900	0.04	0.04	25.61	1.30	0.28	33.03
CTF	890	0.49	0.09	29.42	3.51	1.13	32.84
CTCrF	880	0.16	0.09	29.98	5.57	2.53	36.39
CTCrGF	976	0.16	0.19	34.76	4.09	1.13	34.36
CTCrGL	932	0.38	0.21	30.41	5.91	1.76	32.27
CTCrTiG	942	0.13	0.06	34.16	4.47	0.93	39.24
CTCrTiR	821	0.27	0.05	28.21	3.07	1.17	33.65
MT	1006	0.17	0.06	32.63	3.94	0.75	38.68
MTF	888	0.47	0.12	30.15	4.86	0.97	36.77
MTCrF	781	0.30	0.09	32.26	2.30	1.29	36.59
MTCrGF	1010	0.14	0.24	36.15	7.11	1.41	44.97
MTCrGL	820	0.10	0.21	26.73	5.49	1.72	40.18
MTCrTiG	837	0.23	0.11	29.76	2.75	1.03	27.66
MTCrTiR	935	0.17	0.18	32.00	3.68	1.29	37.35

Nitrogen mineralization from organic materials (maize stover, *T. diversifolia* and goat manure) was simulated using the SurfaceOrganicMatter module. The type, amount, and

C: N ratios of the respective organic materials were specified in the module. Tillage, sowing, fertilizer application, and mulching dates for the SR20 and LR21 cropping seasons are shown in Appendix I and Appendix II. Tillage operations and incorporation of organic materials were simulated using the ‘Tillage on a fixed date’ node. On the other hand, planting operations and inorganic fertilizer applications were parameterised in the ‘Sow on a fixed data’ and ‘fertilise at sowing’ nodes of the soil module. The weather data in the metfile included daily rainfall, radiation, and maximum and minimum temperature.

3.4.6 Determination of P Fractions and Sorption Characteristics

Organic (P_o) and inorganic (P_i) fractions were sequentially determined based on the sequestration method (Hedley *et al*., 1982). One gram (1 g) of soil was emptied into 50-ml centrifuge tubes containing 30 ml of distilled water. One resin strip was added to each tube and shaken for 16 hours on an end-to-end shaker. The strips were removed after shaking and gently submerged in distilled water thrice to wash the soil off. The strips were then immersed into centrifuge tubes containing 20 ml of 0.5 M HCl and shaken for 1 hour. After Resin-Pi extraction, the soil suspensions were centrifuged at 2500 rpm for 10-15 minutes, and phosphates were sequentially extracted using the following extractants; (a) 30 ml of 0.5 M $NaHCO_3$ at pH 8.5 for Pi, (b) 30 ml of 0.1 M NaOH for Fe.Al-P extraction, (c) 20 ml 0.1 M NaOH for NaOH-sonic Pi, and (d) 30 ml of 1 M HCl for Mg.Ca-P extraction. The soil suspensions were shaken overnight for 16 hours after extraction of each P fraction. Organic P fractions were calculated as the difference between each extract’s total phosphorus (TP) and inorganic P (Pi). Residual P was determined according to Brookes and Powlson's (1981) method by H_2SO_4 + H_2O_2 + $MgCl_2$ digestion. The P concentration in each extract was determined by the molybdenum blue method at the wavelength of 882 nm.

Phosphorus adsorption isotherms were determined based on the method by Yan *et al*. (2017), where 3.0 g air-dried soil samples were equilibrated in 50-ml centrifuge tubes filled with 30 ml of 0.01 M $CaCl_2$ solution containing H_2PO_4-P concentrations of 0, 10, 20, 30, 40, 50 and 60 P mg l^{-1}. To impede microbial activity, two to three drops of chloroform were added to every centrifuge tube. After this, the tubes were shaken for 30 minutes daily for six days. On the 6th day, the solutions were filtered using Whatman No. 542 filters, and the P contained in the solution was determined colourimetrically using a spectrophotometer at 880 nm.

The adsorbed P (S′) removed from the solution was calculated as the difference between the concentration of soluble P added in the original solution and the concentration of P in the solution at equilibrium. The Langmuir equation was determined to describe soil P adsorption because the equation provides vital information about the constant *k* (related to the P bonding energy) and the maximum P sorption capacity (S_{max}). The linearized Langmuir model was determined using Equation **3.11**:

$$\frac{C_e}{S} = \frac{C_e}{S_{max}} + \frac{1}{KS_{max}} \qquad \textbf{(3.11)}$$

where C_e and S denote the concentration of P in the equilibrium solution (mg L^{-1}) and the total quantity of adsorbed P (mg kg^{-1}), respectively, in which $S = S' + S_o$; S′ denotes the adsorbed P (mg kg^{-1}) obtained by subtracting final P concentration from the initial P concentration; S_o is the oxalate-extractable P as an estimate of the initially adsorbed P (mg kg^{-1}) P; k (L mg^{-1} P) is a constant associated to the bonding energy (Yan *et al.*, 2017). Maximum P sorption capacity was calculated using Equation **3.12**;

$$\text{Amount of adsorbed P } (Q_e)(\text{mg kg}^{-1}) = \frac{(C_0 - C_e) \text{ x V}}{W} \qquad \textbf{(3.12)}$$

Where C_o and C_e (mg L^{-1}) denote initial and equilibrium P concentrations, respectively; while *W* (g) and *V* (mL) denote adsorbent mass and extract volume, respectively.

The degree of P saturation (DPS) of each treatment was calculated using Equation **3.13**:

$$\text{DPS} = \frac{P_{\alpha x}}{S_{max}} \text{ x } 100\% \qquad \textbf{(3.13)}$$

where P_{ox} denotes oxalate-extractable P concentration (mg kg^{-1}) while S_{max} refers to the maximum P sorption capacity (mg kg^{-1}) derived from Equation **3.13** above.

Phosphorus partial productivity factor (PPF) and agronomic efficiency (PAE) were determined according to Arruda *et al*. (2019) using Equations **3.14** and **3.15**;

$$\text{PPF (kg biomass kg}^{-1}\text{ P)} = \frac{\mathrm{Y_C} + \Delta\mathrm{Y_P}}{\mathrm{P_{input}}} \quad \textbf{(3.14)}$$

$$\text{P agronomic effieciency (PAE)(kg biomass kg}^{-1}\text{ P)} = \frac{\left(\mathrm{Y_{P\_trt}} - \mathrm{Y_C}\right)}{\mathrm{P_{input}}} \quad \textbf{(3.15)}$$

where Y_C denotes crop yield biomass in control plots; ΔY_P is the increment in biomass yield as a result of P application; P_{input} the amount of P applied (kg P ha^{-1}); Y_{P_trt} is the crop yield biomass in P-treated plots.

3.4.7 Determination of Maize Growth Indicators

Plant growth parameters (relative chlorophyll content, leaf area index (LAI), photosynthetically active radiation (PAR), and height) were determined at the 6th leaf stage and 10th leaf stage (Kiboi *et al.*, 2019). Relative chlorophyll content was determined using a Soil Plant Analysis Development; SPAD-502Plus® meter (Konica Minolta Optics, Inc., Japan). The readings of relative chlorophyll were taken from the leaves of four (4) middle-tagged plants in the two middle rows (2 plants per row) and averaged. Photosynthetically active radiation and LAI were determined using LP-80 linear ceptometer (Decagon Devices, Pullman, WA). Ceptometer readings were taken from midpoints between rows to the middle of adjacent rows to take into consideration row and inter-row canopy effects (Johnson *et al.*, 2010). Three readings per plot were taken and averaged. The ceptometer was placed above the crop canopy and below the canopy at 10 cm above the ground level and at a 90° angle to the orientation of the plant rows. The measurements were recorded during sunny, cloudless times of the sampling days, and caution was taken to avoid the researcher’s shadow covering any part of the ceptometer. Before taking each below-canopy measurement, a calibration factor (cf) was taken

(Johnson *et al*., 2010). The fraction of PAR incepted by the plant was calculated using Equation **3.16**. Plant height was determined using a tape measure.

$$\mathrm{PAR} = \frac{\mathrm{PAR_b}}{\mathrm{cf.\,PAR_a}} \tag{3.16}$$

Where PAR is the actual PAR while $\mathrm{PAR_a}$ and $\mathrm{PAR_b}$ are above and below the canopy respectively and *cf* represents the calibration factor.

Maize was harvested manually from net plots measuring 21 m^2. Net plots were determined by discarding the first rows to eliminate edge effects. Cobs were separated from the maize stover and grains were shelled by hand. Grain moisture content was determined at harvest using a Dickey-John MiniGAC® moisture meter. Grains and cobs (separated) were sun-dried for seven days, and moisture content (MC) determined. After drying, grain weight was corrected to a 12.5% moisture content equivalence and extrapolated to per hectare (ha) basis. Stover yield was determined at harvest, and the total dry matter yield was determined as the summation of grain, cobs weight, and stover weights, and also extrapolated to hectares basis.

3.4.8 Calculation of Crop Water Productivity and N Nutrition Index

Crop water productivity (WP) was defined as the amount of maize yield produced per unit of water consumed (Cook *et al*., 2018) and calculated using Equation **3.17**;

$$\mathrm{WP} = \frac{\text{Maize yield (kg ha}^{-1}\text{)}}{\text{Consumptive water use }(\mathrm{E_t})} \tag{3.17}$$

The water balance Equation **(3.18)** was used to estimate E_t as adopted by Oduor *et al*. (2021), thus:

$$\mathrm{E_t} = (\mathrm{R} + \mathrm{I} + \mathrm{C}) - (\mathrm{S_r} + \mathrm{D}) - \Delta\mathrm{S} \tag{3.18}$$

Where E_t is evapotranspiration; R is cumulative rainfall received in a season; I is irrigation water; C is upward flux from the water table; S_r is surface runoff; D is deep percolation and ΔS = soil moisture changes with time within the rooting zone or soil profile.

All the plots were fairly flat; thus no runoff (S_r) losses were experienced. Moreover, the study was purely under rainfed agriculture; hence no irrigation (*I*) was done. The soils at the site are deep and well-drained, with a deep groundwater table; therefore, upward fluxes (C) were assumed to be insignificant.) Deep percolation (D) out of the rooting zone of the crop/soil profile in question was not observed as per the amount of rainfall received and the frequency of the same during the seasons. Water productivity calculation was therefore reduced to Equation **3.19** (Pereira *et al.*, 2012);

$$\mathrm{WP} = \frac{\text{above ground yield}}{\mathrm{E_t} = \mathrm{R} - \Delta \mathrm{S}} \tag{3.19}$$

Daily solar radiation and temperature for the period 1/10/2020 to 30/06/2021 were downloaded from the National Aeronautics and Space Administration (NASA) website (https://power.larc.nasa.gov/data-access-viewer/). Longitude (37.6833) and latitude (-0.33849) coordinates were used to specify the exact location. A file named ‘All Sky Surface Shortwave Downward’ was downloaded from the ‘Solar fluxes and related’ folder.

To check if the treatments invoked N stress in the crops, N nutrition index (NNI) was calculated (Mueller & Vyn, 2018) using Equation **3.20** as;

$$\mathrm{NNI} = \frac{\%\ \mathrm{N_o}}{\%\ \mathrm{N_c}} \tag{3.20}$$

Where % N_o is the measured concentration of N in plant tissues and % N_c is the critical N concentration for a target biomass production. The % N_c is determined as $a_c W^{-b}$; a_c is the minimum N concentration (%) in plant tissue when W = 1 Mg ha^{-1}; W denotes dry matter in Mg ha^{-1}; b is a dimensionless constant. For maize, a_c, and b have been estimated to be 3.4 and 0.37 (Lemaire *et al*., 2008).

3.4.9 Determination of Radiation Use Efficiency

Radiation use efficiency (RUE) was calculated following Kaur *et al*. (2012), as shown in Equations **3.21** to **3.23**.

$$\text{Fraction of PAR intercepted by plants (fPAR)} = 1 - \left(\frac{\text{PAR}_\text{b}}{\text{PAR}_\text{a}}\right) \qquad \textbf{(3.21)}$$

$$\text{Intercepted PAR (iPAR) = Incident PAR x fPAR} \qquad \textbf{(3.22)}$$

$$\text{RUE} = \frac{\text{Aboveground yield (Mg h}^{-1}\text{)}}{\text{iPAR}} \qquad \textbf{(3.23)}$$

Where aboveground yield is grain or stover yield and *i*PAR is the fraction of radiation intercepted by the plant as calculated in equation 3.15. PAR_a and PAR_b represent above and below-ground PAR, respectively.

3.5 Data Processing and Statistical Analysis

Soil and maize yield data were subjected to analysis of variance (ANOVA) using R software version 4.1.2 (R Core Team (2021) to test the model effect. Levene and Shapiro-Wilk tests were used to confirm the homogeneity of variances and normality assumptions. Where the model effect was significant, treatment means were separated using Tukey's honestly significant difference at $\alpha \leq 0.05$ significance level. Soil samples at the beginning and the end of the trials were subjected to paired t-tests at $\alpha \leq 0.05$ significance level to determine changes in available N and P. APSIM was validated using the coefficient of determination (R^2), root means square error (RMSE), and d index of agreement as per Equations **3.24** to **3.26**. The d index of agreement was calculated as proposed by Akponikpè *et al.* (2010) thus:

$$R^2 = \left(\frac{n(\sum xy) - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2]}[n\sum y^2 - (\sum y)^2]}\right)^2 \quad \textbf{(3.24)}$$

$$RMSE = \sqrt{\sum_{i=1}^{n} \frac{(x_i - y_i)^2}{n}} \quad \textbf{(3.25)}$$

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(S_i - O_i)^2}{\sum_{i=1}^{n}(|S_i - Õ| + |O_i - Õ|)^2}\right] \quad \textbf{(3.26)}$$

Where; N= number of observations, $\sum xy = sum\ of\ the\ simulated\ and\ observed\ values, \sum x = sum\ of\ simulated\ values, \sum y = sum\ of\ observed\ values; \sum x^2 = sum\ of\ squares\ of\ simulated\ values,\ \ \sum y^2 = sum\ of\ squiares\ of\ observed\ values;$ S_i = simulated value of the ith treatment, O_i is the measured value of ith treatment, and Õ is the mean of measured values. The model was deemed good for N mineralization prediction when RMSE values were closer to 0 and d values approached 1. D values near 0 and high RMSE values depicted poor model performance.

CHAPTER FOUR

RESULTS

4.1 Introduction

This Chapter sequentially presents the results per the objectives. The results are presented using tables and figures. Specially, the Chapter represents the effects of integrated soil fertility management technologies on; 1) soil microbial biomass C, N, and P, 2) N mineralization, partial factor productivity, and apparent N recovery, 3) simulation of soil N mineralization, 4) phosphorus fractions, degree of saturation, maximum sorption capacity, use efficiency, and legacy, and 5) maize yield, soil moisture content, and water productivity.

4.1.1 Soil Microbial Biomass

The effect of the treatments on soil microbial C, N, and P was highly significant at $p < 0.0001$ **(Table 4.1).** Microbial biomass C averaged 567 mg kg^{-1} in Humic Nitisol. However, its highest value was recorded under CTCrGL and MTCrGL, which was 74% higher than the control. The plots under CTCrTiG, MTCrTiR, CTCrTiR, MTCrGF, CTCrGF, MTCrTiG, CTCrF, MTF, MTCrF, and CTF had significantly higher MBC by 70, 70, 70, 70, 70, 69, 35, 35, 35, and 34%, respectively, than the control. While MT did not significantly affect MBC, applying soil amendments resulted in a 59% increase, on average, relative to the control.

Microbial biomass N averaged 93 mg kg^{-1} in Humic Nitisol but, compared to the control, was substantially higher by 48, 47, 47, 46, 45, 44, 44, and 43% under MTCrTiG, MTCrGL, CTCrTiG, CTCrGL, MTCrTiR, CTCrTiR, CTCrGF, and MTCrGF, respectively. On average, these treatments resulted in 46% higher MBN. The MBN recorded under CTCrF, MTCrF, MTF, CTF, and MT did not differ statistically from the one recorded under the control. The MBP also averaged 31 mg kg^{-1} at the end of the experiment, but MTCrGF and CTCrGF recorded the highest values compared to the control, which was 41% higher. Moreover, MTCrTiG, MTCrTiR, CTCrTiR, CTCrTiG, and MTCrF also resulted in 32, 31, 27, 23, and 20% higher MBP than the control. Overall, these treatments had 31% higher MBP on average compared to the control. However, CTCrF, MTF, CTCrGL, CTF, MT, and MTCrGL insignificantly influenced MBP than the control.

Table 4.1: Soil Microbial Biomass C, N, and P under Different Treatments

Treatment	**MBC**	**MBN**	**MBP**
		mg kg^{-1} soil	
C	221.98^{d}	62.72^{cd}	26.48^{ghi}
CTF	336.27^{c}	63.53^{cd}	24.53^{hi}
CTCrF	342.48^{c}	66.63^{c}	30.42^{efg}
CTCrGF	728.30^{b}	112.26^{ab}	44.52^{a}
CTCrGL	865.16^{a}	116.46^{ab}	27.57^{ghi}
CTCrTiG	744.01^{b}	117.75^{ab}	34.27^{cde}
CTCrTiR	736.32^{b}	112.49^{ab}	36.04^{bcd}
MT	224.59^{d}	54.83^{d}	23.34^{i}
MTF	340.23^{c}	64.23^{cd}	28.83^{fgh}
MTCrF	339.32^{c}	64.39^{cd}	33.11^{def}
MTCrGF	734.59^{b}	110.46^{b}	45.04^{a}
MTCrGL	863.94^{a}	118.78^{ab}	7.33^{ghi}
MTCrTiG	725.13^{b}	120.59^{a}	38.68^{b}
MTCrTiR	739.98^{b}	114.82^{ab}	38.44^{bc}
hsd	38.41	9.69	4.30
p value	***	***	***

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage +

maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference, *** $p < 0.0001$.

The ratio of microbial C to N and P varied significantly ($p < 0.0001$) among the treatments **(Figure 4.1)**. Apart from MT, the ratio of MBC to MBN was generally higher than the control and averaged 6.19. The ratio of MBC to MBN under CTCrGL, MTCrGL, MTCrGF, CTCrTiR, CTCrGF, MTCrTiR, CTCrTiG, MTCrTiG, CTF, MTF, MTCrF, and CTCrF was higher than in the control by 52, 51, 47, 46, 45, 45, 44, 41, 33, 33, 33, and 31%, respectively. Except for MTCrF and MT, the ratios of microbial C to P under the remaining treatments were as high as 52% on average than under the control. The highest MBC to MBP ratios were observed under MTCrGL and CTCrGL, which were higher by 73% compared to the control. Significantly higher (by 61, 59, 56, 55, 49, 49, 39, 29, and 26%) MBC:MBP ratios were also recorded under CTCrTiG, CTCrTiR, MTCrTiR, MTCrTiG, CTCrGF, MTCrGF, CTF, MTF, and CTCrF, respectively, relative to the control.

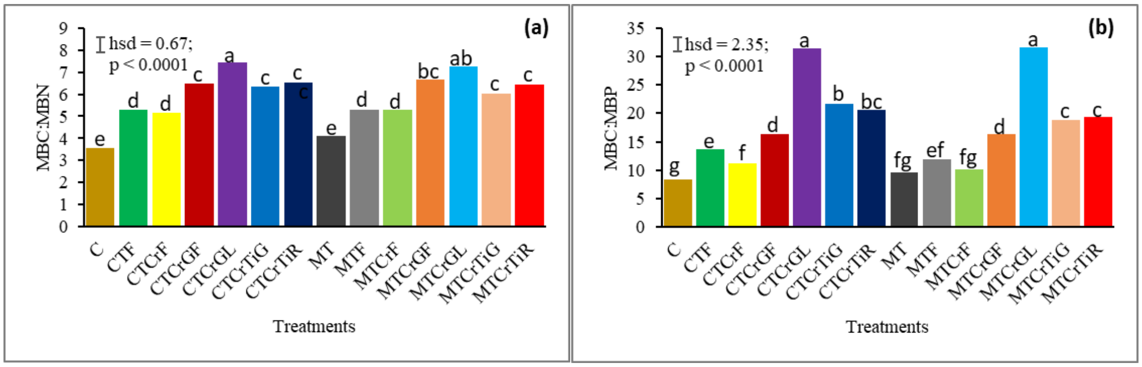


Figure 4.1: (a) Ratio of Microbial Biomass C to N and (b) Microbial Biomass C to P under the Various Treatments

Mean values with the same superscript letter(s) denote no significant difference at $p \leq 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference pooled error bar.

4.1.2 Ammonium-Bound Nitrogen

The treatments significantly affected ammonium-N (NH_4-N) at diverse sampling dates during the SR20 and LR21 cropping seasons **(Table 4.2).** Generally, NH_4-N sharply increased between 0 and 15 days after planting (DAP), then sharply decreased with slight increases at the 75 DAP during the SR20 season. However, NH_4-N was high at the start of the LR21 season and declined after 15 DAP, thereafter, it fluctuated without a clear pattern among the treatments except for the control and MT, which plateaued.

During the SR20 cropping season, the effects of the treatments on NH_4-N were significant at planting and 15th, 30th, 45th, and 105th days ($p < 0.0001$), and at the 75th day ($p = 0.0379$). However, the effects of the treatments were insignificant at 60th ($p = 0.786$) and 90th days ($p = 0.\ 0.890$). The application of MTCrGL at the start of the season resulted in the highest NH_4-N that was 82% higher than the control. Moreover, MTCrGF, CTCrGL, CTCrGF, MTCrTiR, MTF, MTCrTiG, MTCrF, CTF, and CTCrF had exceptionally higher NH_4-N by 81, 80, 77, 77, 67, 67, 63, 57, and 57%, respectively, than the control. On the other hand, NH_4-N recorded under CTCrTiG, CTCrTiR, and MT did not greatly differ from the control. At 15th DAP, MTF and MTCrGL had the highest NH_4-N, which was 98% higher than the control. Similarly, CTCrTiR, CTF, CTCrGF, MTCrGF, MTCrF, CTCrF, CTCrTiG, MT, and MTCrTiG had remarkably higher NH_4-N by 97, 97, 96, 96, 96, 95, 92, 91, and 87%, respectively, than the control. Conversely, the performance under CTCrGL and MTCrTiR did not significantly vary from the control. Apart from MTF, MTCrGF, MTCrTiR, and MTCrF, which had higher NH_4-N by 72, 71, 71, and 55%, respectively, the remaining treatments were similar to the control at 30th DAP. At 45th DAP, only CTCrF, CTCrGF, CTCrTiR, MTCrGF, and MTF had appreciably higher (78, 75, 75, 71, and 71%, respectively) NH_4-N than the control. The effects of the remaining treatments on NH_4-N were statistically the same as the effect of the control. Ammonium N was significantly higher only under CTCrGF and MTCrTiG by 67% and 73% than the control at the 75th and 105th DAP, respectively. However, it did not differ markedly under the remaining treatments relative to the control.

The treatments significantly affected NH_4-N at 60th ($p = 0.007$), 75th, and 90th DAP ($p < 0.0001$) during the LR21 season. Nevertheless, the treatments insignificantly influenced NH_4-N at planting and 15th, 30th, 45th, and 105th DAP at $p = 0.265$, 0.449, 0.242, 0.385, and 0.108, respectively. At 60th and 75th DAP, only CTCrGF and CTF had substantially higher NH_4-N by 73% and 97%, respectively than the control. The remaining treatments recorded statistically similar NH_4-N as the control. Plots with MTF, CTCrGF, and CTCrTiG at 90th DAP recorded considerably higher NH_4-N by 90, 83, and 78%, respectively, than the control. Conversely, it did not vary significantly under the remaining treatments and the control.

Table 4.2: Ammonium-N under Different Treatments over Time during SR20 and LR21 Cropping Seasons

Treatment	SR20								LR21							
	NH-N (ug g^{-1})								NH-N (ug g^{-1})							
	0	**15**	**30**	**45**	**60**	**75**	**90**	**105**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**
C	0.03^{f}	0.10^{h}	0.05^{bc}	0.02^{d}	0.02	0.05^{ab}	0.01	0.03^{b}	0.21	0.20	0.12	0.09	0.09^{ab}	0.04^{b}	0.05^{d}	0.03
CTF	0.07^{cde}	3.21^{bc}	0.08^{bc}	0.03^{cd}	0.03	0.03^{b}	0.07	0.03^{b}	0.85	0.47	0.27	0.17	0.06^{b}	1.30^{a}	0.08^{cd}	0.06
CTCrF	0.07^{cde}	1.88^{e}	0.04^{bc}	0.09^{a}	0.02	0.06^{ab}	0.04	0.07^{ab}	1.92	0.30	0.32	0.13	0.09^{ab}	0.14^{b}	0.12^{cd}	0.05
CTCrGF	0.13^{b}	2.70^{cd}	0.04^{bc}	0.08^{ab}	0.03	0.15^{a}	0.04	0.07^{ab}	0.77	0.09	0.29	0.10	0.33^{a}	0.20^{b}	0.30^{b}	0.12
CTCrGL	0.15^{ab}	0.46^{gh}	0.01^{c}	0.01^{d}	0.03	0.05^{ab}	0.05	0.01^{b}	1.26	0.46	0.22	0.22	0.08^{ab}	0.12^{b}	0.08^{cd}	0.15
CTCrTiG	0.04^{ef}	1.25^{f}	0.025^{c}	0.03^{cd}	0.02	0.03^{b}	0.07	0.03^{b}	0.66	0.30	0.26	0.11	0.12^{ab}	0.23^{b}	0.23^{bc}	0.06
CTCrTiR	0.04^{ef}	3.46^{b}	0.06^{bc}	0.08^{ab}	0.03	0.03^{b}	0.06	0.03^{b}	0.95	0.20	0.24	0.19	0.07^{ab}	0.31^{b}	0.11^{cd}	0.18
MT	0.04^{def}	1.13^{f}	0.05^{bc}	0.05^{bcd}	0.02	0.05^{ab}	0.06	0.02^{b}	0.50	0.30	0.05	0.08	0.17^{ab}	0.16^{b}	0.10^{cd}	0.10
MTF	0.09^{c}	5.04^{a}	0.18^{a}	0.07^{abc}	0.01	0.09^{ab}	0.04	0.07^{ab}	0.73	0.50	0.15	0.12	0.19^{ab}	0.12^{b}	0.48^{a}	0.17
MTCrF	0.08^{cd}	2.31^{de}	0.11^{ab}	0.02^{d}	0.02	0.03^{b}	0.03	0.03^{b}	1.10	0.45	0.21	0.18	0.14^{ab}	0.16^{b}	0.17^{bcd}	0.12
MTCrGF	0.16^{a}	2.69^{d}	0.17^{a}	0.07^{abc}	0.02	0.06^{ab}	0.07	0.04^{b}	0.93	0.10	0.14	0.09	0.28^{ab}	0.27^{b}	0.12^{cd}	0.15
MTCrGL	0.17^{a}	4.87^{a}	0.03^{c}	0.02^{d}	0.02	0.06^{ab}	0.07	0.03^{b}	1.40	0.30	0.23	0.28	0.23^{ab}	0.20^{b}	0.10^{cd}	0.07
MTCrTiG	0.09^{c}	0.76^{fg}	0.01^{c}	0.03^{cd}	0.03	0.07^{ab}	0.03	0.11^{a}	0.82	0.20	0.22	0.13	0.26^{ab}	0.21^{b}	0.06^{d}	0.06
MTCrTiR	0.13^{b}	0.45^{gh}	0.17^{a}	0.01^{d}	0.01	0.06^{ab}	0.06	0.01^{b}	0.92	0.21	0.28	0.13	0.20^{ab}	0.08^{b}	0.06^{d}	0.06
hsd	0.03	0.52	0.07	0.04	0.04	0.11	0.12	0.06	1.83	0.70	0.34	0.27	0.27	0.35	0.15	0.16
p value	***	***	***	***	ns	*	ns	***	ns	ns	ns	ns	**	***	***	ns

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p < 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference, * $p = 0.0379$, ** $p = 0.007$, *** $p < 0.0001$, ns= not significant.

4.1.3 Nitrate-Bound Nitrogen

The concentration of NO_3-N in the soil in the earlier days of the SR20 season was low in all the treatments but increased towards the end of the season. However, NO_3-N was high at the start of the LR21 season but low towards the end of the season **(**Error! Reference source not found.**)**. Like NH_4-N, the control exhibited a steady decline without a clear pattern among the other treatments across the sampling intervals.

The treatments significantly influenced NO_3-N at planting, 15th, 30th, 45th, and 60th DAP at $p < 0.0001$ during the SR20 season. However, the treatments did not markedly affect NO_3-N at 75th, 90th, and 105th DAP ($p = 0.3490$, 0.4400, and 0.297, respectively). At the start of the season, CTF and MTF recorded the highest NO_3-N of 92 and 91%, respectively, which were outstandingly higher than the control. Moreover, NO_3-N was strikingly higher under CTCrGL, MTCrF, CTCrTiR, MTCrTiG, CTCrF, MTCrTiR, CTCrGF, MT, MTCrGF, CTCrTiG, and MTCrGL than under the control by 89, 88, 86, 83, 75, 75, 73, 73, 67, 67, and 63%, respectively. Compared to the control, NO_3-N was notably higher by 80, 74, 70, 63, 57, and 53% under MTCrGL, MTF, MTCrGF, CTCrGF, CTCrTiR, and MTCrF, respectively, on the 15th DAP. Nevertheless, NO_3-N recorded under CTCrGL, CTCrTiG, MT, CTF, CTCrF, MTCrTiG, and MTCrTiR did not vary significantly with the control. At 30th DAP, CTCrTiG was the only treatment that significantly had higher NO_3-N of 78% than the control. Also, MTF, CTCrTiR, CTCrGF, MTCrF, MTCrGL, and CTCrTiG at 45th DAP exceptionally increased NO_3-N by 84, 83, 81, 81, 79, and 76%, respectively, relative to the control. However, the application of MTCrTiR, MTCrTiG, CTF, MTCrGF, CTCrGL, MT, and CTCrF did not result in a significant improvement in NO_3-N relative to the control. The treatments; MTCrF, CTF, and MTCrGF had significantly higher NO_3-N of 80, 79, and 75%, respectively, than the control at 60th DAP. The rest of the treatments had statistically the same NO_3-N as the control.

The effect of the treatments on NO_3-N was significant at 45th, 60th, and 105th ($p = 0.0016$, 0.0039, and 0.0106, respectively), and at 75th and 90th DAP ($p < 0.0001$) during the LR21 season. Nevertheless, NO_3-N treatment means did not vary significantly at planting, 15th, and 30th DAP ($p = 0.3650$, 0.1110, and 0.0984, respectively). Only CTCrGF and CTCrGL at 45th, and MTCrTiR at 60th DAP had incomparably higher NO_3-N by 87 and 85%, and 90%, respectively, than the control. Though the remaining treatments recorded higher NO_3-N, their effects did not differ from that of the control. Also, only CTCrGF and MTCrGF had substantially higher NO_3-N (of 99 and 96%, respectively) than the control at 75th DAP. The other treatments recorded similar NO_3-N as the control. Relative to the control, MTCrTiR, MTCrTiG, MTF, MTCrF, and CTCrF particularly had higher NO_3-N of 0.53, 0.39, 0.38, 0.34, and 0.32%, respectively, at 90th DAP. The NO_3-N under the other treatments did not differ appreciably from the control. Furthermore, CTCrGF, CTCrF, and MTF resulted in significantly higher NO_3-N of 82, 82, and 81%, respectively, than the control at 105th DAP. However, NO_3-N under the rest of the treatments did not remarkably vary with the control.

Table 4.3: Nitrate-N under Different Treatments over Time during SR20 and LR21 Cropping Seasons

Treatment	**SR20**								**LR21**							
	NO-N (ug g^{-1})								**NO-N (ug g^{-1})**							
	0	**15**	**30**	**45**	**60**	**75**	**90.00**	**105**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**
C	0.03^{f}	0.09^{fg}	0.05^{bc}	0.04^{d}	0.04^{d}	0.06	0.09	0.05	0.96	0.15	0.29	0.18^{c}	0.12^{b}	0.02^{c}	0.09^{f}	0.13^{ab}
CTF	0.37^{a}	0.08^{fg}	0.07^{bc}	0.09^{cd}	0.19^{ab}	0.16	0.56	0.23	2.63	1.94	2.14	0.51^{abc}	0.60^{ab}	0.13^{bc}	0.15^{ef}	0.26^{ab}
CTCrF	0.12^{d}	0.08^{fg}	0.06^{bc}	0.02^{d}	0.03^{d}	0.13	1.59	1.08	4.22	1.32	1.13	0.66^{abc}	0.15^{ab}	0.45^{bc}	0.41^{abcde}	0.28^{a}
CTCrGF	0.11^{de}	0.24^{cd}	0.08^{bc}	0.21^{ab}	0.09^{bcd}	0.12	1.11	1.02	2.79	1.07	0.79	1.36^{a}	0.19^{ab}	2.45^{a}	0.21^{cdef}	0.28^{a}
CTCrGL	0.27^{b}	0.16^{def}	0.17^{ab}	0.05^{d}	0.05^{cd}	1.02	0.63	0.47	4.23	2.08	1.28	1.24^{ab}	0.46^{ab}	0.34^{bc}	0.19^{def}	0.19^{ab}
CTCrTiG	0.09^{de}	0.12^{efg}	0.23^{a}	0.17^{abc}	0.02^{d}	0.39	0.91	0.83	3.16	0.32	0.54	0.38^{abc}	0.64^{ab}	0.25^{bc}	0.08^{f}	0.20^{ab}
CTCrTiR	0.22^{bc}	0.21^{d}	0.04^{c}	0.23^{a}	0.13^{abcd}	0.25	0.81	1.11	2.49	1.08	0.21	1.12^{abc}	1.01^{ab}	0.15^{bc}	0.23^{bcdef}	0.16^{ab}
MT	0.11^{de}	0.09^{fg}	0.07^{bc}	0.03^{d}	0.10^{abcd}	0.10	0.07	0.05	2.61	0.42	0.23	0.22^{bc}	0.09^{b}	0.14^{bc}	0.06^{f}	0.05^{b}
MTF	0.35^{a}	0.34^{b}	0.18^{ab}	0.25^{a}	0.10^{abcd}	0.18	0.45	1.70	3.65	0.80	1.49	0.74^{abc}	0.35^{ab}	0.04^{c}	0.47^{abc}	0.27^{a}
MTCrF	0.26^{b}	0.19^{de}	0.13^{abc}	0.21^{ab}	0.20^{a}	0.16	1.06	1.04	1.96	2.14	0.95	0.52^{abc}	0.43^{ab}	0.18^{bc}	0.43^{abcd}	0.12^{ab}
MTCrGF	0.09^{de}	0.30^{bc}	0.07^{bc}	0.06^{d}	0.16^{abc}	0.05	1.44	0.73	4.69	2.07	0.32	1.04^{abc}	0.46^{ab}	0.55^{b}	0.15^{ef}	0.21^{ab}
MTCrGL	0.08^{e}	0.46^{a}	0.09^{bc}	0.19^{abc}	0.12^{abcd}	0.14	0.86	1.69	4.46	2.02	1.60	0.70^{abc}	0.58^{ab}	0.30^{bc}	0.23^{bcdef}	0.15^{ab}
MTCrTiG	0.18^{c}	0.05^{g}	0.11^{abc}	0.11^{bcd}	0.06^{cd}	0.09	0.27	0.21	2.19	1.33	1.99	0.93^{abc}	1.07^{ab}	0.23^{bc}	0.48^{ab}	0.21^{ab}
MTCrTiR	0.12^{de}	0.04^{g}	0.12^{abc}	0.12^{bcd}	0.02^{d}	0.09	0.29	1.18	2.62	0.40	0.99	0.50^{abc}	1.17^{a}	0.26^{bc}	0.62^{a}	0.13^{ab}
hsd	0.05	0.09	0.12	0.11	0.11	1.17	2.34	2.50	3.75	2.87	2.50	1.02	1.04	0.50	0.27	0.21
p value	***	***	***	***	***	ns	ns	ns	ns	ns	ns	**†	**††	***	***	*

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p < 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference, * p = 0.0106, , **† p = 0.0016, **†† p = 0.0039, *** $p < 0.0001$, ns= not significant.

4.1.4 Total Mineral Nitrogen

On average, NO_3-N explained a 62% variation in total N on the 15th DAP before rapidly declining during the SR20 season **(Table 4.4)**. An accelerated increase in NH4-N afterwards explained 89% of the total mineral N from the 15th to 30th DAP. However, the contribution of NO_3-N surged towards the end of the cropping season, contributing, on average, 85% to the total mineral N on the 90th and 105th DAP. Overall, NO_3-N and NH_4-N contributed 65% and 35% to the total mineral N during the SR20 season. Nitrate N was generally high throughout the sampling intervals, contributing 67% to the total mineral N compared to 33% for NH_4-N during the LR21 season.

Total mineral N varied significantly at planting, 15th, 30th, 45th, and 60th DAP at $p < 0.0001$ during the SR20 season **(Table 4.4).** Application of MTF, CTF, and CTCrGL had the highest (86, 86, and 85%, respectively) remarkable improvement in total mineral N at planting. Also, MTCrF, MTCrTiG, CTCrTiR, MTCrGF, MTCrGL, MTCrTiR, CTCrGF, CTCrF, MT, and CTCrTiG had considerably higher mineral N of 82, 79, 77, 76, 76, 76, 75, 68, 63, and 50%, respectively, than the control. After the 15th DAP, the highest mineral N was recorded under MTF and MTCrGL which was 96% higher than the control. Moreover, CTCrTiR, CTF, MTCrGF, CTCrGF, MTCrF, CTCrF, CTCrTiG, MT, and MTCrTiG had 95, 94, 94, 94, 92, 90, 86, 84, and 77%, respectively, substantially higher mineral N than the control. On the other hand, mineral N under CTCrGL and MTCrTiR did not remarkably differ from the control. Additionally, only MTF, MTCrTiR, and CTCrTiG had 72, 66, and 60% higher mineral N compared to the control at 30th DAP. It did not, however, vary greatly from the control. At the 45th DAP, MTF, CTCrTiR, CTCrGF, MTCrF, MTCrGL, and CTCrTiG had 81, 81, 79, 74, 71, and 70%, respectively, appreciably higher mineral N than the control. However, it did not vary when the control was compared with MTCrTiG, MTCrGF, MTCrTiR, CTF, CTCrF, MT, and CTCrGL. Furthermore, only CTF, MTCrF, and MTCrGF recorded outstandingly higher mineral N than the control of 74, 71, and 67%, respectively, at the 60 DAP. The remaining treatments did not vary significantly from the control.

During the LR21 season, the treatments significantly affected mineral N after 45th ($p = 0.0018$), 60th ($p = 0.0028$), 75th ($p <0.0001$), 90th ($p <0.0001$), and 105th ($p = 0.0028$) DAP **(Table 4.4).** The plots with CTCrGF and CTCrGL on the 45th DAP and MTCrTiG on the 60th DAP resulted in 82% and 84% higher mineral N relative to the control. It was high under the remaining treatments but did not vary significantly from the control. On the 75th DAP, CTCrGF, CTF, and MTCrGF recorded 98, 96, and 93% higher mineral N than the control. The rest of the treatments did not significantly affect mineral N compared to the control. The nutrient was significantly higher by 85, 79, 77, 74, 74, and 73%, respectively, under MTF, MTCrTiR, MTCrF, MTCrTiG, CTCrF, and CTCrGF, respectively, than the control on the 90th DAP. The effect of CTCrTiR, MTCrGL, CTCrTiG, CTCrGL, MTCrGF, CTF, and MT on mineral N did not differ from that of control during the same period (90 DAP). At the end of the cropping season (105 DAP), only MTF had a higher mineral N by 64%, while the rest of the treatments did not exert a significant effect compared to the control.

Table 4.4: Total Mineral N under Different Treatments over Time during SR20 and LR21 Cropping Seasons

Treatments	SR20 (ug g^{-1})								LR21 (ug g^{-1})							
	Total								Total							
	0	**15**	**30**	**45**	**60**	**75**	**90.00**	**105**	**0**	**15**	**30**	**45**	**60**	**75**	**90**	**105**
C	0.06^{g}	0.19^{i}	0.10^{cd}	0.06^{d}	0.06^{de}	0.10	0.10	0.08	0.96	0.30	0.40	0.27^{b}	0.21^{b}	0.06^{d}	0.14^{f}	0.16^{b}
CTF	0.43^{a}	3.28^{bc}	0.15^{bcd}	0.12^{bcd}	0.23^{a}	0.19	0.62	0.25	2.63	2.41	2.41	0.68^{ab}	0.66^{ab}	1.43^{b}	0.23^{ef}	0.32^{ab}
CTCrF	0.19^{de}	1.95^{e}	0.10^{cd}	0.11^{bcd}	0.05^{de}	0.20	1.63	1.15	4.22	1.60	1.46	0.79^{ab}	0.24^{b}	0.58^{cd}	0.53^{bcd}	0.32^{ab}
CTCrGF	0.24^{cd}	2.94^{cd}	0.12^{cd}	0.28^{a}	0.11^{abcde}	0.26	1.15	1.08	2.79	1.16	1.08	1.46^{a}	0.52^{ab}	2.65^{a}	0.51^{bcde}	0.39^{ab}
CTCrGL	0.41^{a}	0.62^{hi}	0.17^{bcd}	0.06^{d}	0.08^{cde}	1.07	0.67	0.49	4.23	2.53	1.49	1.46^{a}	0.53^{ab}	0.46^{cd}	0.27^{def}	0.32^{ab}
CTCrTiG	0.12^{f}	1.36^{f}	0.25^{abc}	0.20^{abc}	0.04^{e}	0.41	0.97	0.86	3.16	0.61	0.80	0.48^{ab}	0.75^{ab}	0.48^{cd}	0.31^{def}	0.26^{ab}
CTCrTiR	0.26^{c}	3.67^{b}	0.09^{d}	0.31^{a}	0.16^{abcd}	0.27	0.88	1.14	2.49	1.25	0.45	1.31^{ab}	1.21^{ab}	0.46^{cd}	0.34^{cdef}	0.34^{ab}
MT	0.16^{ef}	1.22^{fg}	0.12^{cd}	0.08^{cd}	0.13^{abcde}	0.14	0.12	0.06	2.61	0.68	0.27	0.30^{b}	0.26^{b}	0.30^{cd}	0.16^{f}	0.15^{b}
MTF	0.44^{a}	5.38^{a}	0.36^{a}	0.32^{a}	0.11^{abcde}	0.27	0.50	1.77	3.65	1.30	1.63	0.86^{ab}	0.53^{ab}	0.17^{d}	0.95^{a}	0.44^{a}
MTCrF	0.33^{b}	2.51^{d}	0.24^{abcd}	0.23^{ab}	0.21^{ab}	0.19	1.09	1.06	1.96	2.58	1.16	0.69^{ab}	0.57^{ab}	0.34^{cd}	0.60^{bc}	0.24^{ab}
MTCrGF	0.25^{cd}	2.99^{cd}	0.24^{abcd}	0.13^{bcd}	0.18^{abc}	0.11	1.51	0.76	4.69	2.16	0.45	1.14^{ab}	0.74^{ab}	0.82^{c}	0.26^{def}	0.35^{ab}
MTCrGL	0.25^{cd}	5.33^{a}	0.11^{cd}	0.21^{ab}	0.15^{abcde}	0.19	0.93	1.73	4.46	2.31	1.83	0.98^{ab}	0.82^{ab}	0.50^{cd}	0.33^{cdef}	0.21^{ab}
MTCrTiG	0.28^{bc}	0.81^{gh}	0.11^{cd}	0.15^{bcd}	0.08^{cde}	0.15	0.31	0.31	2.19	1.53	2.20	1.05^{ab}	1.33^{a}	0.44^{cd}	0.54^{bcd}	0.28^{ab}
MTCrTiR	0.25^{cd}	0.48^{hi}	0.29^{ab}	0.13^{bcd}	0.04^{e}	0.14	0.34	1.19	2.62	0.61	1.27	0.64^{ab}	1.23^{ab}	0.33^{cd}	0.68^{ab}	0.19^{b}
hsd	0.06	0.52	0.15	0.13	0.11	1.16	2.38	2.49	3.75	2.88	2.57	1.08	1.04	0.58	0.29	0.25
p value	***	***	***	***	***	ns	ns	ns	ns	ns	ns	**†	**††	***	***	**††

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p < 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference, **† $p = 0.0018$, **†† $p = 0.0028$, *** $p < 0.0001$, ns= not significant.

4.1.5 Plant Tissue N Concentration, Apparent N Recovery, and N Partial Factor Productivity

The treatments affected nitrogen concentrations in plant tissues significantly **(Figure 4.2)**. Compared to the control, the other treatments, except for MT, significantly enhanced N uptake by 76%. However, the effects on N uptake were more profound under CTCrGF and MTCrGF, resulting in 86 and 84% higher values than under the control. The CTCrGL, MTCrGL, CTCrF, CTF, MTF, MTCrF, CTCrTiG, CTCrTiR, MTCrTiG, and MTCrTiR treatments exceedingly improved N uptake by 82, 81, 80, 79, 74, 73, 72, 69, 67, and 62%, respectively, compared to the control.

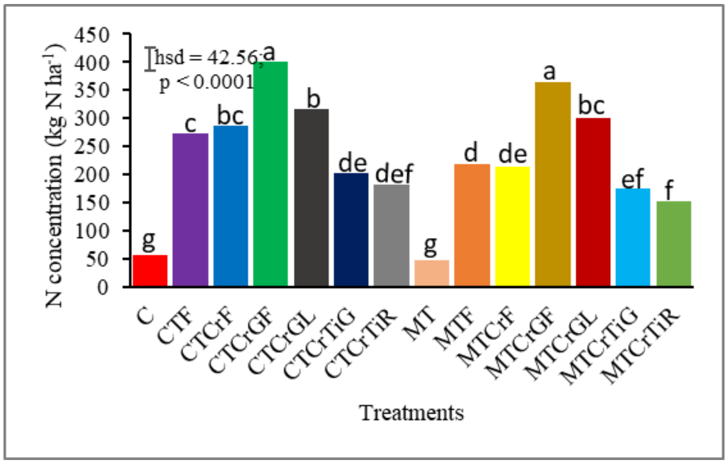


Figure 4.2: Nitrogen Concentrations in Plant Tissues under Different Treatments

Mean values with the same superscript letter(s) denote no significant difference at $p \leq 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer +

goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference pooled error bar.

Apparent N Recovery (ANR) averaged 3.33 and varied significantly among the treatments **(Figure 4.3).** The highest recoveries of 5.11 and 5.75 were recorded under CTCrGF and MTCrGF. Also, ANR was high under CTCrGL, MTCrGL, CTCrF, CTF, MTF, MTCrF, and CTCrTiG but was lower by 25, 29, 34, 38, 53, 55, and 58%, respectively, compared to the highest ANR under CTCrGF. The least ANR values were recorded under CTCrTiR, MTCrTiG, and MTCrTiR. Nitrogen partial factor productivity (NPFP) also significantly varied among the treatments and averaged 32.72 kg N ha^{-1} among the treatments. The highest NPFP of 52.80 kg N ha^{-1} was recorded under CTCrGF. Higher NPFP values were also recorded under CTCrF, MTCrGF, MTCrF, MTCrTiG, CTF, CTCrTiG, CTCrTiR, and MTF but greatly lower under MTCrGL and CTCrGL.

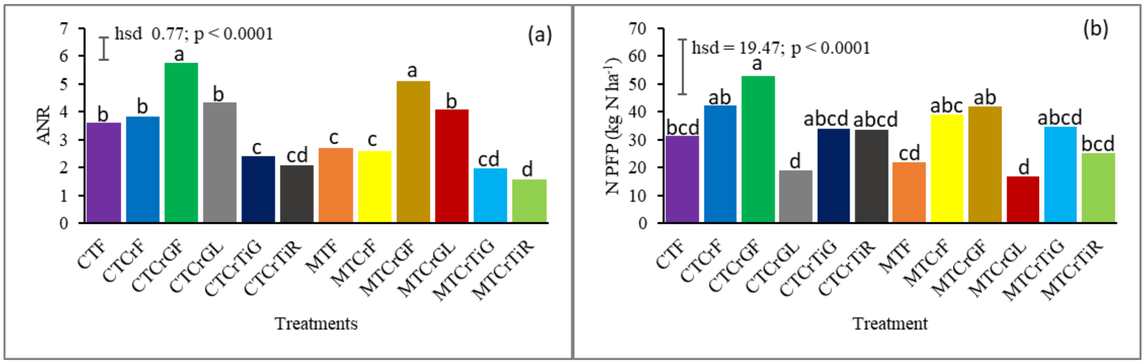


Figure 4.3: (a) Apparent N Recovery and (b) N PFP under Different Treatments during LR21 Cropping Season

Mean values with the same superscript letter(s) denote no significant difference at $p \leq 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference pooled error bar

4.2 Simulated vs Observed N Mineralization under Different ISFM Technologies

The relationship between the observed and the simulated NH_4-N during the SR20 season was weak and insignificant in all the treatments, as shown by the low R^2 values **(Table 4.5).** The APSIM model was not accurate in simulating NH_4-N during the same season as the lowest RMSE, and the highest d-index was only 0.78 kg ha^{-1} and 0.47, respectively, for MT. A positive and significant relationship existed between the simulated and observed NH_4-N only for MTCrF ($R^2 = 0.56$; p= 0.03) and CTCrGL ($R^2 = 0.52$; p = 0.04) during the LR21 cropping season. However, there was generally low model accuracy in simulating NH_4-N during LR21 as the lowest RMSE was only 0.72 kg ha^{-1} while the highest d-index was just 0.58 for CTCrF.

The relationships between simulated and observed NO_3-N for CTCrTiG, CTCrTiR, MTCrF, and CTCrGF were positive and significant (R^2 = 0.63, 0.58, 0.56, and 0.54; p = 0.02, 0.03, 0.03, and 0.04, respectively) during SR20 cropping season as shown in **Table 4.6.** Nevertheless, the model was generally inaccurate in simulating NO3-N during the season, given that the lowest RMSE was just 0.78 kg ha^{-1} and the highest d-index was 0.75 for MTCrGL. The simulated NO_3-N during the LR21 cropping season positively and significantly related to the observed values for MTCrTiG ($R^2 = 0.61$; p = 0.02) and MTCrF ($R^2 = 0.53$; p = 0.04). Overall, APSIM was not accurate in simulating NO_3-N during the

LR21 cropping season but only accurately simulated NO_3-N under CTCrF, depicted by the lowest RMSE of 1.80 kg ha^{-1} and the highest d-index of 0.76.

Table 4.5: Model Performance Analysis for NH_4-N Using R^2, RMSE, and d-Index for Different Treatments during SR20 and LR21 Cropping Seasons

Treatment	**SR20**				**LR21**			
	R^2	**p value**	**RMSE (kg ha^{-1})**	**d-index**	**R^2**	**p value**	**RMSE (kg ha^{-1})**	d-index
C	0.14	0.37	0.83	0.11	0.07	0.54	0.91	0.11
CTF	0.05	0.61	1.40	0.31	0.06	0.56	0.79	0.48
CTCrF	0.16	0.32	0.95	0.11	0.15	0.34	0.72	0.58
CTCrGF	0.01	0.82	1.31	0.26	0.24	0.22	0.95	0.08
CTCrGL	0.03	0.70	0.78	0.23	0.52	0.04	1.16	0.01
CTCrTiG	0.01	0.86	0.85	0.42	0.47	0.06	0.96	0.03
CTCrTiR	0.02	0.74	1.42	0.27	0.42	0.08	1.01	0.03
MT	0.05	0.59	0.78	0.47	0.26	0.20	0.85	0.19
MTF	0.01	0.81	1.01	0.39	0.10	0.44	0.78	0.31
MTCrF	0.01	0.81	1.01	0.39	0.56	0.03	0.98	0.02
MTCrGF	0.01	0.79	1.33	0.25	0.36	0.12	1.11	0.01
MTCrGL	0.00	0.98	0.78	0.34	0.43	0.08	1.12	0.00
MTCrTiG	0.00	0.98	0.78	0.34	0.34	0.13	0.94	0.00
MTCrTiR	0.14	0.37	0.83	0.11	0.46	0.06	1.03	0.02

Chapter Two C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

Table 4.6: Model Performance Analysis for NO_3-N Using R^2, RMSE, and d-Index for Different Treatments during SR20 and LR21 Cropping Seasons

Treatment	SR20				LR21			
	R^2	p-value	RMSE (kg ha^{-1})	d-index	R^2	p-value	RMSE (kg ha^{-1})	d-index
C	0.30	0.16	4.61	0.01	0.30	0.16	4.57	0.03
CTF	0.11	0.43	4.51	0.07	0.34	0.13	4.67	0.20
CTCrF	0.34	0.13	0.73	0.30	0.34	0.13	1.80	0.76
CTCrGF	0.54	0.04	3.97	0.30	0.08	0.50	4.40	0.25
CTCrGL	0.29	0.17	4.12	0.19	0.09	0.47	4.97	0.26
CTCrTiG	0.63	0.02	4.04	0.26	0.02	0.71	4.74	0.19
CTCrTiR	0.58	0.03	4.04	0.24	0.20	0.26	4.53	0.10
MT	0.00	0.90	4.61	0.02	0.08	0.50	5.12	0.17
MTF	0.32	0.15	4.06	0.28	0.10	0.46	5.00	0.22
MTCrF	0.56	0.03	4.05	0.24	0.53	0.04	4.51	0.04
MTCrGF	0.38	0.10	3.97	0.32	0.00	0.91	5.07	0.36
MTCrGL	0.48	0.06	3.91	0.75	0.10	0.45	4.96	0.24
MTCrTiG	0.34	0.13	4.45	0.05	0.61	0.02	4.39	0.03
MTCrTiR	0.39	0.10	4.14	0.23	0.06	0.57	4.36	0.17

C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

Simulated NH_4-N under all the treatments increased from planting date to the 45th DAP then slightly declined on the 60th and 105th DAP during the SR20 cropping season **(Figure 4.4)**. All the treatments had similar simulated NH_4-N along the various sampling intervals apart from CTCrF. Moreover, only CTF, MTF, and control had higher NH_4-N at 15 DAP.

At the start of the cropping season (planting day), the APSIM under-simulated NH_4-N under MTCrGF, CTCrGF, MTCrGL, CTCrGL, and MTCrTiR by 50% **(Appendix III).** The Simulator also recorded 96, 85, 85, 79, 78, 78, 76, 75, 50, 41, and 30% lower NH_4-N under CTCrF, MTCrGL, CTCrTiR, MTF, MTCrGF, CTF, CTCrGF, CTCrTiG, MT, and MTCrF, respectively, than the observed values on the 15th DAP. However, from 30 to 105 DAP, the simulated values exceeded the observed value by over 100%, on average in all the treatments.

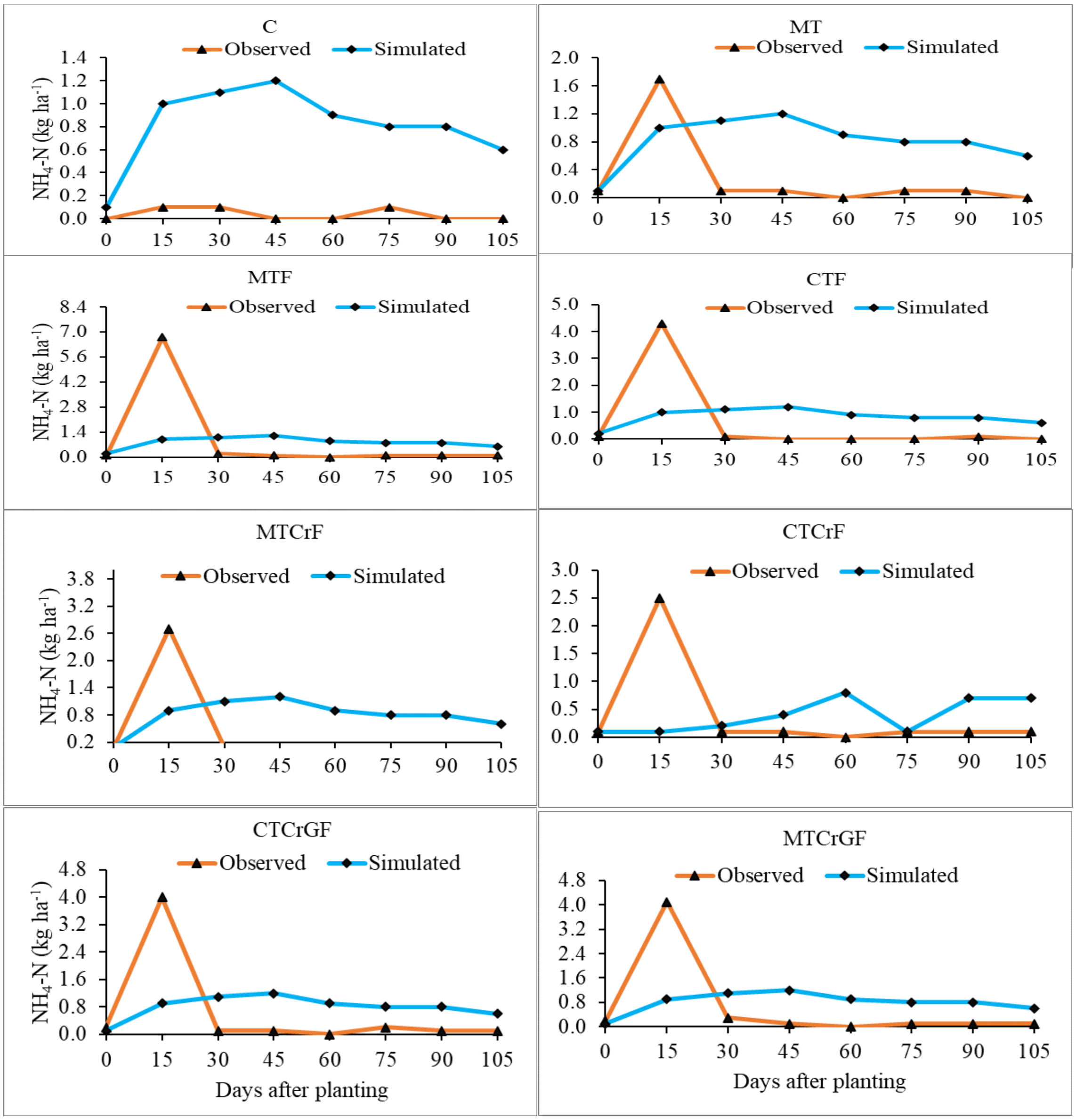


Figure 4.4: Observed and Simulated NH_4-N (kg ha^{-1}) under Different Treatments over Time during the SR20 Cropping System

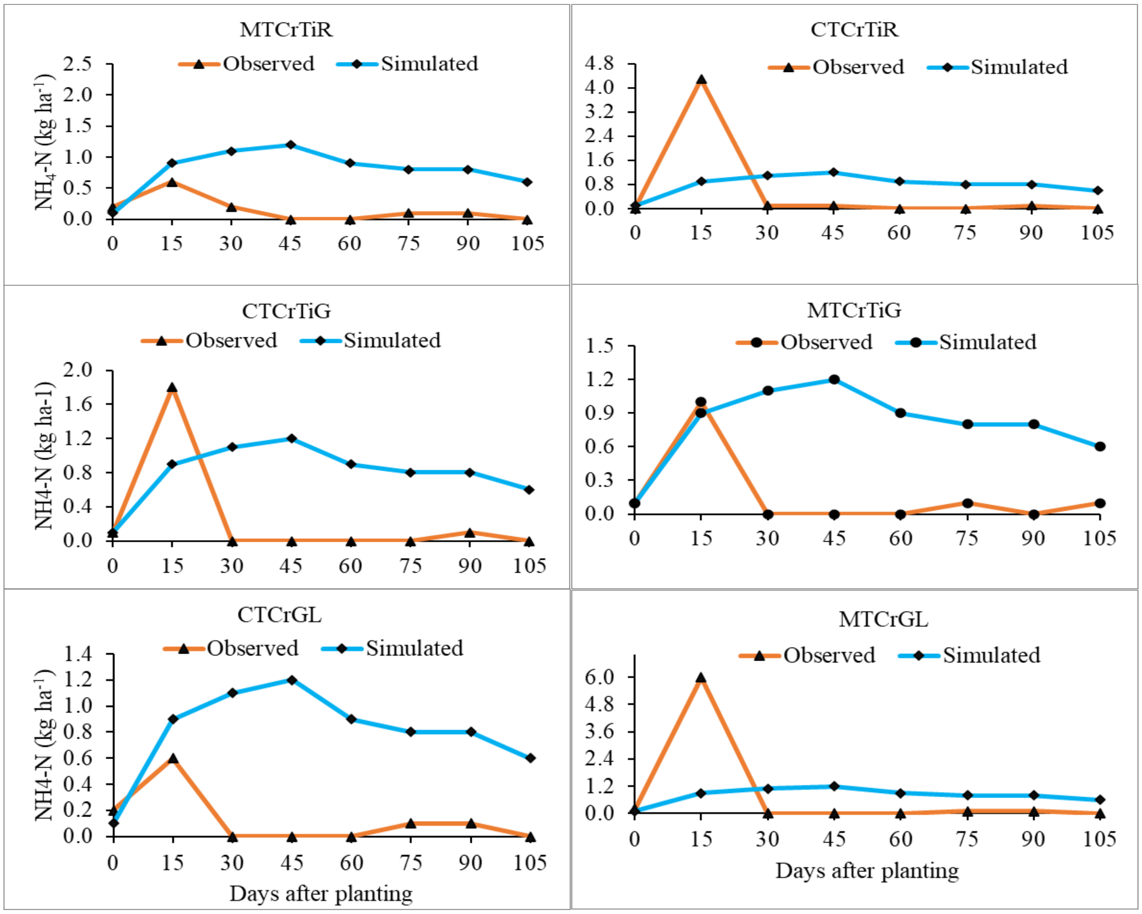


Figure 4.4 (Continued): Observed and Simulated NH_4-N (kg ha^{-1}) under Different Treatments over Time during the SR20 Cropping System

C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat

manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

Simulated NO_3-N showed an increasing trend between the sampling intervals under most of the treatments apart from CTCrF which had no clear pattern during the SR20 cropping season **(Figure 4.5).** Similarly, APSIM under-simulated NO_3-N at 0 DAP under MTCrGF, MTCrGL, CTCrTiR, MTCrTiR, MTCrTiG, and CTCrTiG, respectively, by 100% on the planting day **(Appendix IV).** Additionally, CTCrF on the 15th DAP was 100% higher under the observed value compared to the simulated value. Generally, APSIM overestimated NO_3-N by over 100% from 15 to 105 DAP under most of the treatments.

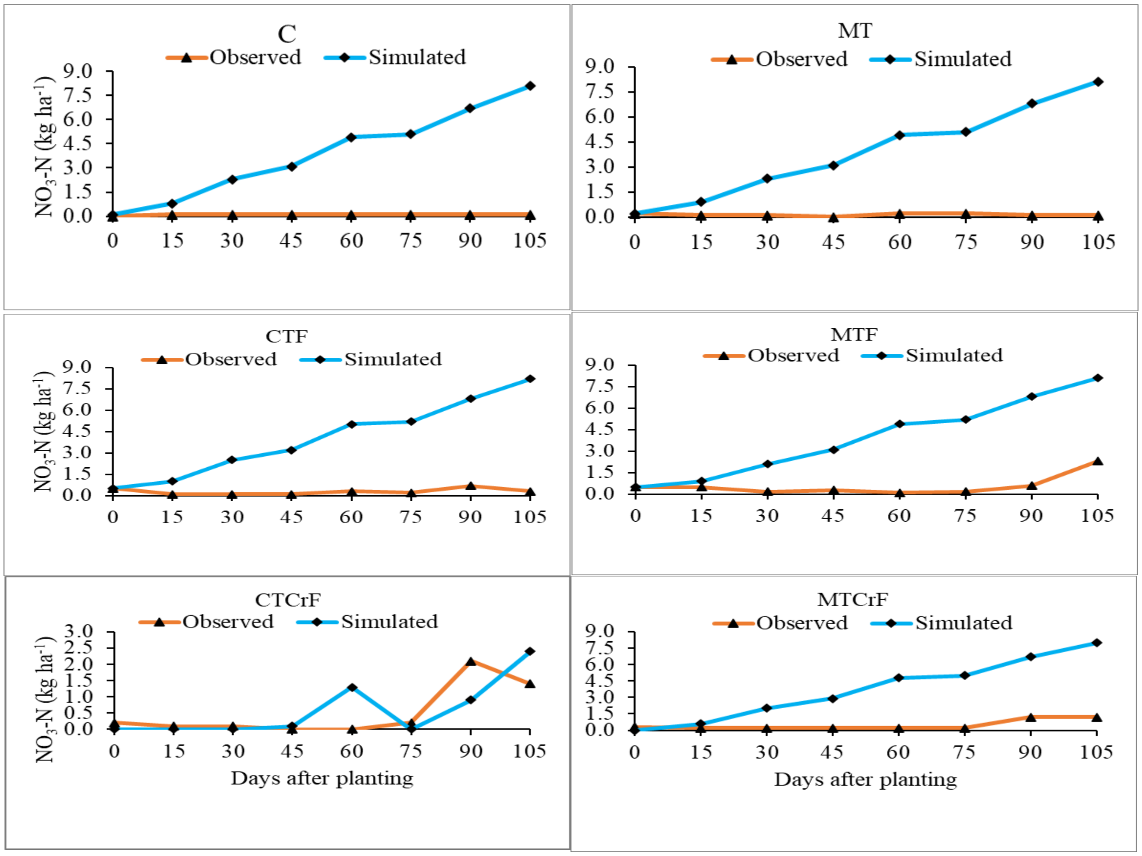


Figure 4.5: Observed and Simulated NO_3-N (kg ha^{-1}) under Different Treatments over Time during the SR20 Cropping System

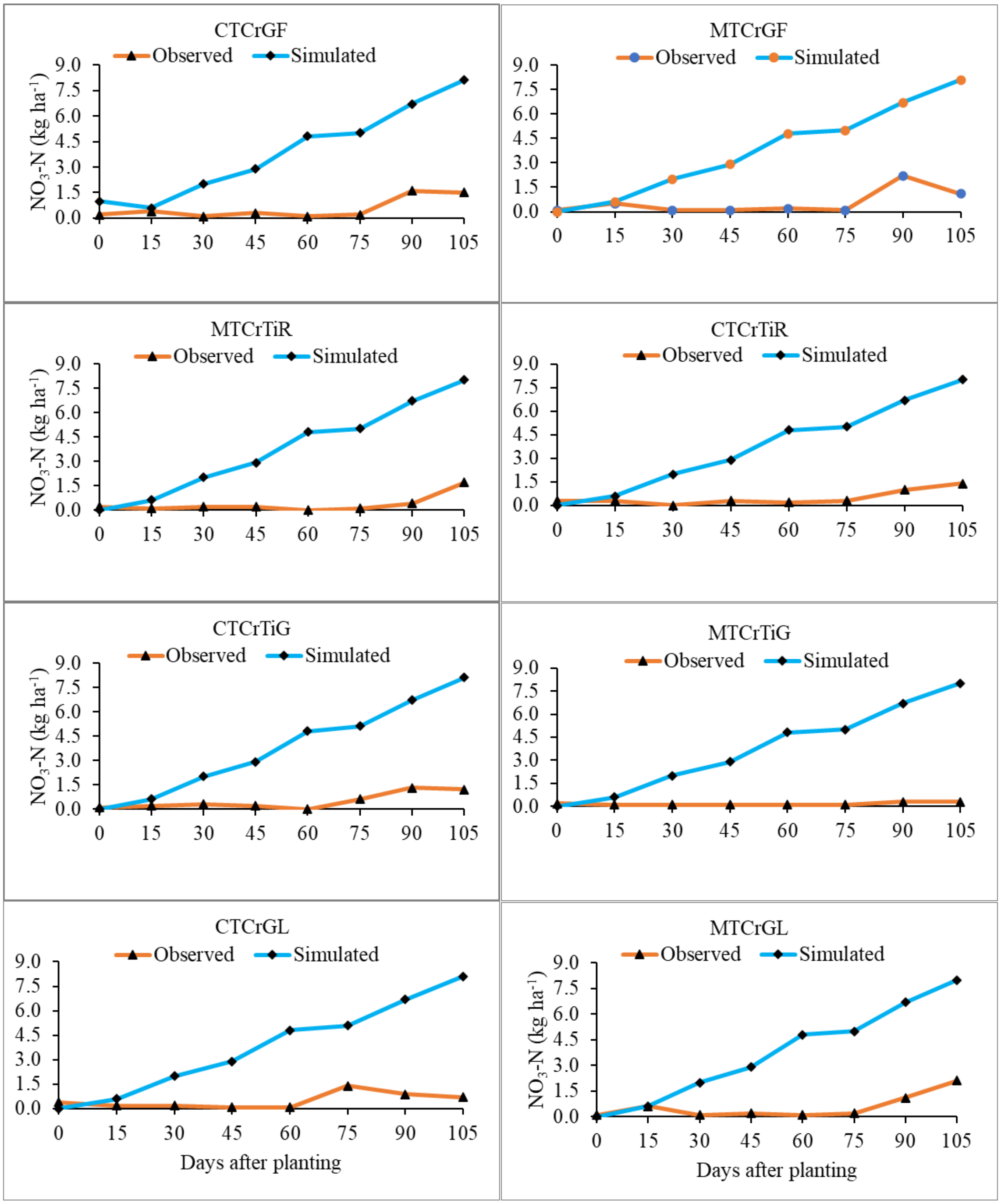


Figure 4.5 (Continued): Observed and Simulated NO_3-N (kg ha^{-1}) under Different Treatments over Time during the SR20 Cropping System

C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

The simulated NH_4-N showed a similar trend in LR21 as was in the SR20 cropping season, in which it increased from 0 DAP to 60 DAP and thereafter declined **(Figure 4.6).** The simulator accurately estimated NH_4-N under CTF and control on the planting day and under CTCrF on the 45th and 60th DAP **(Appendix V).** Nevertheless, it greatly under-estimated NH_4-N at planting day under MTCrGF, MTCrF, MTCrTiR, MTF, CTCrGF, MTCrTiG, CTCrTiG, MTCrGL, CTCrGL, CTCrF, MT, and CTCrTiR by 93, 92, 92, 92, 90, 91, 89, 88, 83, 56, 13, and 10%, respectively. Moreover, APSIM also underestimated NH_4-N under CTCrF and CTF by 50% and 29% at 30 and 75 DAP, respectively. Overall, the simulated NH_4-N was greater than the observed values among the treatments after 0 DAP by more than 100%.

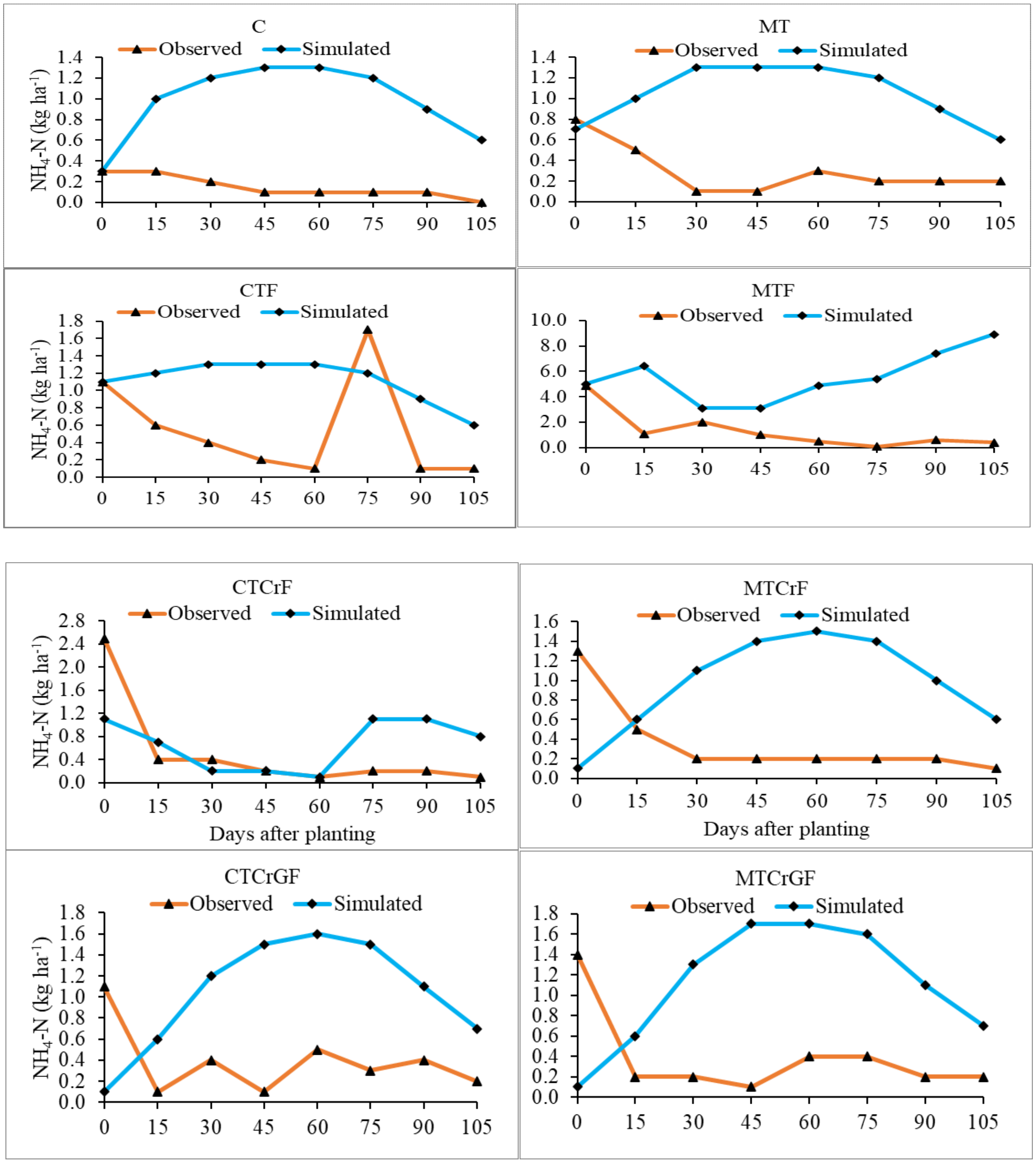


Figure 4.6: Observed and simulated NH4-N (kg ha^{-1}) under Different Treatments over Time during the LR21 Cropping System

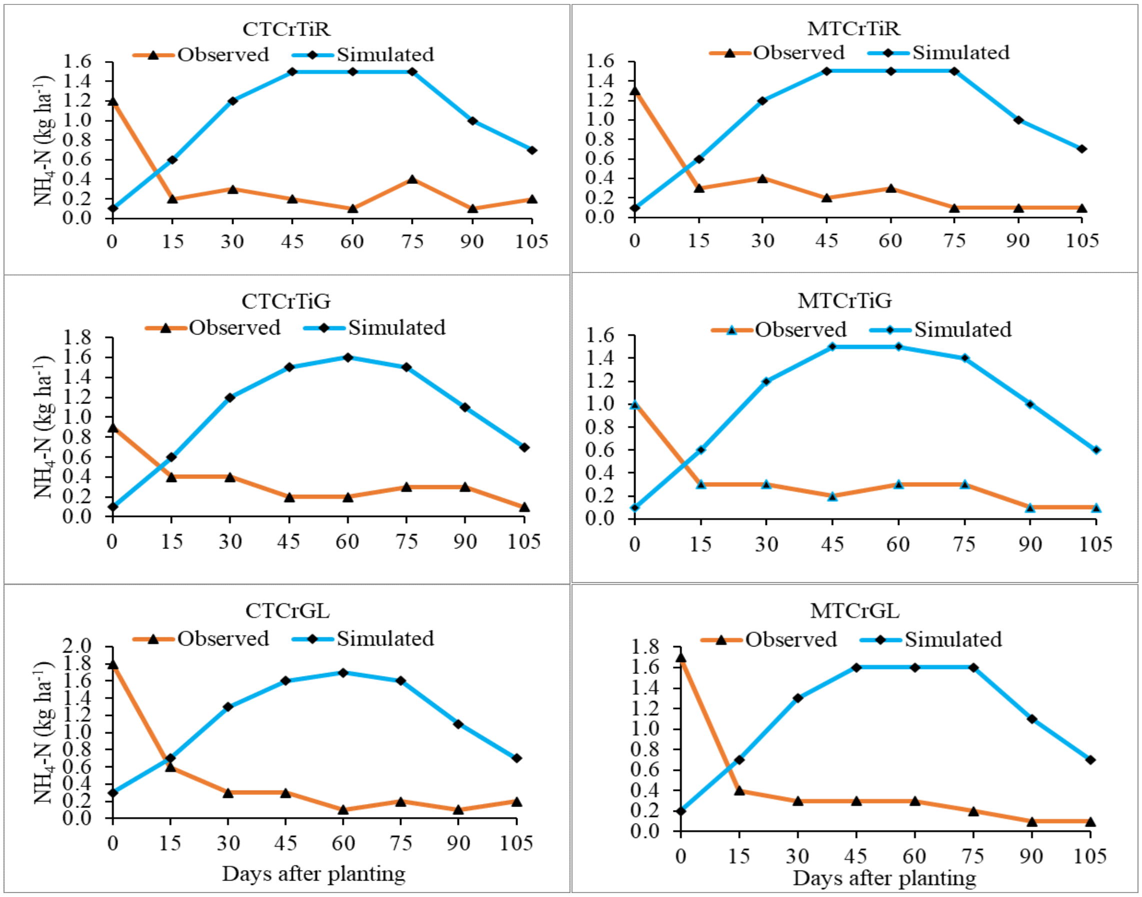


Figure 4.6 (Continued): Observed and Simulated NH4-N (kg ha^{-1}) under Different Treatments over Time during the LR21 Cropping System

C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat

manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

Simulated NO_3-N showed no particular pattern among the treatments across the sampling intervals **(Figure 4.7).** However, similar to the observed values, simulated NO3-N during the LR21 season was higher than during the SR20 cropping season at the start. The NO_3-N was accurately estimated under MTCrGL, CTCrGL, and control on the planting day **(Appendix VI).** The simulator underestimated NO_3-N under MTCrGF by 1% and 90% on the planting day and 15 DAP, respectively. Simulated NO_3-N under CTCrGF was 10%, 81%, and 17% lower than the observed values as it was also lower by 1%, 92%, and 18%, respectively, under MTCrF at 0, 15, and 30 DAP. On planting days 15 and 30 DAP, the simulated NO3-N under MTCrTiR and MTCrTiG were lower than the observed by 5%, 50%, 36%, 15%, 88%, and 64%, respectively. There was also an underestimation of the values under CTCrTiG and CTCrTiR on the planting day and 15 DAP by 13% and 40%, and by 13% and 85%, respectively. On the 15, 30, 45, and 60 DAP, APSIM under-estimated NO_3-N by 82% and 100% under CTCrF and by 7% under CTF on the 30th DAP. Also, the simulated under CTCrGL was lower by 90% and 44% compared to the observed at 15 and 30 DAP, respectively. The remaining estimated values among the treatments across the sampling intervals were generally higher than the observed values.

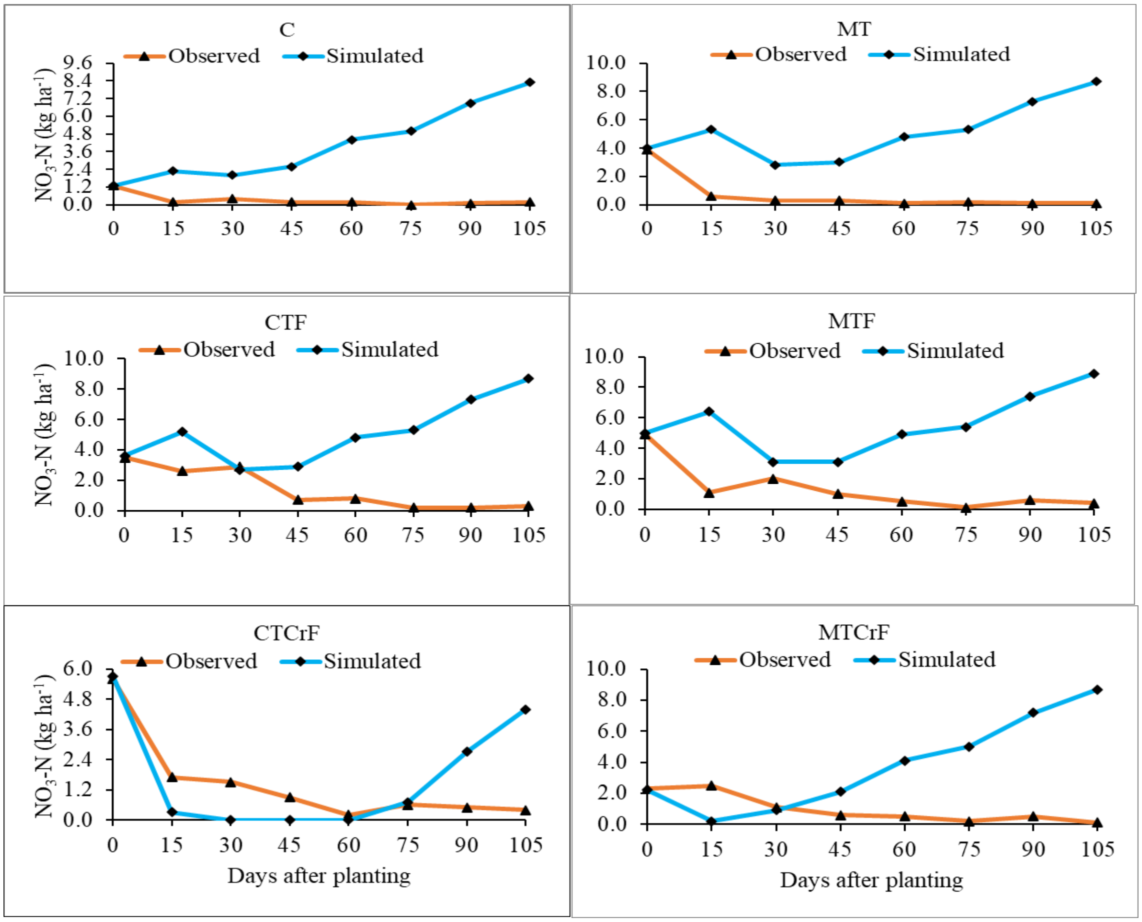


Figure 4.7: Observed and Simulated NO$_3$-N (kg ha^{-1}) under Different Treatments over Time during the LR21 Cropping System

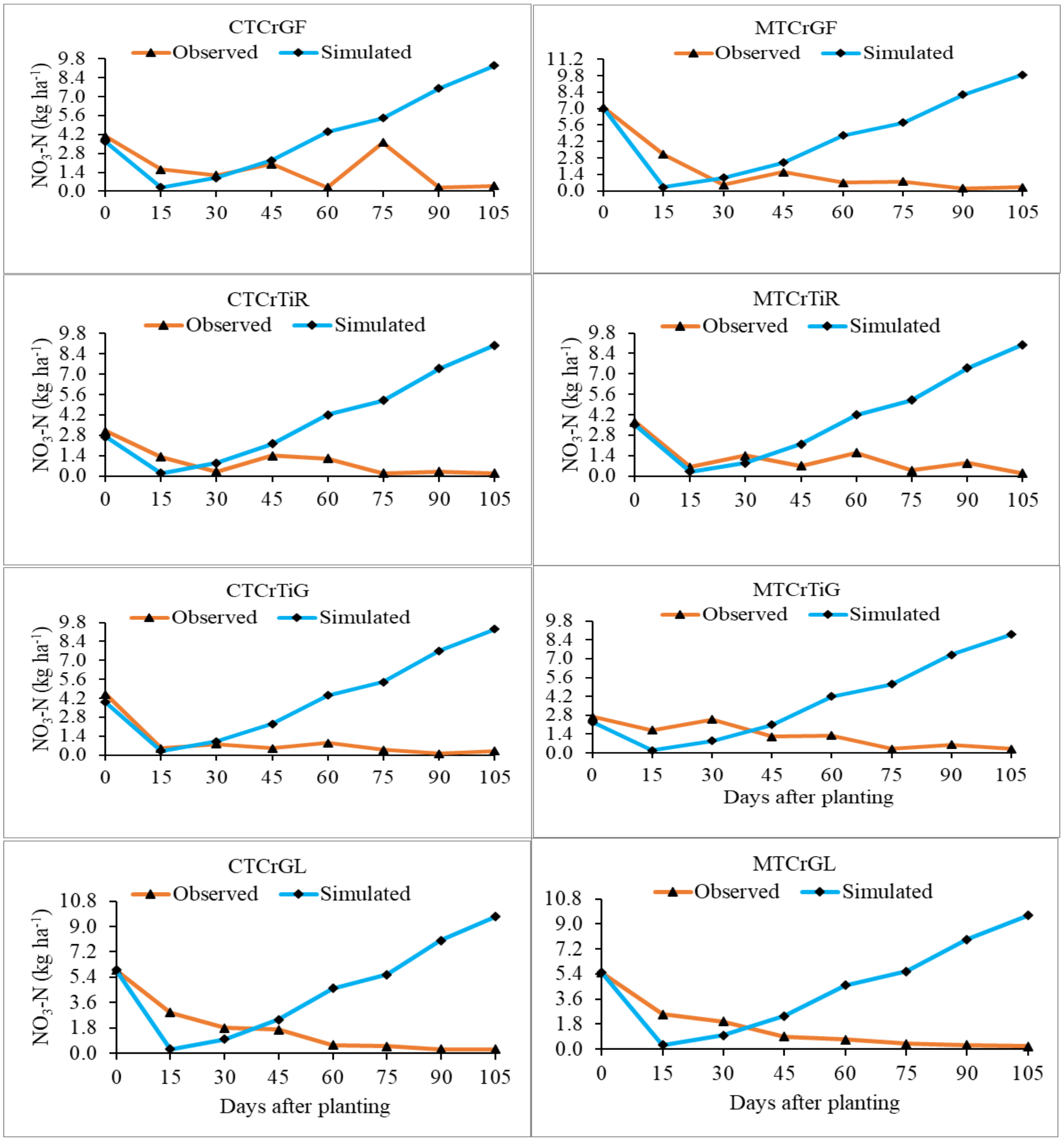


Figure 4.7 (Continued): Observed and Simulated NO_3-N (kg ha^{-1}) under Different Treatments over Time during the LR21 Cropping System

C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

4.3.1 Impact of Various ISFM technologies on Available Soil N

There was a significant treatment effect on available soil N at the end of the experiment **(Table 4.7).** The highest available N was observed under CTCrF, which was 65% higher than the control and differed significantly from the other treatments. Higher N (59, 59, 59, 57, 57, 57, 55, 55, 55, 50, and 50%) than the control was also recorded under MTCrGL, CTCrGL, CTCrTiR, MTCrTiR, MTCrF, CTCrTiG, MTF, CTCrGF, CTF, MTCrTiG and MTCrGF, respectively. Though MT did not differ from the control, the variation between it and other treatments was significant.

The treatments resulted in a significant change in available N. Apart from MT, changes in available N under the treatments at the end of the experiment were exceedingly greater than the change in the control. The greatest positive change in N was observed under CTCrF, which was 300% greater than the change under the control. On average, the amended plots recorded a positive change in N of 214%. The changes under MTCrGL, CTCrGL, CTCrTiR, MTCrTiR, MTCrF, CTCrTiG, MTF, CTCrGF, and CTF were not significantly different but were higher than the changes under MTCrGF and MTCrTiG. Nitrogen declined by 160% under MT but did not differ with the reduction of 183% under the control.

Table 4.7: Available and Change in N under Various Treatments at the End of Experimentation

Treatment	N (%)	Change	t value	Pr > |t|
C	0.09^{e}	-0.06^{d}	-11.10	0.0016
CTF	0.20^{bcd}	0.05^{bc}	13.17	0.0009
CTCrF	0.26^{a}	0.12^{a}	26.59	0.0001
CTCrGF	0.20^{bcd}	0.06^{bc}	9.03	0.0029
CTCrGL	0.22^{b}	0.08^{b}	25.31	0.0001
CTCrTiG	0.21^{bcd}	0.07^{bc}	6.54	0.0073
CTCrTiR	0.22^{b}	0.08^{b}	9.24	0.0027
MT	0.11^{e}	-0.03^{d}	-5.65	0.011
MTF	0.20^{bcd}	0.06^{bc}	13.35	0.0009
MTCrF	0.21^{bc}	0.07^{bc}	7.67	0.0046
MTCrGF	0.18^{d}	0.04^{c}	8.08	0.004
MTCrGL	0.22^{b}	0.08^{b}	11.97	0.0013
MTCrTiG	0.18^{cd}	0.04^{c}	13.66	0.0008
MTCrTiR	0.21^{b}	0.07^{b}	8.72	0.0032
hsd	0.03	0.03	na	na
p-values	***	***	na	na

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$, (3) HSD = honestly significant difference, (4) not applicable, *** $p < 0.0001$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

4.4 Phosphorus Fractions under Different ISFM Technologies

The treatments significantly influenced the distribution of P fraction (**Figure 4.8** and **Table 4.8)**. Total labile Pi was higher than the total labile Po, respectively. Total labile P (summation of labile and moderate labile) was greater than the total recalcitrant P (summation of less labile and none labile P) under all the treatments.

Generally, most P fractions were higher under MTCrGF and CTCrGF, with a few exceptions **(Table 4.8).** Sequential fractionation showed residual P as the largest P fraction, followed by NaOH-Pi, while the lowest was $NaHCO_3$-Po. The residual P was significantly ($p < 0.0035$) higher by 3471 mg kg^{-1} under MTCrGF than under control. Resin-Pi was the most dominant fraction under the labile P fractions and was significantly ($p < 0.0001$) higher under MTCrGF, MTCrF, CTCrF, CTCrGF, CTF, and MTCrTiR by 182, 115, 100, 100, 83, and 69 mg kg^{-1}, respectively, than the control. The remaining treatments had a similar impact on resin-Pi as the control. The second prominent labile P fraction was $NaHCO_3$-Pi which was significantly ($p < 0.0001$) higher under MTCrGF, MTCrF, CTCrGF, CTF, CTCrF, and MTF by 76, 53, 48, 45, 42, and 31 mg kg^{-1}, respectively, relative to the control. The rest of the treatments were comparable to the control. The lowest labile P fraction was $NaHCO_3$-Po and was only significantly ($p = 0.0285$) impacted by CTCrTiR, causing a 32 mg kg^{-1} increment from the control. Plots under CTCrGF, MTCrF, CTF, CTCrF, MTCrGF, and MTF treatments had the highest (216, 214, 210, 186, 183, and 123 mg kg^{-1}, respectively) concentrations of NaOH-Pi than the control. Only MTCrTiG and CTCrTiG performed exceedingly well, leading to 101 and 77 mg kg^{-1} higher NaOH-Po than the control.

The greatest contributor to a recalcitrant fraction (less labile and none labile P) was sonic NaOH-Pi. It was significantly ($p < 0.0001$) higher by 45, 40, 31, and 28 mg kg^{-1} under CTCrGF, MTCrGF, CTF, and CTCrF than the control. Though the remaining technologies had higher sonic NaOH-Pi, the variations were insignificant compared to the control. Additionally, sonic NaOH-Po was significantly ($p < 0.0001$) higher under MTCrGF, MTCrTiR, MTCrF, and MTCrGL (80, 49, 48, and 43 mg kg^{-1}) than in control.

The other treatments had higher sonic NaOH-Po, but the differences were insignificant to the control. On the other hand, none labile HCl-Pi was greater under MTCrTiR, MTCrGF, and CTCrGF by 24, 19, and 14 mg kg^{-1}, respectively, compared to the control. Despite recording appreciably high none labile HCl-Pi, except MT, the remaining treatments had statistically the same labile HCl-Pi as the control.

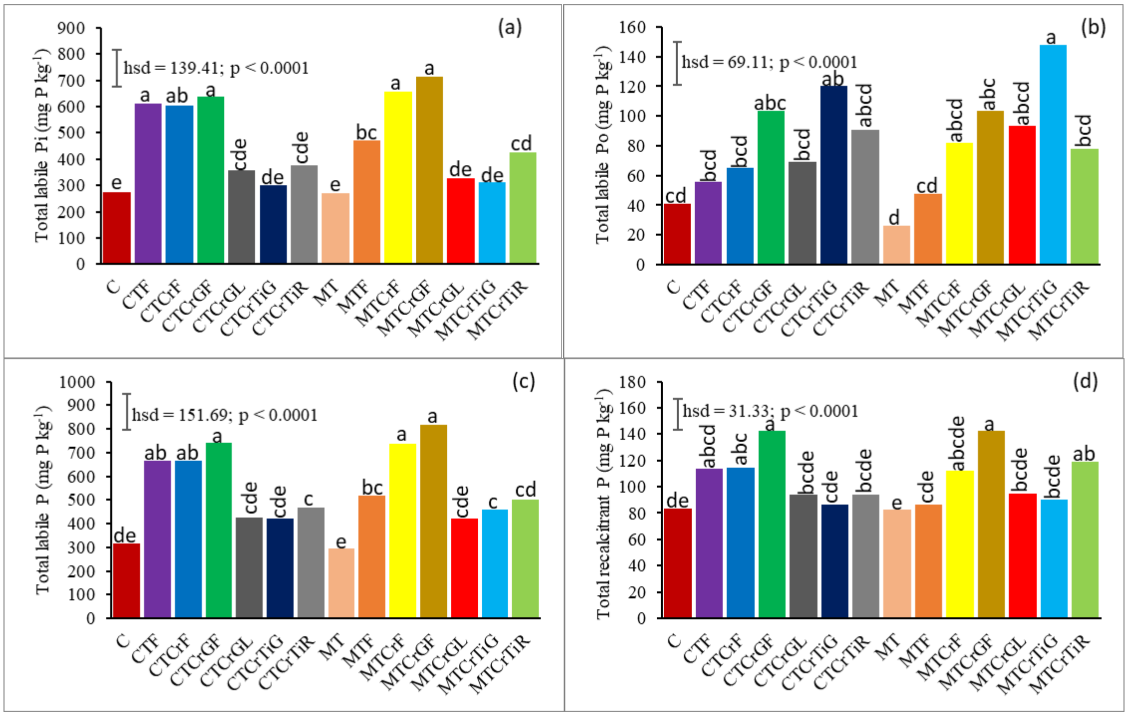


Figure 4.8: Distributions of (a) Total Labile Pi, (b) Total Labile Po, (c) Total Labile P, and (d) Total Recalcitrant P under Different Treatments

Mean values with the same superscript letter(s) denote no significant difference at $p < 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues +

inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference pooled error bar.

Table 4.8: Quantitative Distributions of Soil P Fractions among Different Treatments

Treatment	Labile			Moderate labile-P		Less labile		None labile	Residual P
	Resin-Pi	NaHCO$_3$-Pi	NaHCO$_3$-Po	NaOH-Pi	NaOH-Po	Sonic NaOH-Pi	Sonic NaOH-Po	HCl-Pi	
					mg P kg^{-1}				
C	24.35^{f}	13.74^{e}	11.61^{b}	235.16^{c}	29.13^{c}	68.61^{e}	4.52^{d}	14.63^{d}	7465.20^{b}
CTF	107.17^{bcd}	58.75^{bc}	17.14^{ab}	444.66^{a}	38.39^{c}	99.35^{abc}	31.36^{bcd}	14.69^{d}	9259.60^{ab}
CTCrF	124.74^{bc}	56.13^{bc}	19.54^{ab}	421.52^{a}	45.51^{bc}	96.71^{abcd}	44.27^{abcd}	17.87^{cd}	9321.30^{ab}
CTCrGF	124.65^{bc}	61.25^{bc}	29.19^{ab}	450.80^{a}	74.20^{abc}	113.76^{a}	44.30^{abcd}	28.36^{abc}	8057.00^{ab}
CTCrGL	75.25^{cdef}	20.67^{e}	13.41^{ab}	259.52^{bc}	55.89^{bc}	75.25^{de}	40.55^{bcd}	18.41^{cd}	8902.80^{ab}
CTCrTiG	46.05^{ef}	14.11^{e}	14.20^{ab}	240.54^{c}	106.20^{ab}	71.09^{e}	13.33^{bcd}	15.35^{cd}	7642.90^{b}
CTCrTiR	77.45^{cdef}	30.11^{de}	43.67^{a}	270.53^{bc}	46.80^{bc}	75.48^{de}	26.74^{bcd}	18.83^{cd}	7766.20^{b}
MT	26.20^{f}	13.66^{e}	7.07^{b}	229.54^{c}	18.99^{c}	69.59^{e}	7.45^{cd}	12.77^{d}	8215.60^{ab}
MTF	66.71^{def}	44.55^{cd}	16.73^{ab}	358.36^{ab}	30.95^{c}	71.92^{e}	15.21^{bcd}	14.69^{d}	7616.50^{b}
MTCrF	139.46^{b}	66.74^{b}	28.82^{ab}	449.25^{a}	53.45^{bc}	87.26^{bcde}	52.35^{ab}	24.78^{bcd}	8638.50^{ab}
MTCrGF	206.26^{a}	89.74^{a}	23.62^{ab}	417.84^{a}	79.60^{abc}	108.32^{ab}	84.03^{a}	33.81^{ab}	10936.50^{a}
MTCrGL	$61.89d^{ef}$	17.64^{e}	21.14^{ab}	246.84^{c}	72.15^{abc}	70.99^{e}	47.86^{abc}	23.82^{bcd}	9603.20^{ab}
MTCrTiG	50.73^{ef}	20.59^{e}	17.81^{ab}	239.16^{c}	129.78^{a}	71.37^{e}	12.25^{bcd}	18.53^{cd}	10096.60^{ab}
MTCrTiR	93.23^{bcde}	27.83^{de}	14.74^{ab}	304.03^{bc}	63.16^{bc}	80.08^{cde}	53.12^{ab}	38.61^{a}	9415.20^{ab}
hsd	54.79	22.07	31.38	102.40	62.61	23.83	41.56	13.42	3045.20
p-value	***	***	*	***	***	***	***	***	**

Mean values followed with the same letter(s) within the same column do not differ at $p \leq 0.05$; hsd = honestly significant difference. * $p < 0.0285$, ** $p < 0.0035$, *** $p < 0.0001$; C = Control (no amendments) , CTF = Conventional tillage + inorganic fertilizer, CTCrF = Conventional tillage + maize residue + inorganic fertilizer, CTCrGF = Conventional tillage + maize residue + inorganic fertilizer + goat manure, CTCrTiR = Conventional tillage + maize residue + *Tithonia diversifolia* + rock phosphate, CTCrGL =

Conventional tillage + maize residue + goat manure + legume intercrop, CTCrTiG = Conventional tillage + maize residue + *Tithonia diversifolia* + goat manure, MT = Minimum tillage + no amendments, MTF = Minimum tillage + inorganic fertilizer, MTCrF = Minimum tillage + maize residue + inorganic fertilizer, MTCrGF = Minimum tillage + maize residue + inorganic fertilizer + goat manure, MTCrTiR = Minimum tillage + maize residue + *Tithonia diversifolia* + rock phosphate, MTCrGL = Minimum tillage + maize residue + goat manure + legume intercrop, MTCrTiG = Minimum tillage + maize residue + *Tithonia diversifolia* + goat manure. $NaHCO_3$-Pi = sodium bicarbonate-extractable inorganic P, $NaHCO_3$-Po = sodium bicarbonate-extractable organic P, NaOH-P = sodium hydroxide-extractable Fe.Al-P, and HCl-Pi= hydrochloric acid-extractable Mg.Ca-P.

4.4.1 Phosphorus Sorption Characteristics under Different ISFM Technologies

Phosphorus sorption parameters and P legacy were significantly impacted by the treatments **(Figure 4.9).** Maximum P sorption (S_{max}) was exceedingly higher under MTCrGF and CTCrGF by 52 and 49 mg P kg^{-1}, respectively, than the control. As revealed by the greater ķ values (the bonding energy), P is highly fixed under the control (2.57 L mg^{-1}) and MT (4.59 L mg^{-1}) than in all the other treatments. Fixation of P was twice higher under MT than the control. The lowest ķ was recorded under CTCrGF and MTCrGF (0.04 L mg^{-1}), which was 98% lower than the control. Compared to the control, ķ was also markedly lower by 2.42, 2.41, 2.40, 2.38, 2.37, 2.37, 2.32, 2.21, 2.10, and 1.91 L mg^{-1} under MTCrGL, MTCrF, CTCrGL, CTCrF, CTCrTiR, MTCrTiG, MTCrTiR, CTCrTiG, CTF, and MTF, respectively. Apart from CTCrF, CTCrGF, and MT, the rest of the treatments had substantially higher Degrees of Phosphorus Saturation (DPS) with a 40% increment on average from the control. The highest DPS was recorded under MTCrTiG, which was higher than the control by 66%.

Legacy P was highest under MTCrGF. Significantly higher legacy P of 51, 48, 43, 38, 37, 36, and 27% were also recorded under MTCrGF, CTCrGF, MTCrF, CTF, CTCrF, MTCrGL, and CTCrTiG, respectively, relative to the control. However, it showed no variations under MTCrGF, CTCrGF, and MTCrF. No significant differences in legacy P were observed among CTF, CTCrF, MTCrGL, and CTCrTiG. It varied significantly under MTCrGF and CTCrGF from the amounts recorded under CTF, CTCrF, MTCrGL, and CTCrTiG.

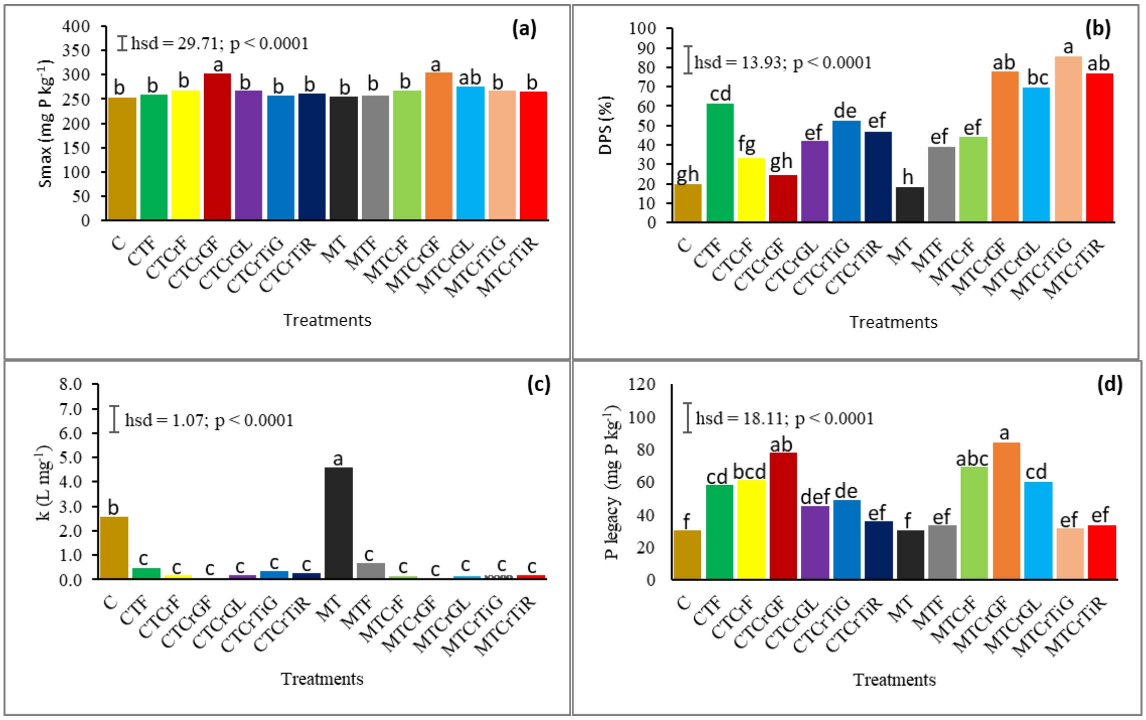


Figure 4.9: Mean Maximum P Sorption capacity (Smax), Bonding Energy (k), and Degrees of P Saturation (DPS) as Influenced by Different Treatments

Mean values with the same superscript letter(s) denote no significant difference at $p < 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference pooled error bar.

4.4.2 Response of Aboveground P Use Efficiencies to ISFM Technologies

Phosphorus use efficiency parameters significantly ($p < 0.0001$) varied among the treatments during the two seasons **(Figure 4.10).** The effects of the treatments on Phosphorus Partial Productivity Factor (PPF) and Phosphorus Agronomic Efficiency (PAE) were consistent across the two seasons. The highest Phosphorus Use Efficiency (PUE), as indicated by PPF (0.093 and 0.140 kg biomass kg^{-1} P) and PAE (0.080 and 0.073 kg biomass kg^{-1} P) during SR20 and LR21, respectively, were observed under CTCrGF. However, PPF (0.043 and 0.078 kg biomass kg^{-1} P) and PAE (0.030 and 0.008 kg biomass kg^{-1} P) were the lowest under MTCrTiR during the two seasons. The lowest PPF (0.045 kg biomass kg^{-1} P) was also recorded under MTCrGL during the SR20 season.

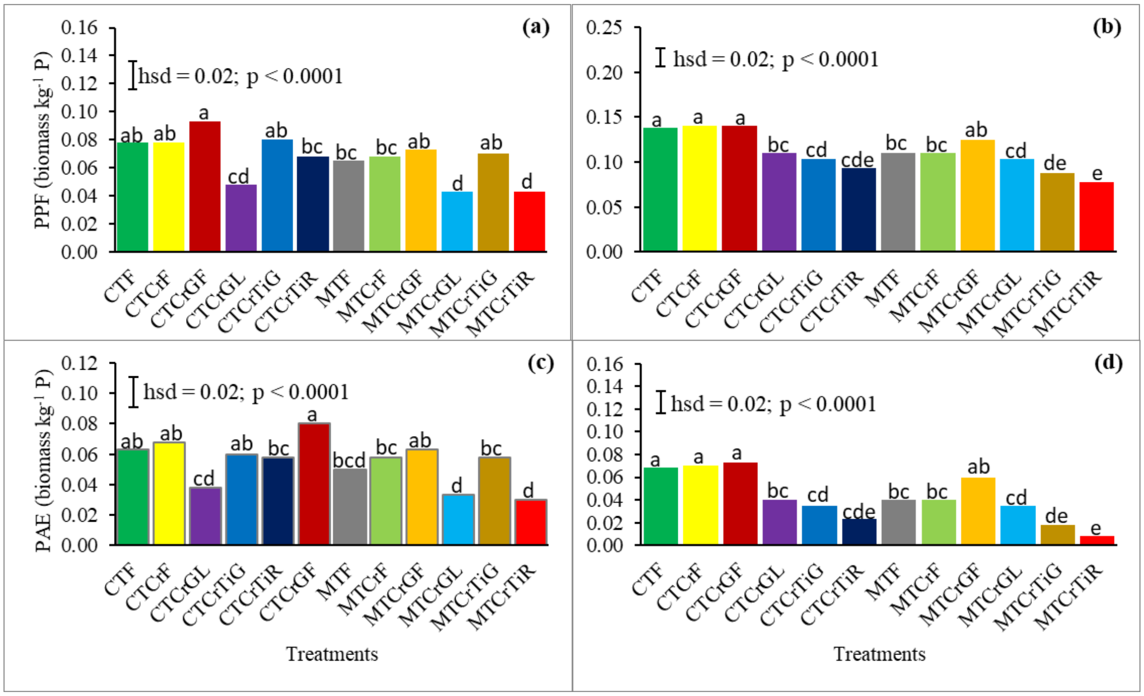


Figure 4.10: Mean Phosphorus PPF (a & b) and PAE (c & d) under Different Treatments during SR20 and LR21 Cropping Seasons, Respectively

Mean values with the same superscript letter(s) denote no significant difference at $p < 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference pooled error bar.

4.4.3 Available P under various ISFM technologies

The treatments had significant effects on available P **(Figure 4.11).** Its highest value was recorded under MTCrGF. Generally, it was remarkedly higher by 64, 61, 56, 51, 50, 48 and 39% under MTCrGF, CTCrGF, MTCrF, CTCrF, MTCrGL, CTF, and CTCrTiG, respectively, compared with the control. Similar amounts of available P were also observed under MTCrGF, CTCrGF, and MTCrF. Differences under MTCrGL, CTF, and CTCrTiG were insignificant. The other six treatments had comparable available P to the control.

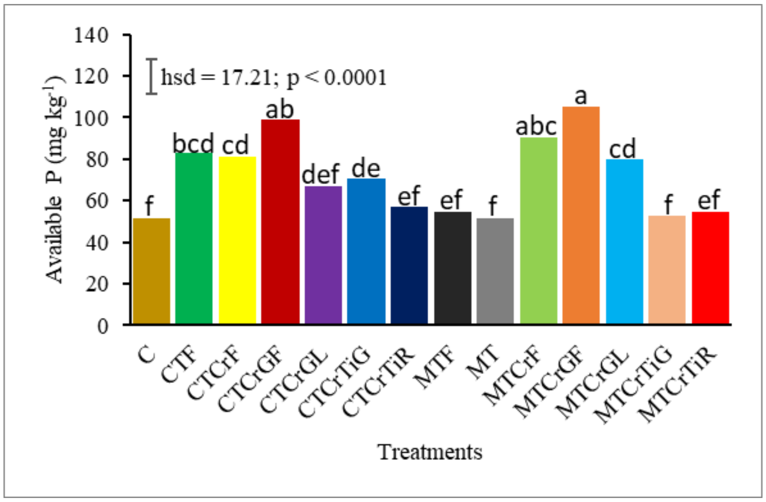


Figure 4.11: Available P under Treatments after 11 Cropping Seasons.

Mean values with the same superscript letter(s) denote no significant difference at $p < 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab,* CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer +

goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure, hsd = honestly significant difference pooled error bar.

4.5. Effects of Different ISFM Technologies on Maize Productivity

The treatments recorded significant variations in relative chlorophyll content and Leaf Area Index (LAI) in all phenological stages (**Error! Reference source not found.**). D uring the SR20 cropping season, the highest chlorophyll content was recorded under CTCrF and was 38% to 61% significantly higher under amended plots than the control at the 6th leaf stage. Besides CTCrF and CTF, chlorophyll differences under the remaining treatments were insignificant. At the 10th leaf stage, MTCrF, CTCrF, CTCrGF, CTF, CTCrTiG, and CTCrGL had exceptionally higher chlorophyll content than the control of 37, 36, 33, 32, 31, and 30%, respectively. The highest chlorophyll was recorded under MTCrF, which also performed exceedingly well than MTCrTiR and MT. High chlorophyll content was also recorded under MTCrTiG, MTCrGF, MTF, CTCrTiR, MTCrGL, MTCrTiR, and MT, though it did not vary greatly from that of the control. The LAI at the 6th leaf stage was the highest under CTCrGL (68%) and also significantly higher under MTCrGL, CTCrF, MTCrGF, and CTCrGF by 67, 60, 49, and 48%, respectively, relative to the control. However, the contents under MTCrGL and CTCrF were comparable to CTCrGL. It was also high under MTF, CTF, MTCrF, CTCrTiG, MTCrTiG, MTCrTiR, and CTCrTiR, but similar to that under the control. At the 10th leaf, it was greater by 59% and 49% under CTCrGF and MTCrGF, respectively, compared to the control. The remaining treatments had a similar LAI as the control.

The treatments also significantly affected chlorophyll content and LAI during the LR21 season **(Table 4.9).** At the 6th leaf stage, the highest chlorophyll was recorded under MTF, which was 31% more than the control. Chlorophyll content was also considerably higher under CTF and MTCrGL than the control, by 25% and 23%, respectively. However, there was no significant increase in chlorophyll under the remaining treatments compared to the control. The highest chlorophyll at the 10th leaf stage was under CTF, which was a 31% improvement from the control. Also, CTCrGF, MTF, CTCrF, and MTCrGL had markedly higher chlorophyll than the control by 28, 27, 27, and 21%, respectively, at the same growth stage. The differences in chlorophyll content under the remaining treatments and the control were insignificant. At the 6th leaf stage, the highest LAI was recorded under MTCrGL and CTCrGL, representing a 66% and 65% increase from the control, respectively. The LAI was also substantially higher under MTCrGF, MTCrF, and MTCrTiR than the control by 46, 44 and 39%, respectively. Conversely, insignificant differences in LAI under the other treatments compared to the control were recorded. At the 10th leaf stage, the greatest LAI resulted from CTCrGL and MTCrGL, which were 72 and 69% higher than the control. Exceptionally higher LAI was also observed under MTCrGF, MTCrF, MTF, CTCrGF, MTCrTiG, CTCrF, and CTCrTiG (51, 51, 50, 48, 41, 39, and 38%, respectively) compared to the control. However, it was significantly lower under CTF, CTCrTiR, MTCrTiR, and MT than CTCrGL and MTCrGL but comparable to the control.

Table 4.9: Relative Chlorophyll Content and LAI at 6th and 10th Leaf Stages under Different Treatments during the SR20 and LR21 Seasons

Treatment	SR20				LR21			
	Relative chlorophyll		LAI		Relative chlorophyll		LAI	
	6th leaf	10th leaf	6th leaf	10th leaf	6th leaf	10th leaf	6th leaf	10th leaf
	SPAD values		m^{2} m^{-2}		SPAD values		m^{2} m^{-2}	
C	18.73^{e}	28.10^{d}	0.74^{d}	2.10^{c}	29.23^{d}	33.47^{ef}	0.77^{d}	1.39^{f}
CTF	40.80^{ab}	41.58^{ab}	1.35^{bcd}	2.12^{c}	38.95^{ab}	48.28^{a}	1.06^{bcd}	2.07^{bcdef}
CTCrF	47.97^{a}	43.63^{ab}	1.84^{ab}	2.28^{c}	35.70^{abcd}	45.63^{abc}	1.08^{bcd}	2.29^{bcde}
CTCrGF	38.37^{bc}	41.93^{ab}	1.42^{bc}	2.49^{c}	36.77^{abcd}	46.25^{ab}	1.11^{bcd}	2.69^{bcd}
CTCrGL	33.75^{bcd}	40.23^{abc}	2.29^{a}	5.10^{a}	32.25^{bcd}	41.08^{abcde}	2.20^{a}	5.00^{a}
CTCrTiG	34.83^{bcd}	40.63^{abc}	1.14^{cd}	2.63^{c}	35.40^{abcd}	37.47^{cdef}	1.06^{bcd}	2.26^{bcde}
CTCrTiR	32.68^{cd}	36.60^{abcd}	1.00^{cd}	2.11^{c}	30.05^{cd}	38.08^{abcde}	1.08^{bcd}	2.03^{cdef}
MT	30.28^{d}	29.80^{cd}	0.72^{d}	2.58^{c}	29.30^{d}	30.93^{f}	0.94^{cd}	1.86^{ef}
MTF	37.73^{bcd}	38.13^{abcd}	1.38^{bcd}	2.43^{c}	42.07^{a}	45.90^{abc}	1.25^{bcd}	2.77^{bc}
MTCrF	34.97^{bcd}	44.57^{a}	1.34^{bcd}	2.10^{c}	35.98^{abcd}	41.25^{abcde}	1.37^{bc}	2.82^{bc}
MTCrGF	32.00^{cd}	39.08^{abcd}	1.46^{bc}	2.18^{c}	35.65^{abcd}	39.85^{abcde}	1.42^{b}	2.84^{b}
MTCrGL	33.60^{bcd}	33.87^{abcd}	2.24^{a}	4.12^{b}	37.73^{abc}	42.25^{abcd}	2.27^{a}	4.49^{a}
MTCrTiG	34.50^{bcd}	39.13^{abcd}	1.12^{cd}	2.59^{c}	32.73^{bcd}	36.90^{def}	1.25^{bcd}	2.35^{bcde}
MTCrTiR	31.03^{cd}	32.70^{bcd}	1.01^{cd}	2.35^{c}	34.18^{abcd}	35.00^{def}	1.26^{bc}	1.92^{def}
hsd	7.49	11.67	0.68	0.90	8.13	8.46	0.48	0.80
p value	***	***	***	***	***	***	***	***

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$, hsd = honestly significant difference, *** $p < 0.0001$;C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

There were significant variations in Photosynthetically **Table 4.10).** Active Radiation (PAR) and Radiation Use Efficiency (RUE) among the treatments (During the SR20 season, the highest PAR (76%) was recorded under MTCrGF at the 6th leaf stage. Similarly, MTCrF, CTF, CTCrTiG, CTCrGF, CTCrGL, CTCrTiR, MTF, CTCrF, MT, MTCrTiR, and MTCrTiG had remarkedly higher PAR of 75, 75, 74, 74, 72, 70, 68, 67, 65, 64 and 57%, respectively, compared to the control. However, MTF, CTCrF, MT, MTCrTiR, and MTCrTiG significantly differed from the best-performing treatment (MTCrGF) but did not vary notably under MTCrGL and the control. At the 10th leaf, PAR was substantially higher under MTCrTiR, CTCrTiR, MTCrGL, CTCrGL, CTF, MTCrTiG, MTCrF, MTF, and CTCrTiG by 50, 50, 49, 48, 47, 45, 43, 40 and 40%, respectively. Only MTCrGF, CTCrGF, MT, and CTCrF recorded statistically the same PAR as the control. Apart from MT, PAR was 52% to 73% higher under the other amended treatments than under the control during the LR21 season at the 6th leaf. In the same season, PAR was 27% to 43% higher under the amended treatments, apart from MT, compared to the control at the 10th leaf stage. Significant higher PAR was also recorded under CTCrF, CTF, MTCrGL, and CTCrGL than under MTCrF and MTCrTiR.

Grain RUE was significantly higher under CTCrGF, MTCrF, CTCrTiR, CTF, MTCrTiG, CTCrF, MTCrGF, CTCrTiG, and MTCrTiR than the control by 95, 93, 93, 93, 92, 92, 92, 91 and 88%, respectively, during SR20 cropping season. However, it did not differ under CTCrGL, MTF, MTCrGL, and MT relative to the control. In the LR21 season, it was impressively higher under CTCrGL, MTCrGL, CTCrGF, CTF, MTCrGF, CTCrF, MTF, MTCrF, MTCrTiG, MTCrTiR, CTCrTiG, and CTCrTiR than the control by 80, 79, 78, 77, 77, 74, 73, 72, 70, 67, 66 and 62%, respectively. Apart from MT, amended treatments had from 74% to 88% significantly higher stover RUE relative to the control during the SR20 season. In the LR21 cropping season, there was a significant increase in stover RUE of 63, 62, 59, 57, 54, 53, 51, 44, 43, 42, 34, and 33% under CTF, CTCrF, CTCrGF, MTCrGF, CTCrGL, MTCrGL, MTF, CTCrTiG, MTCrF, CTCrTiR, MTCrTiG, and MTCrTiR respectively compared to the control.

Table 4.10: PAR and RUE under Different Treatments during the SR20 and LR21 Cropping Seasons

Treatment	SR20				LR21			
	PAR (μ mol m^{-2})		RUE (kg MJ^{-1})		PAR (μ mol m^{-2})		RUE (kg MJ^{-1})	
	6th leaf	10th leaf	Grain	Stover	6th leaf	10th leaf	Grain	Stover
C	0.09^{f}	0.36^{d}	0.03^{e}	0.18^{f}	0.16^{c}	0.45^{d}	0.24^{g}	1.16^{f}
CTF	0.36^{ab}	0.68^{a}	0.41^{ab}	1.20^{ab}	0.47^{ab}	0.78^{ab}	1.05^{abc}	3.10^{a}
CTCrF	0.27^{bcd}	0.43^{d}	0.37^{bc}	1.14^{b}	0.47^{ab}	0.79^{a}	0.92^{bcde}	3.07^{a}
CTCrGF	0.34^{abc}	0.47^{bcd}	0.57^{a}	1.49^{a}	0.37^{b}	0.71^{abc}	1.10^{abc}	2.81^{ab}
CTCrGL	0.32^{abc}	0.69^{a}	0.20^{cde}	1.04^{bc}	0.43^{b}	0.74^{ab}	1.21^{a}	2.52^{bc}
CTCrTiG	0.35^{abc}	0.60^{abc}	0.35^{bc}	1.32^{ab}	0.44^{b}	0.66^{bc}	0.71^{ef}	2.07^{cde}
CTCrTiR	0.30^{abcd}	0.72^{a}	0.43^{ab}	1.37^{ab}	0.46^{ab}	0.71^{abc}	0.63^{f}	2.00^{de}
MT	0.26^{cd}	0.46^{cd}	0.06^{de}	0.36^{ef}	0.15^{c}	0.44^{d}	0.15^{g}	0.80^{f}
MTF	0.28^{bcd}	0.60^{abc}	0.16^{de}	1.15^{ab}	0.44^{b}	0.72^{abc}	0.89^{cde}	2.37^{bcd}
MTCrF	0.36^{ab}	0.63^{ab}	0.43^{ab}	1.19^{ab}	0.33^{b}	0.62^{c}	0.86^{cdef}	2.04^{cde}
MTCrGF	0.38^{a}	0.50^{bcd}	0.36^{bc}	1.14^{b}	0.37^{b}	0.68^{bc}	1.03^{abcd}	2.67^{ab}
MTCrGL	0.15^{ef}	0.71^{a}	0.13^{de}	0.68^{de}	0.45^{ab}	0.74^{ab}	1.15^{ab}	2.49^{bcd}
MTCrTiG	0.21^{de}	0.66^{a}	0.37^{bc}	1.17^{ab}	0.41^{b}	0.66^{bc}	0.79^{def}	1.77^{e}
MTCrTiR	0.25^{cd}	0.72^{a}	0.25^{bcd}	0.73^{cd}	0.60^{a}	0.62^{c}	0.73^{ef}	1.73^{e}
hsd	*0.10*	*0.16*	0.19	0.34	0.15	0.12	0.25	0.51
p values	***	***	***	***	***	***	***	***

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$, hsd = honestly significant difference, *** $p < 0.0001$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

The treatments significantly affected plant height except at the 6th leaf stage during the SR20 season **(Table 4.11).** In the SR20 cropping season, the tallest plants were recorded under CTCrGF, similar to MTCrGF and MTCrGL at the 10th leaf stage. Plants under these treatments were substantially taller than those in the control by 55, 54, and 52%, respectively. The heights of plants under CTCrF, CTCrGL, CTCrTiR, CTCrTiG, CTF, MTCrF, MTCrTiG, and MTCrTiR similarly increased by 52, 50, 49, 48, 47, 46, 45, and 44%, respectively, relative to the control. Plants under MTF and MT were not statistically taller than the control but were significantly shorter than those under CTCrGF, MTCrGF, and MTCrGL. In the LR21 season, only MTCrF and MTCrGL had 30 and 29% notably taller maize plants at the 6th leaf relative to the control. Apart from MT, maize height in the other amended treatments did not differ from those under MTCrF, MTCrGL, or control. At the 10th stage during the LR21 season, maize under MTCrF, CTCrGL, CTCrGL, CTCrGF, MTCrGF, CTCrTiR, CTF, and MTCrTiG at the 10th leaf stage was taller than under the control by 39, 36, 33, 31, 28, 24, 20 and 20%, respectively. However, maize height in MTF, CTCrF, MTCrTiR, CTCrTiG, and MT did not vary significantly from the control.

Table 4.11: Mean Maize Height (cm) at Different Phenological Stages under Different Treatments during SR20 and LR21 Cropping Seasons

Treatment	**SR20**		**LR21**	
	6th leaf	**10th leaf**	**6th leaf**	**10th leaf**
C	13.44	35.63^{c}	18.94^{bc}	61.69^{ef}
CTF	19.69	67.06^{ab}	21.31^{abc}	77.25^{bcde}
CTCrF	20.94	73.94^{ab}	21.00^{abc}	74.19^{cdef}
CTCrGF	23.56	78.88^{a}	23.38^{abc}	88.81^{abcd}
CTCrGL	20.35	71.56^{ab}	26.13^{ab}	96.63^{ab}
CTCrTiG	25.63	68.88^{ab}	20.88^{abc}	73.00^{def}
CTCrTiR	20.38	69.75^{ab}	20.63^{abc}	81.13^{bcde}
MT	16.94	49.75^{bc}	17.69^{c}	56.06^{f}
MTF	21.25	50.31^{bc}	21.25^{abc}	75.13^{cdef}
MTCrF	24.44	66.31^{ab}	27.19^{a}	100.94^{a}
MTCrGF	21.19	76.88^{a}	22.375^{abc}	85.31^{abcd}
MTCrGL	22.19	74.88^{a}	26.31^{a}	92.75^{abc}
MTCrTiG	19.97	64.38^{ab}	24.00^{abc}	76.94^{cde}
MTCrTiR	20.88	63.88^{ab}	23.06^{abc}	73.19^{cdef}
hsd	15.85	24.49	7.20	19.57
p value	ns	***	**	***

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$, hsd = honestly significant difference at $p \leq 0.05$, ns =

not significant at p = 0.5454, ** p= 0.001, *** p < 0.0001; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

Grain and stover yields were significantly affected by the treatments during SR20 and LR21 seasons **(Table 4.12).** Grain yield was exceptionally higher under CTCrGF, MTCrF, CTCrF, MTCrGF, MTCrTiG, CTCrTiR, CTF, CTCrTiG, and CTCrTiR than under the control in SR20 season by 95, 93, 93, 93, 92, 92, 92, 92 and 88%, respectively. Variations in the yields under MTF, CTCrGL, MTCrGL, and MT were inconsiderable from the yield in the control. During LR21, apart from MT, the rest of the treatments greatly affected grain yield. Similarly, CTCrGF recorded the highest grain yield, which was 74% higher than the control. The other treatments; CTCrGL, MTCrGF, MTCrGL, CTF, MTCrF, CTCrF, MTF, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR, had higher yields than the control by 73, 71, 70, 69, 69, 66, 65, 64, 58, 55 and 49%, respectively. Conversely, CTCrF, MTF, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR had notably lower grain yields than the best-performing treatment (CTCrGF).

Compared to the control, the amended treatments had a higher stover yield during SR20 and LR21 cropping seasons. During the SR20 season, stover yield was the highest under CTCrGF, which was 88% higher than in the control. Stover yield was also substantially higher under CTCrF, CTF, CTCrTiG, MTCrGF, MTCrF, MTCrTiG, CTCrTiR, MTF, CTCrGL, MTCrGL, and MTCrTiR by 85, 85, 85, 84, 84, 84, 83, 83, 76, 73 and 73%, respectively, relative to the control. However, CTCrGL, MTCrGL, and MTCrTiR had lower yields than the best-performing treatments. Compared to the control, only MTCrTiR and MT did not greatly increase the yield during the LR21 season. The stover yield was significantly higher by 51, 51, 50, 46, 38, 37, 37, 34, 32, 25, 23, and 39% under CTCrF, CTCrGF, CTF, MTCrGF, MTF, MTCrF, CTCrGL, MTCrGL, CTCrTiG, CTCrTiR, and MTCrTiG, respectively, compared to the control.

Table 4.12: Maize Grain and Stover Yields under Different Treatments during SR20 and LR21 Cropping Seasons

Treatment	Grain yield (t ha^{-1})		Stover yield (t ha^{-1})	
	SR20	**LR21**	**SR20**	**LR21**
C	0.15^{e}	1.30^{f}	1.02^{d}	6.18^{f}
CTF	1.87^{bc}	4.20^{abc}	6.84^{b}	12.39^{a}
CTCrF	2.24^{b}	3.86^{bcd}	6.90^{ab}	12.66^{a}
CTCrGF	3.20^{a}	4.90^{a}	8.41^{a}	12.55^{a}
CTCrGL	0.82^{de}	4.72^{ab}	4.20^{c}	9.84^{bc}
CTCrTiG	1.81^{bc}	3.12^{de}	6.83^{b}	9.11^{cd}
CTCrTiR	1.87^{bc}	2.54^{e}	6.05^{b}	8.20^{de}
MT	0.36^{e}	0.82^{f}	2.17^{d}	4.33^{g}
MTF	0.82^{de}	3.74^{bcd}	5.84^{b}	9.97^{bc}
MTCrF	2.25^{b}	4.13^{abc}	6.27^{b}	9.87^{bc}
MTCrGF	2.02^{b}	4.41^{abc}	6.48^{b}	11.43^{ab}
MTCrGL	0.75^{de}	4.31^{abc}	3.78^{c}	9.35^{cd}
MTCrTiG	1.99^{b}	3.55^{cd}	6.26^{b}	7.97^{de}
MTCrTiR	1.29^{cd}	2.90^{de}	3.78^{c}	6.85^{ef}
hsd	0.69	0.99	1.53	1.62
p value	***	***	***	***

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$, hsd = honestly significant difference at $p \leq 0.05$, *** $p < 0.0001$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab*, CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

Using Nitrogen Nutrition Index (NNI), the study assessed if the aboveground maize production was limited by N stress. The results showed that maize production under the control and MT suffered from N stress during the LR21 cropping season (**Error! Reference source not found.**). Generally, NNI varied significantly (p< 0.0001) among the treatments. Apart from MT, there was no N stress under the remaining treatments that had 68% higher NNI, on average compared to the control. The CTCrGF, MTCrGF, CTCrGL, MTCrGL, CTCrF, CTF, MTF, MTCrF, CTCrTiG, CTCrTiR, MTCrTiG, and MTCrTiR recorded 78, 77, 76, 76, 69, 68, 65, 64, 64, 63, 62, and 60% higher NNI, respectively, than the Control.

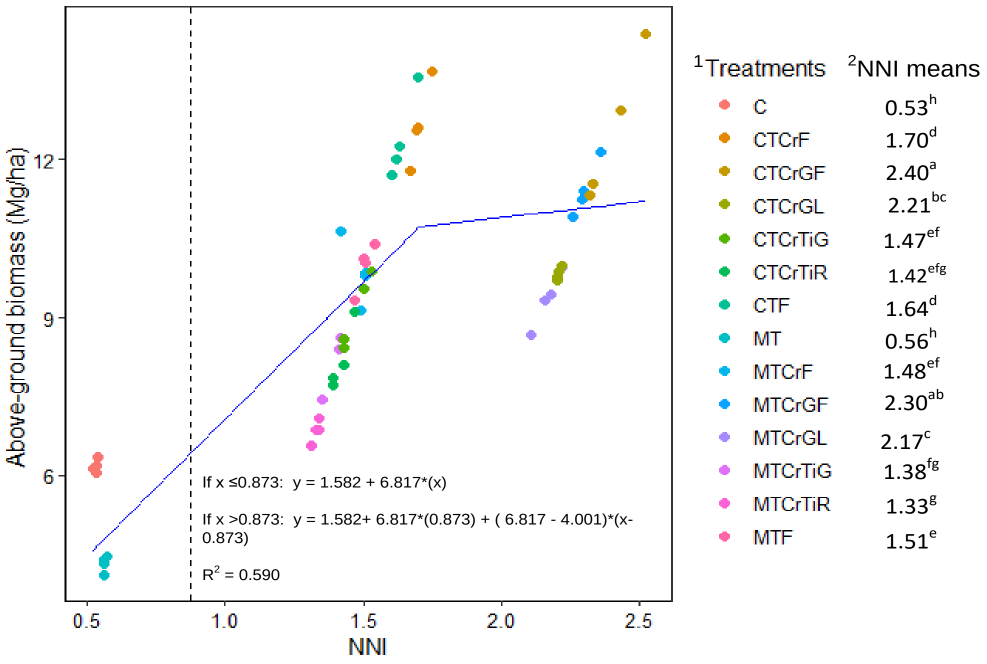


Figure 4.12: Segmented Linear Relationship between Maize Above-Ground Biomass (LR21 Season) and N Nutrition Index (NNI)

The dotted and blue solid lines represent breakpoint regression line, respectively.

[2] NNI greater than 1.0 indicated that crop biomass was not limited by its N status, while a value less than 1.0 showed biomass was limited by N stress (Mueller & Vyn, 2018).

4.5.1 Soil Moisture Content

The treatments significantly ($p < 0.0001$) influenced soil moisture content (SMC) at planting, on the 45th and 60th days after planting (DAP) during SR20 cropping season **(Table 4.13).** Generally, treatments with goat manure had the highest SMC across the season, followed by treatments that embraced Dolichos intercrop. Soil moisture content was exceedingly higher under MTCrGF, CTCrGL, MTCrGL, CTCrGF by 32, 30, 29, and 29%, respectively, compared to the control at planting date. The effect of the remaining treatments was insignificant relative to the control. The SMC on the 45th DAP was substantially higher under MTCrGF, MTCrGL, CTCrGF, CTCrGL, and MTCrTiR by 30, 28, 27, 26, and 22%, respectively than the control. The moisture recorded under the control was comparable to that recorded under the rest of the treatments. On the 60th day after planting, MTCrGF, CTCrGF, MTCrGL, CTCrTiG, CTCrTiR, MTCrTiR, MTCrTiG, CTCrGL, and MTCrF markedly increased SMC by 20, 19, 19, 17, 17, 17, 17, 16, and 14% compared to the control. The other treatments had comparable SMC as the control. The treatments, however, did not significantly affect SMC on 15th, 30th, 75th, 90th, and 105th DAP at $p = 0.469$, 0.095, 0.256, 0.066, and 0.407, respectively.

Table 4.13: Cumulative Mean Soil Moisture Content (mm) from 0 - 20 cm soil depth under Various Treatments across Sampling Intervals during SR20 Cropping Season

Treatment	Days after planting							
	0	15	30	45	60	75	90	105
C	57.39^{c}	61.83	61.36	49.12^{cd}	52.12^{e}	53.71	51.26	51.44
CTF	63.12^{c}	63.33	62.75	56.65^{abcd}	55.00^{cde}	53.16	51.52	50.69
CTCrF	65.68^{c}	62.75	59.76	57.07^{abcd}	55.24^{bcde}	53.32	51.71	50.98
CTCrGF	80.51^{ab}	65.14	68.44	67.20^{a}	64.35^{a}	53.78	52.96	51.53
CTCrGL	81.76^{a}	63.77	68.43	66.18^{ab}	62.23^{abc}	54.54	52.81	52.12
CTCrTiG	67.29^{c}	66	64.67	63.19^{abc}	63.09^{abc}	53.31	51.85	51.25
CTCrTiR	67.13^{c}	59.09	56.09	56.75^{abcd}	62.69^{abc}	53.4	51.81	50.95
MT	60.58^{c}	64.5	60.79	53.08^{bcd}	52.95^{de}	53.34	51.69	50.29
MTF	64.48^{c}	62.47	58.62	58.77^{abcd}	55.58^{bcde}	53.04	51.61	51.60
MTCrF	66.37^{c}	59.22	55.08	48.97^{d}	60.90^{abcd}	54.34	51.61	50.69
MTCrGF	84.05^{a}	70.49	70.14	69.98^{a}	65.25^{a}	53.68	53.01	51.32
MTCrGL	81.23^{ab}	63.29	68.86	67.83^{a}	63.97^{ab}	54.75	52.63	50.99
MTCrTiG	62.73^{c}	53.46	55.28	58.21^{abcd}	62.50^{abc}	53.60	51.61	51.71
MTCrTiR	69.24^{bc}	66.14	64.39	63.38^{ab}	62.55^{abc}	54.19	51.70	50.82
hsd	12.39	20.45	17.17	14.12	8.74	2.36	2.19	2.37
p value	***	ns	ns	***	***	ns	ns	ns

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$, hsd = honestly significant difference at $p \leq 0.05$, ns = not significant, *** $p < 0.0001$.

C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab,* CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat

manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

The treatments significantly ($p < 0.0001$) affected SMC at planting and on the 15th, 30th, 45th, 60th, and 75th DAP during the LR21 cropping season **(Table 4.14).** Treatments integrating *Dolichos lablab* intercrop generally had the highest SMC followed by those with goat manure across the season. Compared to the control, SMC was remarkably higher by 24, 23, 21, and 19% under CTCrGL, MTCrGF, CTCrGF, and CTCrTiG, respectively, on the planting date. It was nevertheless, the same under the control and the remaining treatments. Whereas significantly higher SMC of 28, 24, 20, 19, and 19% was recorded under CTCrGL, MTCrGF, CTCrTiG, CTCrGF, and MTCrGL, respectively, the rest of the treatments had insignificant effect relative to the control on the 15th DAP. Compared to the control, only MTCrGF, CTCrGL, and CTCrGF, had higher SMC of 25, 21, and 21%, respectively, on the 30th DAP. Similarly, only MTCrGF, CTCrGF, and MTCrF had significantly higher SMC of 33, 28, and 26%, respectively, than the control on the 45th DAP. On the 60th DAP, notably higher SMC of 29, 28, 25, 25, and 15% was recorded under MTCrGF, MTCrGL, CTCrGL, CTCrGF, and CTCrTiG, respectively, relative to the control. Soil moisture content greatly increased by 26% under MTCrGL, CTCrGL, and MTCrGF on the 75th DAP compared to the control. The treatments did not significantly affect SMC on the 90th and 105th DAP ($p = 0.542$ and 0.255, respectively) during the season.

Table 4.14: Cumulative Mean Soil Moisture Content (mm) from 0 to 20 cm Soil Depth under Various Treatments across Sampling Intervals during LR21 Cropping Season

Treatment	Days after planting							
	0	15	30	45	60	75	90	105
C	53.64^{e}	57.76^{e}	65.40^{b}	57.99^{bcd}	61.01^{bc}	55.56^{d}	60.64	51.17
CTF	57.24^{cde}	62.60^{cde}	64.72^{b}	61.24^{bcd}	63.71^{bc}	59.13^{cd}	61.8	52.44
CTCrF	61.81^{abcde}	63.51^{cde}	64.68^{b}	60.21^{bcd}	63.44^{bc}	59.45^{bcd}	62.65	52.83
CTCrGF	67.64^{abc}	71.15^{abcd}	82.71^{a}	66.53^{abcd}	80.84^{a}	67.42^{abcd}	63.28	54.3
CTCrGL	70.52^{a}	79.73^{a}	83.22^{a}	78.53^{a}	81.65^{a}	75.09^{ab}	64.01	53.43
CTCrTiG	66.60^{abcd}	72.20^{abc}	72.64^{ab}	66.80^{abcd}	71.90^{ab}	66.28^{abcd}	61.92	52.68
CTCrTiR	57.65^{bcde}	61.84^{cde}	78.76^{ab}	57.34^{cd}	58.62^{bc}	56.35^{d}	62.66	50.98
MT	54.39^{e}	59.76^{de}	65.57^{b}	57.17^{cd}	54.53^{c}	66.14^{abcd}	63.28	52.61
MTF	55.44^{de}	65.91^{bcde}	72.26^{ab}	60.79^{bcd}	62.21^{bc}	58.72^{d}	63.26	53.46
MTCrF	56.97^{cde}	63.63^{cde}	65.28^{b}	53.00^{d}	54.62^{c}	60.16^{abcd}	63.17	52.54
MTCrGF	69.28^{ab}	76.18^{ab}	86.98^{a}	71.91^{abc}	85.80^{a}	74.71^{abc}	63.18	53.95
MTCrGL	61.39^{abcde}	71.05^{abcd}	74.79^{ab}	73.32^{ab}	84.36^{a}	75.41^{a}	65.1	53.14
MTCrTiG	56.06^{cde}	58.01^{e}	70.16^{ab}	61.25^{bcd}	61.58^{bc}	61.90^{abcd}	63.5	52.85
MTCrTiR	64.87^{abcde}	64.65^{bcde}	63.89^{b}	66.00^{abcd}	69.45^{abc}	66.65^{abcd}	63.14	51.98
hsd	11.67	11.90	16.89	15.80a	16.82	15.74	5.52	4.14
p value	***	***	***	***	***	***	ns	ns

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$, hsd = honestly significant difference at $p \leq 0.05$, ns = not significant, *** $p < 0.0001$.

C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab,* CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat

manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

4.5.2 Water Productivity

The treatments significantly affected grain and stover water productivity (WP) during SR20 and LR21 cropping seasons (**Error! Reference source not found.**). Grain WP was remarkedly higher by 88, 82, 82, 81, 80, 80, 79, 79, and 70% under CTCrGF, MTCrF, CTCrF, MTCrGF, MTCrTiG, CTCrTiR, CTCrTiG, CTF and MTCrTiR, respectively, than the control during SR20 season. However, MTCrGL, MTF, CTCrGL, and MT recorded similar grain WP to the control. During LR21, apart from MT, the other treatments; CTCrGF, CTCrGL, MTCrGF, MTCrGL, CTF, MTCrF, CTCrF, MTF, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR, had substantially higher grain WP than the control by 74, 73, 71, 70, 70, 69, 67, 66, 64, 59, 56 and 50%, respectively. Grain WP under CTCrGF, CTCrGL, MTCrGF, MTCrGL, CTF, and MTCrF was exceptionally higher than WP under TillCrTiG, NoTillCrTiR, and TillCrTiR. Except MT during the SR20 season, stover WP was 88, 85, 85, 85, 84, 84, 83, 83, 82, 76, 72, and 72% higher under CTCrGF, CTCrF, CTCrTiG, CTF, MTCrGF, MTCrF, MTCrTiG, CTCrTiR, MTF, CTCrGL, MTCrGL, and MTCrTiR, respectively, than under the control. Conversely, stover WP was markedly lower under CTCrGL, MTCrGL, and MTCrTiR compared to the other best-performing treatments. Stover WP was exceedingly higher than under the control by 52, 51, 51, 47, 38, 38, 38, 34, 33, 25 and 23% under CTCrF, CTCrGF, CTF, CTCrGF, CTCrF, CTF, CTCrGL, MTCrGL, CTCrTiG, CTCrTiR, and MTCrTiG, respectively.

Similarly, the treatments significantly ($p < 0.0001$) affected consumptive water use (Et) during SR20 and LR21 cropping seasons **(Table 4.15).** Consumptive water use was slightly reduced by 18.25, 17.19, and 15.39 mm under CTCrGF, CTCrGL, and MTCrGF compared to the control during SR20 season. The highest Et was recorded under MT, followed by the control. Similarly, the highest Et was recorded under MT followed by MTF and the control during LR21. Compared to the control, Et was marginally lower by 11.46, 10.71, and 9.49 mm under CTCrTiG, MTCrGF, and CTCrGL, respectively, during the same season.

Table 4.15: Maize grain and Stover Water Productivity and Consumptive Water Use under Different Treatments during SR20 and LR21 Cropping Seasons

Treatment	SR20			LR21		
	Grain	**Stover**	**Et**	**Grain**	**Stover**	**Et**
	kg m^{-3}		**mm**	**kg m^{-3}**		**mm**
C	0.01^{e}	0.08^{e}	781.42^{a}	0.16^{f}	0.77^{fg}	1302.04^{abc}
CTF	0.14^{bc}	0.53^{ab}	778.56^{ab}	0.54^{abc}	1.58^{a}	1299.70^{abcd}
CTCrF	0.17^{b}	0.53^{ab}	772.36^{abc}	0.49^{bcd}	1.59^{a}	1295.52^{abcde}
CTCrGF	0.25^{a}	0.65^{a}	763.17^{bc}	0.62^{a}	1.58^{a}	1291.16^{bcde}
CTCrGL	0.06^{de}	0.33^{c}	762.69^{bc}	0.60^{ab}	1.24^{bc}	1287.41^{e}
CTCrTiG	0.14^{bc}	0.53^{ab}	774.12^{ab}	0.39^{de}	1.15^{cd}	1290.58^{cde}
CTCrTiR	0.15^{bc}	0.47^{b}	775.93^{ab}	0.32^{e}	1.03^{cde}	1297.83^{abcde}
MT	0.03^{e}	0.17^{de}	781.90^{a}	0.10^{f}	0.55^{g}	1302.72^{a}
MTF	0.06^{de}	0.45^{b}	780.36^{a}	0.47^{cd}	1.25^{bc}	1302.52^{ab}
MTCrF	0.17^{b}	0.49^{b}	771.79^{abc}	0.52^{abc}	1.25^{bc}	1300.07^{abcd}
MTCrGF	0.16^{b}	0.51^{b}	756.23^{c}	0.56^{abc}	1.44^{ab}	1289.17^{de}
MTCrGL	0.06^{de}	0.29^{c}	766.26^{abc}	0.54^{abc}	1.17^{cd}	1296.26^{abcde}
MTCrTiG	0.15^{bc}	0.48^{b}	776.07^{ab}	0.45^{cd}	1.00^{de}	1301.29^{abc}
MTCrTiR	0.10^{cd}	0.29^{cd}	775.41^{ab}	0.36^{de}	0.86^{ef}	1291.61^{abcde}
hsd	0.05	0.12	16.575	0.12	0.23	11.48
p values	***	***	***	***	***	***

Mean values with the same superscript letter(s) within the same column denote no significant difference at $p \leq 0.05$, hsd = honestly significant difference, *** $p < 0.0001$.

C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + *Dolichos lablab,* CTCrTiG = conventional tillage + maize residues + *Tithonia diversifolia* + goat manure, MT = minimum tillage (no amendments), MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat

manure + *Dolichos lablab*, MTCrTiG = minimum tillage + maize residues + *Tithonia diversifolia* + goat manure.

CHAPTER FIVE

DISCUSION OF RESULTS

5.1 Introduction

The Chapter presents the discussions of the results of the study per objectives. It discusses the effects of integrated soil fertility management technologies on; 1) microbial biomass C, N, and P, 2) N mineralization, partial factor productivity, and apparent N recovery, 3) simulation of soil N mineralization, 4) phosphorus fractions, degree of saturation, maximum sorption capacity, use efficiency, and legacy, and 5) maize yield, soil moisture content, and water productivity. The discussions are compared and validated with other studies.

5.1.1 Effects of Treatments on Soil Microbial C, N, and P, and MBC:MBN and MBC: MBP

The high MBC, MBN, and MBP under various treatments that integrated organic amendments reflected the effect of the quality and quantity of organic materials entering the soil. Such treatments could have enhanced substrate richness and therefore influenced microbial community and activities (Shrestha *et al*., 2019). The quality and quantity of organic inputs have been found to influence soil microbial biomass (Kiboi *et al*., 2018). Further, the treatments could have increased C input into the soil thus the observed high biological elements. Positive correlations between organic C and microbial C, N, and P have also been observed by Susanne & Tabatabai (2017).

5.1.2 Influence of Different Treatments on MBC

Integrating manure and *Dolichos lablab* intercrop (CTCrGL and MTCrGL) resulted in the highest MBC concentrations compared to the control (**Error! Reference source not found.**). This finding is attributed to the positive interaction between the goat manure and legume intercrop that could have increased soil organic carbon. A short-term study also reported a similar finding (Kiboi *et al*., 2018), where significantly higher MBC was observed under combined crop residue, manure, and *Dolichos lablab* intercrop. In the current study, the Dolichos and the residues may have resulted in increased availability of N-fixing micro-organisms and moisture retention leading to the high MBC. This finding corroborates the results of another study that found high MBC under Dolichos and residue retention (Shrestha *et al*., 2019). Manure in the integrated system could have also contributed to a lower C: N ratio that favoured microbial activity and MBC concentration. Similarly, Das *et al*. (2023), attributed increased MBC under manure treatment to a narrow C: N ratio.

T. diversifolia could have positively interacted with manure (CTCrTiG and MTCrTiG) and rock phosphate (CTCrTiR and MTCrTiR), resulting in increased MBC than in the control (**Error! Reference source not found.**) through increased organic carbon input. O ther studies have illustrated increased organic carbon under *T. diversifolia* (e.g., Dahunsi *et al*., 2017). Moreover, *T. diversifolia* probably triggered activities of soil microorganisms allelopathy (Dahunsi *et al*., 2017; Tongma & Kobayashi, 2019), resulting to the observed higher MBC. Combining crop residues and *T. diversifolia* could have lowered the C: N ratio and improved the quality of substrates to the microbial population leading to increased MBC. This finding agrees with Tongma & Kobayashi (2019), who ascribed the increased soil microbial biomass (SMB) to a decreased C: N ratio when maize residue was mixed with *T. diversifolia.* Phosphorus nutrition through CTCrTiR and MTCrTiR could have improved the quality of the soil and improved P-solubilizing soil micro-fauna reflected in the high MBC concentrations. Akin to this study, Gaind & Pandey (2006) attributed the increase in MBC to P nutrition via rock phosphate, while other researchers have found abundant phosphate-solubilizing microbes under rock phosphate treatments (Qarni *et al*., 2021).

Contrary to the findings of Kiboi et al. (2018), applying sole inorganic fertilizer (CTF and MTF) or combined with residues (CTCrF and MTCrF) had higher MBC than the control in this study. While this difference could be due to variations in experiment duration and time of sampling, other studies have also reported increased microbial abundance and organic carbon under inorganic fertilizer applications (Huang *et al.*, 2021), which could have translated to high MBC. In this study, the influence of inorganic N fertilizers (NPK and CAN applied at planting and topdressing, respectively) could have been through their impact on the bacterial residue to contribute to organic carbon. Hu *et al*. (2023) also observed an improved contribution of bacterial residue to organic carbon owing to inorganic N fertilization. In addition to creating a suitable micro-climate (soil moisture conservation and regulating soil temperature) for the soil microbes, residues under CTCrF and MTCrF could also have increased substrate to the micro-organisms leading to the relatively high MBC. A similar finding was reported by Zhu *et al*. (2023), in which 33 % of maize stover retention improved microbial growth and MBC. Abbasi & Khizar (2012) also reported high MBC values under combined residue retention and inorganic fertilizer.

Microbial biomass carbon concentrations were also higher under treatments that combined inorganic fertilizer with goat manure (MTCrGF and CTCrGF). This could be linked to a synergy between the inorganic fertilizer and the goat manure on the bioavailability of nutrients and the general influence of manure on soil properties that favour the growth of soil microbes. The quality of applied manure significantly influences soil quality and nutrient availability to microorganisms (Ghosh *et al*., 2020). The finding is consistent with the results of Kiboi *et al*. (2018), who similarly reported higher MBC under a combined inorganic and organic amendment. Mangalassery *et al*. (2019) also reported enhancement in MBC due to integrating inorganic fertilizer with organic manure. The application of sole organics and their integration with inorganic fertilizers also had higher MBC in a study conducted by Ghosh *et al*. (2020).

5.1.3 Influence of Different Treatments on MBN

Microbial biomass nitrogen (MBN) in this study could have been sensitive to factors that affected the size of Soil Microbial Biomass (SMB), such as soil pH, amount of Soil Organic Matter (SOM), and fertilization (Susanne & Tabatabai, 2017), among others. It could have also been boosted by increased N inputs from the treatments where N seldom limited microbial growth. It was observed that MBN was only significantly higher under sole organic amendments (MTCrTiG, MTCrGL, CTCrTiG, CTCrGL, MTCrTiR, CTCrTiR) or combined with inorganic fertilizer (CTCrGF, and MTCrGF; **Error! Reference source not found.**). The results support the earlier findings of Kiboi *et al*. (2018), who also reported higher MBN under either sole organics or integrated with inorganic fertilizer. Furthermore, such integrated approaches could have increased N input in the soil, and enhanced substrate quantity and quality, thus promoting the growth and activities of enzymes involved in N assimilation (Cardarelli *et al*., 2023). The results align with the findings of Abbasi & Khizar (2012), who also reported higher MBN under co-application of urea, crop residue retention, and poultry manure.

The high concentration of MBN under treatments that integrated manure and Dolichos intercrop (CTCrGL and MTCrGL) may also be due to increased N-fixing microbes. Consistent with the findings of a short-term study, the highest MBN concentration was similarly recorded under combined residues retention, manure, and Dolichos intercrop (Kiboi *et al*., 2018). Shrestha *et al*. (2019) also found increased MBN under Dolichos used as green manure. In this study, goat manure could have raised the need for additional organic molecules to be oxidized by N-fixing microorganisms to obtain energy (Cardarelli *et al*., 2023). The enhanced MBN could be explained by the possible maize-Dolichos interspecific interactions that may have increased the SMB network's stability and improved functions (Li *et al*., 2023).

Application of sole inorganic fertilizer (CTF and MTF) or in combination with crop residues (CTCrF and MTCrF) did not substantially influence MBN relative to the control. The protonation of Calcium Ammonium Nitrate (CAN) during the nitrification process could have further lowered soil pH **(Appendix VII)**, thus, inhibiting the growth and activities of the SMB. A similar finding was reported by Ghosh *et al*. (2020), in which the application of inorganic fertilizer per farmers’ practice did not significantly affect MBN. Long-term application of inorganic N fertilizers has been reported to have a negative impact on SMB and its elemental properties (Yang *et al*., 2022).

5.1.4 Influence of Different Treatments on MBP

The treatments with organic amendments (CTCrGF, MTCrGF, MTCrTiG, MTCrTiR, CTCrTiR, and CTCrTiG) in this study (**Error! Reference source not found.**) could have increased readily available carbon, which might have stimulated high amounts of P uptake among soil microbes. Crop residues, goat manure, *T. diversifolia*, and rhizodeposition promoted an ample supply of Soil Organic Carbon (SOC), thus stimulating the growth and activity of SMB, leading to higher MBP, as was also noted by Ghosh *et al*. (2018).

The addition of inorganic P through NPK and TSP fertilizers under CTCrGF and MTCrGF may have increased the abundance of inorganic P-cycling microbes (Liao *et al*., 2023), leading to the observed high MBP.

The higher MBP concentrations recorded under CTCrTiR and MTCrTiR may be because of the increase in P-solubilizing microbes that breaks down rock phosphate. Bolo *et al*. (2021) reported an increased abundance of SMB and P solubilizers. Microbial solubilization of rock phosphate nourishes soil microbes with P. It could have been aided by organic substances released during the decomposition of *T. diversifolia* and maize residues. Positive interaction between *T. diversifolia* and phosphate-solubilizing microorganisms probably enhanced P availability to the soil microbes. This finding agrees with the result of another study that also reported increased MBP under rock phosphate-treated compost (Meena & Biswas, 2015).

A negative effect of long-term application of inorganic N fertilizer on soil pH and low substrate availability could have explained the non-responsiveness of MBP under treatments consisting of sole inorganic fertilizer (CTF and MTF) or in combination with maize residues (CTCrF) (Ghosh *et al*., 2020). Reductions in P solubilizing microbial abundance under sole inorganic fertilizers have been reported in another study (Bolo *et al*., 2021). The reason why CTCrGL and MTCrGL did not significantly influence MBP in comparison to the control could be because of the microbial-crop competition for limited soil P. The competition could have inhibited the growth and activity of phosphate-solubilizing microorganisms. Similar to the finding, Ghosh *et al*. (2020) also reported lower MBP under a nutrient-exhaustive cropping system (soybean-wheat system) compared to a soybean-chickpea system.

5.1.5 Influence of Different Treatments on MBC: MBN and MBC: MBP Ratios

The average ratio of MBC to MBN of 6.19, under the treatments that significantly influenced the ratio (Figure 4.1), was within the 5.2 to 6.7 range of most soils (Susanne & Tabatabai, 2017). Fungal isolates could have dominated MBC: MBN ratio under CTCrGL and MTCrGL as the values were above 7.0. Phosphorus addition through goat manure may have increased fungal biomass (Chen & Xiao, 2023). This is supported by a global meta-analysis study that found an abundance of fungi under intercrop systems (Morugán-Coronado *et al*., 2022). Bacterial isolates could have dominated the remaining treatments because ratios were below 7.0. Microbial biomass C: N range between 3 to 6 under bacterial isolates and 7 to 12 in fungal isolates (Jenkinson & Polvlson, 1974; Marumoto, 1984).

The slightly lower MBC: MBN ratios under CTCrGL, MTCrGL, MTCrGF, and CTCrGF could be ascribed to greater immobilization by soil microbes than N availability through mineralization. The result could also be partly attributed to the diminishing decomposition of organic carbon. The result agrees with the finding of Abbasi & Khizar (2012), who reported a lower MBC: MBN ratio under poultry manure compared with inorganic fertilizer and crop residue retention. Also, the relatively lower MBC: MBN ratios under CTCrTiR, MTCrTiR, CTCrTiG, and MTCrTiG could be due to the greater availability of N through the mineralization process than immobilization by microbes. While supporting their results, Sabahi *et al*. (2010) attributed the high MBC: MBN ratios in plots under purely organic amendments to changes in microbial community composition.

The low MBC: MBN ratios under the sole application of inorganic fertilizers (CTF and MTF) or in combination with maize residues (CTCrF and MTCrF) may have resulted as a result of readily available N from the inorganic N fertilizers. In another study, MBC: MBN ratio was also found to be lower under integrated inorganic fertilizers and organic amendments or sole organic and inorganic fertilizers (Sabahi *et al*., 2010). On the other hand, the significant variations in MBC to MBP ratio under MTCrGL, CTCrGL, CTCrTiG, CTCrTiR, MTCrTiR, MTCrTiG, CTCrGF, and MTCrGF could be attributed to increased input of high-quality litter (goat manure and *T. diversifolia*). The result is consistent with those of Kooch *et al*. (2019), who attributed the high MBC: MBP ratio to the quality of the added litter. The comparatively lower MBC: MBP values under CTF and MTF could be linked to reduced organic carbon (Mooshammer *et al*., 2014) and increased bioavailable P.

5.1.6 Effect of Tillage on Microbial C, N and P

The high concentrations of microbial C, N, and P in MT-treated plots (MTCrGL, MTCrTiR, MTCrGF, MTCrTiG, MTF, and MTCrF for microbial biomass carbon, MTCrTiG, MTCrGL, MTCrTiR, and MTCrGF for microbial biomass nitrogen, and MTCrGF, MTCrTiG, and MTCrTiR for MBP) in **Table 4.1** was probably a result of improved soil physical aggregate stability. The results corroborate the findings of a study in which reduced tillage conditioned with crop residues increased MBC in Western Kenya and was attributed to improved aggregate stability (Bolo *et al*., 2023). Microbial biomass P and abundance of P solubilizers also increased under reduced tillage with residues addition in a study by Bolo *et al*. (2021). Similar to increased microbial C, N, and P under MT amended with organic materials, Morugán-Coronado *et al*. (2022) reported increased total SMB, which could translate to higher microbial C, N, and P. Microbial biomass N was higher under MTCrF but was not markedly affected by CTCrF. This could be associated with relatively lower MBC: MBN that may have suppressed the loss of N and better MBN assimilation under MT in the presence of readily accessible N (Biswas *et al*., 2019).

Significantly higher microbial biomass C, N, and P under conventional tillage (CTCrGL, CTCrTiG, CTCrTiR, CTCrGF, CTCrF, and CTF for MBC, CTCrTiG, CTCrGL, and CTCrGF for MBN and CTCrGF, CTCrTiR, and CTCrTiG for MBP was probably because of the increased active microbes. According to Zuber & Villamil (2016), soil microbes are more active under CT than under MT. This could be because tillage may have improved soil aeration and mediated oxygen circulation to microbial activity sites. Moreover, tilling plots and retaining residues could have redistributed carbon and altered the microbial community and turnover (Kabiri *et al*., 2016).

5.1.7 Response of NH_4-N to Various Treatments

Mineralization of NH_4-N was rapid in the first 15 DAP, then decreased in the subsequent sampling dates during the SR20 season **(Table 4.2),** which could be ascribed to the priming effect of adding N into the soil. Furthermore, intra-season rainfall fluctuations could have explained the variations in the NH_4-N pattern as they may have affected moisture availability to microbes and altered ecosystem functioning (Wallenstein & Hall, 2012). Ammonium-N was higher at the start of the LR21 season than at the beginning of the SR20 season due to the higher rainfall received during the LR21 season **(Figure 3.2),** highlighting the effect of rainfall change on the N mineralization process. This high rainfall could have promoted the rapid conversion of ammonia to nitrates (Nitrification process) thus, explaining the differential patterns at the start of the two seasons.

The NH_4-N was low, and variations were insignificant between the 60th and 90th DAP during the SR20 season. The result can partly be attributed to a change in the quality of litter to more recalcitrant materials and microbial community (Song *et al*., 2016). On the other hand, there could have been net denitrification on the 105th DAP during the SR20 and from the 60th to 90th DAP during the LR21 season among the treatments resulting in significant changes in NH_4-N. This finding further underscores the effect of rainfall through its influence on soil moisture in the mineralization process.

The exceptionally higher NH_4-N under sole organic amendment treatments (MTCrGL, MTCrTiG, CTCrTiG, CTCrGL, CTCrTiR, and MTCrTiR) could be due to possible increased N via organic matter accumulation and improved microbial activity. Consistent with the present result, Cassity-Duffey *et al*. (2020) attributed enhanced net N mineralization under organic amendments to improved microbial activity due to organic matter accumulation. Integrating inorganic fertilizers and organic amendments under MTCrGF and CTCrGF could have lowered soil C: N and promoted the ammonification process. Goat manure may have increased NH_4-N through increased aggregate-protected and unprotected carbon fractions (Ashraf *et al*., 2022), while inorganic fertilizers could have provided readily available N. The result agrees with Wu *et al*. (2021), who reported higher NH_4-N under straw retention combined with inorganic fertilizers and cattle manure. Also, Tao *et al*. (2017) attributed higher NH_4-N to the influence of ammonia-oxidizing archaea and bacteria under a combination of inorganic fertilizers and cattle manure.

Sole application of inorganic fertilizers (MTF and CTF) or in combination with maize residues (MTCrF and CTCrF) may have enhanced NH_4-N mineralization by regulating biomass accumulation and bacterial community. Similarly, Wu *et al*. (2021) ascribed the increased NH_4-N under sole inorganic fertilization to its influence on bacterial community and biomass production. Moreover, maybe Dolichos in the MTCrGL and CTCrGL treatments promoted nodulation and the population of N-fixing bacteria such as Rhizobia, Azotobacter, and Bacillus, among others, thus the observed higher NH_4-N. A review by Huiling *et al*. (2022) illustrates the influence of legume intercrop on N-fixing microbes through exudates.

5.1.8 Response of NO_3-N to Different Treatments

Intra and inter-seasonal rainfall variabilities similarly influenced the nitrification process as NO_3-N concentration during the earlier DAP in the SR20 season was low in all the treatments and increased during the later days of the season **(Table 4.3).** Meanwhile, NO_3-N was high at the start of the LR21 season and low at the later stage. The differential NO_3-N concentrations during the two seasons in the present study could be due to ammonification-nitrification processes regulated by rainfall. The finding supports the results of another study that reported spatial and seasonal differences in ammonification-nitrification processes (Xie *et al*., 2022). Ammonification was higher than nitrification on the 15th DAP in the SR20 season, while it was lower than ammonification on the same day during the LR21 season, possibly due to the effect of in-season rainfall events. Arce *et al*. (2018) found higher NH_4-N in wetter conditions and lower NO_3-N as influenced by rainfall amounts and occurrence.

Similar to NH_4-N, the significant influence of MTCrGL, MTCrTiG, CTCrTiG, CTCrGL, CTCrTiR, and MTCrTiR can be linked to increased N and microbial activity. Both *T. diversifolia* and goat manure contained easily mineralizable N and could have promoted the activity of nitrifying microbes. According to Ali *et al*. (2021) study, manure application substantially improved the net nitrification rate due to enhanced nitrite-oxidizing bacteria in the soil. Maize-Dolichos interaction under the intercrop (MTCrGL and CTCrGL) may have also increased nitrifiers' diversity, resulting in great NO_3-N (Huiling *et al*., 2022). Under MTCrGF and CTCrGF, the inorganic fertilizers could have enhanced the diversity and abundance of nitrifiers, while the manure could have changed the community structure of the microbes. Abundant Nitrospira and Nitrosomonas promoted rapid nitrification under manure application in a study by Zhang *et al*. (2016).

Applying inorganic fertilizers (CTF, MTF, CTCrF, and MTCrF) could have promoted ammonia-oxidizing bacteria. Rudisill *et al*. (2016) found a positive correlation between ammonia-oxidizing bacteria and potential nitrification activity. Another study also reported that ammonia-oxidizing bacteria promoted nitrification under inorganic fertilizer (urea) treatment (Zou *et al*., 2022).

5.1.9 Total Mineralized N as Influenced by Different Treatments

Total mineralized N (MN; **(Table 4.4)** showed the same seasonal and DAP patterns as NH_4-N and NO_3-N. Generally, the N nitrification rate was reduced with low rainfall frequency (Zhang *et al*., 2020), and ammonification increased with increased soil wetting via rainfall (Arce *et al*., 2018). In addition to rainfall, the contribution of either NH_4-N or NO_3-N to the total MN could have been influenced by competitive or synergetic metabolism among soil microbes that could have altered operational conditions and the contents of substrates (Zhu *et al*., 2021). Nevertheless, N mineralization, as influenced by the treatments largely showed no clear trend. This observation has also been reported in another study (Kiboi *et al*., 2020). The effects of the treatments on increased mineral N can partly be attributed to increased MBN **(Table 4.1)** due to the positive correlation between these parameters. Liu *et al*. (2017) found rapid MBN turnover and greater mineralization potential that contributed to traceable mineral N.

Akin to the finding of Lazicki *et al*. (2020), MN was significant and variable under MTCrGL, MTCrTiG, CTCrTiG, CTCrGL, CTCrTiR, and MTCrTiR which was possibly caused by increased organic N. Similarly, Li & Li (2014) found exceedingly higher N mineralization under different types of animal manure which positively related with organic N. Manures differ in the chemical and physical properties which profoundly affect N mineralization in a study by Mubarak *et al*. (2010). Similar to the present study (MTCrGL and CTCrGL), Xu & Qiu (2018) also reported greater gross and net organic N mineralization and gross immobilization of inorganic N under the intercropping system. The improved MN under MTCrGF and CTCrGF is consistent with the finding of Mohanty *et al*. (2013), who reported remarkably higher MN under a combination of NPK and manure, which was ascribed to improved soil physical properties.

Rock phosphate in MTCrTiG and CTCrTiG could have influenced the increase of MN through lowering litter C: N. The finding agrees with Tapiwa *et al*. (2018), who reported lower final C: N of litter following the application of rock phosphate. Phosphorus addition has been shown to affect the respiration of SMB, which affect nitrification and denitrification processes. Inorganic fertilizers under CTF, MTF, CTCrF, and MTCrF could have mineralized soil native N. Liu *et al*. (2017) found that inorganic fertilizers tended to enhance the mineralization of soil native N. The low quantity and quality of organic carbon may explain the instances where MN was not significantly increased under CTF, MTF, CTCrF, and MTCrF relative to the control. The low quality of organic carbon may have limited the amount of energy available for soil microbes, thus the low mineral N.

5.1.10 Effect of Tillage on N Mineralization

Conventional tillage (CT) could have enhanced MN under CTCrF, CTCrTiG, CTCrGF, CTCrGL, and CTCrTiR by raising soil pH, thus, favouring microbial activities. Evidence from a past study showed lower soil acidity under CT (Thapa *et al*., 2023). Moreover, this tillage system could have affected soil microbes through better distribution of soil organic carbon (SOC). Kheyrodin and Antoun (2011) found that CT amended with manure had a higher N mineralization rate and potential mineralizable N. In another study by Li *et al*. (2015), CT promoted the dominance of ammonia-oxidizing bacteria rather than ammonia-oxidizing archaea, which promoted rapid nitrification. The addition of wheat straw resulted in a 40% to 80% increase in NH_4-N but decreased NO_3-N by 60% to 93% under CT in a study by Liu *et al*. (2021). Soil N-mineralizing microbes may have been better nourished by the addition of goat manure (CTCrGF and CTCrGL) which could have altered organic carbon and P storage (Oliveira *et al*., 2022) and influenced microbial community structure (Li *et al*., 2022).

Minimum tillage could have increased mineralizable N under MTCrF, MTCrTiG, MTCrGF, MTCrGL, MTCrTiR, and MT through its impact on soil pH and microbial activity. The result corroborates the findings of Vazquez *et al*. (2019), who attributed the significantly higher MN to the impact of minimum tillage on SOC and microbial activity and the impact of organic amendments on reducing soil pH. Other studies have also reported an increase under various reduced tillage systems with residue retention (e.g., Pecci *et al*., 2021). Martínez *et al*. (2017) linked the increased soil organic N under reduced tillage to the enhanced MN. Amending conservation tillage with inorganic fertilizer or poultry manure also increased ammonia-oxidizing archaea and bacteria, which was positively associated with improved N mineralization in a study by Cabrera (2016).

5.1.11 Effects of Different Treatments on N Concentrations in Plant Tissues

The higher concentration of N (N uptake) under treatments that integrated goat manure (CTCrGF and MTCrGF) **(Figure 4.2)** could be due to the increased availability of particulate organic matter N from maize residues and goat manure. Probably, the increase of organic matter N from this treatment could be attributed to the goat manure. The result supports the finding of Geng *et al*. (2019), who reported increased maize N uptake under the chicken and cow manure. The increase in plant tissue N concentration could have also resulted from a synergetic interaction between inorganic fertilizers and goat manure (Otieno *et al*., 2021; 2023). Inorganic N may have accelerated the mineralization of manure while manure, in turn, could have improved the uptake of inorganic N. qbal *et al*. (2019) also reported increased N concentration in maize tissues under combined inorganic fertilizers and manure. Zhihui *et al*. (2016) attributed the improved N concentration to combining N and P inorganic fertilizers with manure to stimulate root growth.

Dolichos-integrated treatments (CTCrGL and MTCrGL) may have increased N concentration through biological fixation (Massawe *et al*., 2016). Additionally, Dolichos could have contributed to the N concentration by; 1) acting as a cover crop and reducing N loss through soil erosion, 2) its roots may have decomposed and released N, which became available for the subsequent crops (Massawe *et al*., 2016), and 3) the roots could have relocated N in the deep zones to near soil surface zone making it available for maize uptake (Nyawade *et al*., 2020). Sitienei *et al*. (2017) also found increased N concentration in Maize-Dolichos intercrop systems. Maize residues could have provided additional N and improved soil physical conditions, thus enhanced N cycling and increasing N uptake by the maize crop.

T. diversifolia applied under CTCrTiG, CTCrTiR, MTCrTiG, and MTCrTiR contained substantial amounts of N (3.80% N) that were possibly mineralized and taken up by the maize. This shrub has a high nutrient absorption capacity and nutrient contents (Dahunsi *et al*., 2017). In addition to releasing labile P, *T. diversifolia* could have released organic acid that solubilized Rock Phosphate and reduced P fixation (Margenot *et al*., 2017). The released P could have enhanced root development and promoted N uptake by maize. On the other hand, the enhanced concentrations of N on plant tissues under CTCrF, CTF, MTF, and MTCrF probably was because of the readily available inorganic N, which maize crops easily accessed and absorbed. This finding agrees with Mugi-Ngenga *et al*. (2022), who reported increased concentrations of N in maize tissues following the application of inorganic N and P fertilizers. Jalpa *et al*. (2021) found that inorganic fertilizer contributed to 62 % of N accumulation in plants' tissues. Similar to CTCrF and MTCrF in the present study, Pandiaraj *et al*. (2015) reported higher concentrations of N on maize tissues in treatments that combined inorganic fertilizer and residue retention.

5.1.12 Influence of Different Treatments on Apparent Nitrogen Recovery (ANR) and Nitrogen Partial Factor Productivity (NPFP)

The apparent nitrogen recovery (ANR) **(Figure 4.3)** may have increased because of the N addition through fertility amendments. Goat manure and inorganic fertilizers under CTCrGF and MTCrGF could have added great amounts of N. Similarly, Kramer *et al*. (2002) observed high N recovery in both inorganic fertilizer and poultry manure. Hua *et al*. (2020) attributed the higher N recovery to increased Soil Organic Matter (SOM) and nutrient availability. Akin to CTCrF, CTF, MTF, and MTCrF, the application of inorganic fertilizers improved N recovery by regulating its uptake, water and radiation use efficiencies, root distribution, and photosynthesis in a study by Su *et al*. (2020). In another study, the co-application of inorganic N, P, and K also increased ANR in wheat (Duncan *et al*., 2018). Maize-Dolichos intercrop (CTCrGL and MTCrGL) may have partly improved ANR by regulating soil moisture and temperature (Nyawade *et al*., 2019) and biological N fixation. The result agrees with Costa *et al*. (2021), who also reported increased N recovery under maize-legume intercrop.

The ANR may have also improved under CTCrTiG due to organic acids that may have been released during the decomposition of *T. diversifolia* and goat manure. The organic acids could have chelated aluminium and raised soil pH, possibly enhancing N uptake and utilization by maize crops. Asbon *et al*. (2015) also reported high ANR under combined *T. diversifolia* and goat manure. However, the slow release of P from Rock Phosphate could have negated the effect of *T. diversifolia* under CTCrTiR and MTCrTiR, resulting in lower ANR. Previous studies have found a negative impact of the slow nutrient release on N recovery (e.g., Zheng *et al*., 2016).

Applying inorganic fertilizers and goat manure (CTCrGF and MTCrGF) could have increased N PFP through increased multi-nutrient emanating from, reduced nutrient loss, and supplementary and synergic interactions between the two amendments. The finding agrees with Chen *et al*. (2021), who also found higher N PFP under combined straw retention, manure, and inorganic fertilizers. The improved N PFP under CTF and MTF were attributed to applying the recommended rates of N and P. However, maize residue retention under CTCrF and MTCrF could have improved soil moisture which might have interacted with the inorganic fertilizers (Wang *et al*., 2018), to increase N PFP. Wang *et al*. (2019) found that mulch interacted with inorganic fertilizer to improve soil water content.

T. diversifolia and goat manure under MTCrTiG and CTCrTiG may have increased N PFP through mineralized N and the release of organic anions that could have reduced soil acidity. Rock phosphate under CTCrTiR partly contributed to the improved N PFP due to the accelerated release of P, which may have improved root growth and development because of the solubility effect of *T. diversifolia*. In line with this finding, Naher & Biswas (2021) also recorded higher N PPF under treatments containing rock phosphate and *T. diversifolia*. The finding of the low N PFP under MTCrGL and CTCrGL could be ascribed to the competition for resources, especially P between maize and Dolichos, agreed with Wang *et al*. (2022), who attributed the low N PFP to maize competition for N. The results contrasted the findings of Liang *et al*. (2020), who reported increased N PFP in cotton/mung bean intercrop, respectively. This could be due to differences in the type of crop and P availability in various soil types.

5.1.13 Effect of Tillage on N Concentration in Plant Tissues, ANR, N PFP

Minimum tillage treated with fertility amendments and maize residue retention **(Figure 4.3)** could have increased nitrogen use efficiency (NUE) indicators (i.e., N concentration in plant tissues, ANR, and N PPF) by increasing fertilizer spikes and regulating the interaction between crop roots and the soil (Yang *et al*., 2023). The organic amendments under MTCrGF, MTCrTiG, and MTCrTiR could have increased NUE indicators by improving moisture retention and soil aggregation (structure) that may have reduced N losses. Crop residue retention combined with inorganic fertilizers, like MTCrF in the present study, increased different NUE indicators in a maize cropping system (Jug *et al*., 2019). Like MTCrGL, higher NUE indicators have been observed under different legume crops acting as cover crops in a maize-legume intercropping system under reduced tillage (Büchi *et al*., 2018).

The effect of conventional tillage on NUE indicators can be associated with the uniform distribution of resources and improved air circulation within the rhizosphere. Tilling could have stimulated N mineralization under CTCrGF, CTCrTiG, CTCrGL, and CTCrTiR, thus, improving NUE indicators. Sawyer *et al*. (2017) reported increased N PFP under conventional tillage treated with inorganic fertilizers and with or without residue retention, as was in the case of CTF and CTCrF. Also, Habtegebrial *et al*. (2007) found the same N recoveries under both inorganic N-treated CT and MT systems. Coupled with improved oxygen circulation to the root zone, Dolichos could have created a suitable environment for N-fixing and N-oxidizing microbes (Tang, 2021) that may have improved N uptake, increasing NUE indicators.

5.1.14 Available and Change in Soil N as Influenced by Different Treatments

The goat manure and *T. diversifolia* applied contained substantially high mineralizable N concentrations (1.7% and 3.80% N, respectively), which could be associated with the recorded increase in N under CTCrGL, CTCrTiG, CTCrGF, CTCrTiR, MTCrGL, and MTCrTiR. Cattle manure has been reported to be rich in mineral and organic elements that can improve soil nutrients (Zhang *et al*., 2021). Therefore, the application of manure-containing technologies may explain the increase in available soil N in the intra- and intertreatments at the end of the experiment **(Table 4.7).** Application of inorganic fertilizer (NPK at planting and topdressing using CAN) could cause the high available N and the resultant changes under CTF, CTCrGF, MTF, MTCrF, and MTCrGF. This finding agrees with the previous study by Uwah & Eyo (2014). The low C: N ratio of *T. diversifolia* promotes rapid decomposition of the organic input to release N into the soil solution. Goat manure combined with residue retention could have induced N-related enzyme activity leading to the release of available N, as was also reported by Tayyab *et al*. (2018). Moreover, the significant increase in N recorded under *Dolichos lablab* treatments (MTCrGL and CTCrGL) was attributed to biological fixation (Palmero *et al*., 2022). Also, the experimental site was affected by high soil acidity and low inorganic N; hence the legume crop could have responded to the N stress by recycling and remobilizing N, partially altering root distribution and nodulation capacity (Zheng *et al*., 2022), resulting to increased N in the topsoil.

The higher N reported under MTCrF, MTCrGF, and MTCrGL in this study could be partly attributed to the effectiveness of minimum tillage to store the nutrients at the 0-20 cm depth (Vazquez *et al*., 2019). Minimum tillage could have enhanced soil microbe diversity and population size (Li *et al*., 2020), which may have accelerated the mineralization of N from the organic materials. Additionally, aeration and water infiltration could have been improved under MT, making conditions suitable for rhizobia root infection and consequent N fixation, partly explaining the observed high N under CTCrGL.

5.2 Simulating N Mineralization under Different Treatments

Like the observed values, APSIM captured well the seasonal variabilities of the mineralized N between the two cropping seasons **(Figure 4.7)**. The model has been proven to accurately predict seasonal variabilities in other studies (e.g., Ogbazghi *et al*., 2016). However, the estimated radiation from the NASA website could have partially explained why mineralized N was not accurately predicted, leading to either under- or overestimation. This may have led to the poor model accuracy parameters obtained for most treatments. Similar to treatments with organic amendments in the present study during some sampling dates, Vogeler *et al*. (2019) found that APSIM underestimated N released from crop residues, especially under low temperatures.

The simulated NH_4-N for MTCrF, NO_3-N for MTCrTiG and MTCrF during LR21, and NO_3-N for CTCrTiG, CTCrTiR, MTCrF, and CTCrGF during SR20 season positively corresponded with the observed values. The findings are in agreement with previous studies. For instance, Munir *et al*. (2018) found that simulated mineral N in inorganic-fertilized soils had a high d-index (0.90). Like CTCrTiG and CTCrGF, Mohanty *et al*. (2011) found high APSIM predictability of N mineralized from the farmyard and green manures.

The differences in observed and simulated NH_4-N and NO_3-N during SR20 and LR21 could be attributed to using APSIM default values that were not in sync with the actual mineralization processes (Luo *et al*., 2014). For instance, an influx of carbon pools, though not measured in the current study, affects N mineralization. Estimated APSIM inputs are permissible in cases where the measured values are unavailable, but such inputs can affect the model's performance (Cichota *et al*., 2021). Over- and under-estimation of both NH_4-N and NO_3-N under unfertilized and fertilized plots using APSIM has previously been reported by Smith *et al*. (2019).

The nearly similar simulated mineralized N under conventional and conservation tillage systems in the current study agrees with the finding of Ram *et al*. (2018), who modelled the effect of tillage on soil chemical and physical properties. The lack of strong associations, as depicted by low R^2, between the observed and simulated values under treatments with inorganic fertilizers could be due to the inability of the simulator to simulate P dynamics (Raymond *et al*., 2021), which could have affected N mineralization. Like CTCrTiG, CTCrTiR, MTCrTiG, and MTCrTiR, Mohanty *et al*. (2011) found a lack of correspondence between the predicted mineral N release under green manure and the actual values. Inaccurate prediction of mineralized N under CTCrGF, CTCrTiG, MTCrGF, and MTCrTiG could be due to the varying carbon qualities from the organic amendments and their C: N ratios.

5.2.1 Phosphorus Fractions Status as Influenced by Different Treatments

Generally, the distribution of different fractions of P could have been partly influenced by significant relationships between the various fractions **(Appendix VIII).** For instance, sonic NaOH-Po positively correlated with and could have significantly contributed to residual P. Relationships between various fractions have been reported. Mahmood et al. (2021) found a positive correlation between residual and NaOH-Pi.

In tropical and sub-tropical soils such as the Nitisols, residual P **(Table 4.8)** often is the largest fraction of total P under long-term fertilization. This finding concurs with the results of Arruda *et al*. (2019), who found that residual P was the largest fraction of total P in Mollisols under long-term cumulative fertilization. This fraction is a long-term P sustainability indicator (Maharjan *et al*., 2018). The moderately bioavailable NaOH-Pi fraction was equally higher in the studied soil, which could be ascribed to the addition of inorganic P fertilization from NPK and TSP fertilizers and mineralization from organic amendments (Damon *et al*., 2014). The labile $NaHCO_3$-Po is an important reserve that can buffer P once available soil P is insufficient to meet crop demand. In such a situation, the labile $NaHCO_3$-Po is quickly mineralized by phosphatase and taken up by the crop. Such a mineralization event could have explained the low status of labile $NaHCO_3$-Po in this study. Maize rhizosphere hosts phoC- and phoD harbouring bacterial communities responsible for mineralizing organic P (Guo *et al*., 2022). This could explain the high NaOH-Pi and low $NaHCO_3$-Po and the overall distribution of total P fractions.

Integrated soil fertility management technologies, MTCrGF and CTCrGF had the highest concentrations of most P fractions. The high concentrations could be ascribed to the substantial quantities of mineralizable P in goat manure and inorganic fertilizers. This finding agrees with Chen *et al*. (2022), who reported an increased impact of long-term P fertilization on iron and aluminium-bound and soluble P fractions in an orchard. Also, Shi & Ziadi (2015) found a similar impact of P fertilization on P fractions under maize-soybean rotation with tillage. Long-term N fertilization could impact soil enzymes such as acid phosphatase and phosphodiesterase activities, as was also reported by Qaswar *et al*. (2022) under manure and NPK fertilizer co-application that influenced P fractions. In agreement with the study findings, Mahmood *et al*. (2021) reported increased different P fractions, especially moderate-available P fractions, in response to long-term N fertilization under the Winter wheat cropping system. Still, the co-application of manure and inorganic fertilizer under MTCrGF and CTCrGF could have stimulated synergetic interactions hence the release of P (Otieno *et al*., 2021), eliciting an increase in some of the P fractions.

Different P fractions responded indiscriminately under conservation tillage (CT) and minimum tillage (MT) systems treated with fertility amendments. The impact of tillage on soil processes, such as biological, physical, and chemical changes, could have triggered the observed positive responses of P fractions in this study. Similar to the findings of this study (under CTCrGF, CTF, and CTCrF), Sharma *et al*. (2022) reported significantly higher HCl-P, $NaHCO_3$-Pi, and NaOH-Po fractions under CT and conservation (zero tillage) tillage systems with wheat straw retention. Moreover, inorganic P fractions (Al-P, Fe-P, Ca-P, and residual-P) substantially increased under CT treated with biofertilizer for 32 years in a Ferralsol (Thomas *et al*., 2022), similar to treatments under MT system (MTCrGF, MTCrGL, MTCrTiR, and MTCrTiG) in this study. However, while Selles *et al*. (1997) reported increased P fractions (labile organic and inorganic) under MT in Ferralsols in a study conducted for five years, Pavinato *et al*. (2009) reported nonresponsive labile P fractions after ten years of conservation tillage under soybean cropping system. The inconsistency could be attributed to the duration of experimentation and the type of cropping system.

5.2.2. Fractions of P and their Distribution in Response to Treatments

The labile P fraction (resin-Pi, $NaHCO_3$-Pi, NaOH-Pi, and $NaHCO_3$-Po) is the readily bioavailable fraction of P for plants (Pizzeghello *et al*., 2016). The higher contents of resin-Pi, $NaHCO_3$-Pi, and NaOH-Pi fractions under amended minimum tillage (MTCrGF, MTCrF, MTCrTiR, and MTF) and conservation tillage (CTCrF, CTCrGF, and CTF) can be explained by the application of soil fertility amendments that provided readily available inorganic P (NPK and TSP fertilizers) and easily mineralizable P (goat manure and *Tithonia diversifolia*). These findings vindicate the results of previous studies that found the response of P fractions to inorganic and organic fertilization (Chen *et al*., 2022; Qiong *et al*., 2022) and contrasting tillage systems (Tiecher *et al*., 2018). The higher resin-Pi under MTCrTiR can be attributed to the nexus between *T. diversifolia* and rock phosphate (slow P-releasing fertilizer) under a minimum tillage system. Similarly, the higher content of the readily mineralizable P fraction ($NaHCO_3$-Po) under CTCrTiR can be explained by the interaction of *T. diversifolia* and rock phosphate under the conventional tillage system. *T. diversifolia* could have released organic compounds that hastened the solubilisation of rock phosphate (Wei *et al*., 2017). The higher concentration of moderately labile organic P (NaOH-Po) under MTCrTiG and CTCrTiG underpins the synergic interaction between organic amendments with different nutrient concentrations in the mineralization processes. Similarly, co-application of NPK and manure, as was under CTCrGF and MTCrGF, also had markedly higher labile P fraction ($NaHCO_3$-Pi, NaOH-Pi) in a Black soil under continuous maize cropping (Qiong *et al*., 2022).

The higher recalcitrant fractions (sonic NaOH-Pi and HCl-Pi) can be attributed to the soil pH of approximately 5.5 under all the treatments at the end of the study **(Appendix VII).** Low soil pH is a common challenge in the acidic Nitisols being associated with high concentrations of Al^{3+} and Fe^{3+} that adsorb P (Maharjan *et al*., 2018; Mahmood *et al*., 2021). The significant increase in sonic NaOH-Pi under CTCrGF, MTCrGF, CTF, and CTCrF and HCl-Pi under MTCrTiR, MTCrGF, and CTCrGF **(Table 4.8**) and the total P distributions **(Error! Reference source not found.)** can be associated with long-term N t ransformation which probably led to enhanced protonation during the nitrification process (Raza *et al*., 2019). These results corroborate the findings of Sun *et al*. (2022), who opined that N fertilization lowered soil pH, leading to low labile Pi but high recalcitrant Pi under the maize cropping system in Mollisols. Moreover, goat manure, *T. diversifolia*, and inorganic fertilizers used in this study supplied P that could have also contributed to the high recalcitrant P fractions. Similarly, several other studies have reported a positive response of recalcitrant fractions to P fertilization (e.g., Shi & Ziadi, 2015).

The enhanced recalcitrant sonic NaOH-Po under the amended minimum tillage system (MTCrGF, MTCrTiR, MTCrF, and MTCrGL) can be attributed to increased stable soil organic matter (SOM) contributed by the applied organic amendments. A previous study reported Stable SOM under a minimum tillage system (Zhao *et al*., 2021). Similar to the findings of this study, Cao *et al*. (2020) reported increased recalcitrant NaOH-Po under maize stover retention co-joined with NPK. The higher residual P under MTCrGF probably was due to the transformation of P fractions (from stover residues, goat manure, and inorganic fertilizer), resulting in a build-up of residual P and occluded within soil micro-aggregates. Phosphorus added mainly as soluble Pi often precipitates as Al and Fe phosphate in acidic soils, while insoluble P forms, such as from organic amendments, physicochemically stabilize into SOM complexes (Shen *et al*., 2011). Because of these reactions, P usually accumulates in the soil following the annual long-term addition leading to residual P build-up (Arruda *et al*., 2019).

5.2.3. Phosphorus Sorption Characteristics under Different Treatments

Phosphorus sorption parameters are controlled mainly by soil properties such as clay, SOM content, pH, and amorphous Fe and Al (Debicka *et al*., 2016). Maximum P sorption (S_{max}) in this study **(Table 4.11)** was within the range of 60 to 5500 mg kg^{-1} of a set of humid tropical soils investigated by Campos *et al*. (2016), who credited Al and Fe as important ions controlling P sorption in those soils. The high S_{max} recorded in the soil under the current study indicates that the soil has high sorption surfaces and can retain more P (Lambano *et al*., 2022).

The superior S_{max} under MTCrGF and CTCrGF **(Error! Reference source not found.)** c an be attributed to the direct and indirect effect of inorganic fertilizers and organic amendments that possibly increased SOM. Past studies have found a positive correlation between SOM and S_{max} (e.g., Yang *et al*., 2019), and it increases S_{max} by creating extra sorption sites (Debicka *et al*., 2016). Also, continuous application of inorganic fertilizers for five years under MTCrGF and CTCrGF could have maintained soil pH at approximately 5.5 through the buffering effect of organic amendments resulting in increased P sorption. Consistent with this finding, Nobile *et al*. (2020) found significantly higher S_{max} after a decade of inorganic fertilizer application in an Andosol.

The lowest bonding energy (k) under the various treatments may have resulted as a consequence of P saturation caused by continuous P application. As the degree of P saturation (DPS) increases, soil sorption sites decrease (Yan *et al*., 2017). Thus, additional P is loosely held by the lowest binding affinity (k). Similarly, Debicka *et al*. (2016) and

Dunne *et al*. (2021) reported an inverse relationship between k_l and DPS in sandy soil. Furthermore, organic amendments under CTCrGF, CTCrGL, CTCrTiR, CTCrTiG, MTCrGF, MTCrGL, MTCrTiR, and MTCrTiG could have exudated carboxylates and low molecular organic compounds blocking adsorption sites, therefore, increasing P availability (Arruda *et al*., 2019; Maharjan *et al*., 2018), and can explain the low k_l and high DPS values in this study. These findings agree with Bhattacharyya *et al*. (2015), who found low k_l and significantly higher DPS under NPK + manure treatment.

Similar to treatments with manure (MTCrGF and MTCrTiG), Shafqat & Pierzynski (2010) found higher S_{max} and lower k when No Tillage (NT) was amended with manure compared to conservation tillage (CT). However, improved P sorption characteristics in treatments with conventional tillage system (CTCrGF, CTF, CTCrF, CTCrTiG, CTCrGL, and CTCrTiR) agrees with the work of Fink *et al*. (2016). The highest k_l under minimum tillage (MT) can be attributed to improved soil aggregates under a minimum tillage system that could have enhanced contact between amorphous Fe and Al with soil P leading to strong fixation (Rechberger *et al*., 2021). Phosphorus sorption relates with soil proprieties (Xu *et al*., 2022); thus, soils with high contents of clay and Al, such as the Nitisols under this study, could experience a low P lixiviation and, therefore, least P contamination/pollution risk (Campos *et al*., 2016).

5.3.4. Effects of Various Treatments on P Use Efficiency (PUE) Parameters

Phosphorus use efficiency (PUE) depends mainly on P reactions, retention, and mobility (Bhattacharyya *et al*., 2015) and could have also been affected by P sorption characteristics **(Appendix IX).** Therefore, the treatments that improve P retention and mobility (labile P) most likely enhanced PUE. Rainfall variability may also influence PUE, as was the case on partial productivity factor (PPF) in the present study, in which it was higher during short rains where maize yield was constrained by low rainfall than during long rains. This finding concurs with a study where maize PUE was greater in a year when low rainfall restricted maize yield (Pavinato *et al*., 2017). Nevertheless, phosphorus agronomic efficiency (PAE) in this study **(Error! Reference source not found.)** is slightly below the global average PAE (12.4%) for cereals (Yu *et al*., 2021), indicating a great potential to still improve PUE even after the five-year project period (11 cropping seasons) of P fertilization.

The recorded high PAE and PPF may be attributed to the labile Pi fractions **(Table 4.8)** that could have improved P availability for crop uptake and utilization (Arruda *et al*., 2019). Also, the P addition can explain the response of the two PUE parameters. This finding agrees with the results of Caspersen & Bergstrand (2020), who also reported enhanced PAE of poinsettia and chrysanthemum under P fertilization. Still, N inputs by applying inorganic and organic amendments may be credited for the significantly higher PAE and PPF, particularly under CTCrGF **(Figure 4.10).** The effect of N addition on PAE and PPF has also been reported in other studies (Asrade *et al*., 2022; Zhang *et al*., 2023). With a possible abundance of phosphatase within the maize rhizosphere (Guo *et al*., 2022), the enzyme could have facilitated the decomposition of organophosphates (Xu *et al*., 2022) from organic amendments, thus increasing PAE and PPF. There may have been an interactive effect between the released humic acids during the decomposition and P addition (under treatments that combined inorganic fertilizer and organic amendments) that could have enhanced P availability and PUE.

The slowly solubilised P under MTCrTiR could have been quickly immobilised, thus restricting P uptake and utilisation by the crop, thus, decreasing PUE (Caspersen & Bergstrand, 2020). Maize-*Dolichos lablab* under CTCrGL and MTCrGL could have improved soil enzyme activity under limited P conditions during adequate rainfall (LR21 season), leading to a significantly higher PUE. Pang *et al*. (2018) also elaborated on the importance of legume crops on P acquisition and use efficiency. However, the activity of P-solubilising enzymes may have been suppressed by low soil moisture (Bolo *et al*., 2021) relating to low rainfall received during the SR20 season, explaining the low PUE under CTCrGL.

5.2.5 Influence of Different Treatments on Available and Legacy P

The significant increase in available P **(Figure 4.11)** and legacy P **(Figure 4.9)** under MTCrF, MTCrGF, CTCrF, CTCrGF, and CTF was explained by P addition from both inorganic fertilizers, residue retention and organic amendments (Asrade *et al*., 2022;

Otieno *et al*., 2021). Legacy P was enhanced by the application of inorganic P from NPK and TSP, as was also reported by Somavilla *et al*. (2021). Inorganic P fertilization could have increased the mineralization of P from goat manure (Kiboi *et al*., 2020) by lowering the carbon (C) to P (C:P) ratio and promoting activities of litter-decomposing microorganisms (Jia *et al*., 2022). Similarly, Shafqat & Pierzynski (2013) reported significantly higher legacy P in soil treated with animal manure. Similar to the observation by Musyoka *et al*. (2017), goat manure used in this study contained high P content (0.39%), which could have explained the high available and legacy P. Residue retention under the treatments could have additionally activated P-related enzymes leading to increased available P (Cao *et al*., 2022). Improved soil N and P under combined inorganic fertilizer and manure have also been reported by Brunetti *et al*. (2019).

Low soil pH is a primary problem in the current study site which is associated with low P due to fixation. Increased soluble organic substances under organic amendments (MTCrGL and CTCrTiG) could have raised soil pH, chelated exchangeable acidity, and increased desorption of phosphates hence improving the concentration of available P in the soil solution (Zhang *et al*., 2021). Furthermore, *Dolichos lablab* has an extensive rooting system that may have captured and redistributed N to topsoil hence the significantly higher legacy and available P under MTCrGL. Additionally, the Dolichos probably responded to low soil P by enhancing mycorrhizal associations and phosphatase activity, thereby increasing available P (Arruda *et al*., 2021). The low P status under CTCrTiR, MTCrTiG, and CTCrGL could be explained by the release of organic acids from the organic amendments (maize residues, *T. diversifolia*, and manure) that promoted solubility of P and its subsequent uptake by maize evidenced by the higher yield **(Table 4.12).** Nutrient mining through crop harvest contributes to low soil P (Asrade *et al*., 2022). Moreover, Nitisols are acidic, containing hydroxides and oxides of aluminium and iron, which strongly fix P (Werner *et al*., 2017), which could have explained the low available P under MTF.

5.3.5 Effects of the Treatments on Soil Moisture Content

The significant increase in SMC under CTCrGF, MTCrGF, CTCrTiG, CTCrTiR, and MTCrTiR during the SR20 season, which experienced relatively lower rainfall, could be attributed to improved soil organic matter (SOM) resulting from increased biomass production **(Table 4.12).** A positive relationship exists between SOM and increased water retention (Lal, 2020). Combining goat manure and inorganic fertilizer treatment could have enhanced soil hydraulic properties by releasing soil organic carbon (SOC). Saputra *et al*. (2023) showed a positive impact of SOC on soil hydraulic properties that increased soil water holding capacity.

The enhanced SMC under CTCrGL and MTCrGL perhaps partly resulted from the covering effect of the *Dolichos lablab*, a legume crop. Cover crops are one of the components of conservation agriculture aimed at maintaining ground cover and retaining soil moisture (Nordblom *et al*., 2023). Additionally, the legume crop could have contributed to the significant increase in SMC by influencing soil hydraulic properties during the growing season. Haruna *et al*. (2023) found improved soil hydraulic properties under several cover crops. Moreover, the retention of maize residue may have also contributed to the improved SMC under CTCrGF, MTCrGF, CTCrTiG, CTCrTiR, and MTCrTiR. Several studies have linked significant improvements in SMC to crop residue retention (e.g., Rahman *et al*., 2022).

5.2.6 Effect of Different Treatments on Maize Productivity

The high chlorophyll content recorded under the various amended treatments was partly attributed to N fertilization from inorganic (NPK and CAN) under CTF, CTCrGF, MTF, MTCrF and MTCrGF, and organic (manure and *T. diversifolia*) amendments under CTCrGL, CTCrTiG, CTCrGF, CTCrTiR, MTCrGL, and MTCrTiR. Consistent with the current findings, Skudra & Ruza (2017) reported higher chlorophyll content of Winter wheat fertilized with NPK. Moreover, Kiboi *et al*. (2019) reported significantly higher chlorophyll at the 6th leaf stage under N inputs. However, the low relative chlorophyll under MTCrGL at the 10th leaf during SR20 and CTCrGL at the 6th and 10th leaf during LR21 cropping seasons could be attributed to interspecific competition for the biologically fixed N between maize and the legume (Gong *et al*., 2021). The leaf area index (LAI) is a consequence and determinant of critical vegetation canopy processes (Parker, 2020) regulated by N. Therefore, the higher LAI under this study could be linked to N input through CTF, CTCrF, CTCrGF, CTCrGL, CTCrTiG, CTCrTiR, MTF, MTCrF, MTCrGF, MTCrGL, MTCrTiG, and MTCrTiR. This finding vindicates Zhang *et al*. (2018), who reported significantly improved LAI in various crops at different phenological stages, such as in *Solanum tuberosum* L. under N and P addition from manure, NPK, and TSP.

Photosynthetically active radiation (PAR) and radiation use efficiency (RUE) are closely related and are important in determining crop yields (Shi *et al*., 2022). An optimum biomass accumulation, accentuated by soil fertilization, allows maize to intercept and effectively use solar radiation (Yan *et al*., 2022). Therefore, the observed higher PAR and RUE may be attributed to higher biomass accumulation **(Table 4.10)** supported by nutrients addition from CTCrGF, CTCrGL, CTCrTiG, CTCrTiR, MTCrGF, MTCrGL, MTCrTiG, and MTCrTiR. Zhang *et al*. (2021) reported high PAR in rice under high N, P, and K fertilization rates in China. Like CTF, CTCrF, MTF, and MTCrF, Singh *et al*. (2017) also reported the highest PAR in maize 60 days after planting under NPK application. Radiation use efficiency depends on the intercepting surface (leaf) affected by fertilization and water use efficiency. Cosentino *et al*. (2016) reported high RUE in giant reed (*Arundo donax* L.) under increased water availability and N fertilization in a semi-arid Mediterranean area. Consistent with the impact of CTCrGL and MTCrGL in the current study, maize-soybean intercrop greatly enhanced RUE under Eutric Cambisol in Shangqiu (Gao *et al*., 2010). Additionally, residue retention and organic amendments under CTCrTiG, CTCrGF, CTCrTiR, MTCrTiG, and MTCrTiR in the current study could have conserved soil moisture for a longer duration leading to improved resource-use efficiency (Parihar & Nayak 2019) hence the higher RUE. Conversely, the observed insignificant effect of CTCrGL, MTCrGL, MTF and MT on RUE could also be attributed to interspecific P competition under the intercrop treatment and fixation under sole inorganic fertilizer application. This finding corroborates the results of the study conducted by Salvagiotti *et al*. (2017).

The rapid growth rate observed under the various amended treatments in the current study was attributed to N, P, and K fertilization that promoted active vegetive growth by stimulating growth hormones (Yue *et al*., 2022). Plant growth occurs in meristematic cells of the internodes, in which P plays a critical role. In the current study, fertilization by

NPK 17:17:17 under CTF, CTCrF, CTCrGF, MTCrF, and MTCrGF probably provided K, which could have promoted the growth of meristematic tissues and key in N metabolism leading to taller maize crops. Furthermore, the enhanced growth under organic-based amendments (CTCrGL, CTCrTiG, MTCrGL, and MTCrTiG) could be attributed to improved soil P **(Figure 4.11)** and N **(Table 4.7).** This finding confirms the results of an earlier study that recorded rapid crop growth under organic amendments (Yousaf *et al*., 2021). Moreover, a similar effect of rock phosphate on maize height as under CTCrTiR and MTCrTiR in this study was reported by Kaur and Reddy (2015).

The significant increase in maize yield could be attributed to its response to N and P application through fertilization under the various amended treatments to a soil characterized by low N and P, as shown in **Table 3.1.** The increased grain and stover yields under treatments with integrated inorganic fertilizers and organic amendments (CTCrGF and MTCrGF) demonstrate the importance of ISFM in improving crop productivity through complementarity (Vanlauwe *et al*., 2015). A similar finding was reported in rice (Mi *et al*., 2018) and tomatoes (Brunetti *et al*., 2019). Combining resources under CTCrTiR, CTCrTiG, MTCrTiG, and MTCrTiR enhanced resource use efficiencies, as shown through the observed improved RUE (Table 4.14). This finding agrees with a short-term study conducted in the farmers' fields in the Central Highlands of Kenya (Otieno *et al*., 2021). The result also corroborates the assertion of Hassen (2018) and reveals the potential of integrated sole organic amendments (CTCrGL, MTCrGL, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR) replacing the use of inorganic fertilizers. Increased yield has been reported in rice under a treatment that combined rock phosphate and *T. diversifolia* (Imani *et al*., 2020), similar to increased maize performance under CTCrTiR and MTCrTiR in this study.

The enhanced maize yield under MTF, MTCrF, CTF, and CTCrF is a demonstration of the responsiveness of acidic Nitisols to sole inorganic fertilizer application that regulates crop growth parameters (**Table 4.9** and **Table 4.11**) and yield **(Table 4.12).** This result supports the findings of Wu *et al*. (2017), who reported a positive effect of inorganic P application on maize growth and yield. Positive effects of inorganic fertilizer on the growth and yield of other crops have also been reported in another study (Cheptoek *et al*., 2021). The increased maize yield under the application of inorganic fertiliser and residue retention (CTCrF and MTCrF) agrees with the finding of Zhang *et al*. (2021), where NPK combined with straw retention increased wheat yield. On the other hand, maize yield under CTCrGL, and MTCrGL was associated with increased available P **(Figure 4.11)** and N (Table 4.7) under these treatments. Other studies have associated increased crop yield under cereal-legume intercrop with the ability of the legume crop to enhance soil N and P within the system (Arruda *et al*., 2021; Arruda *et al*., 2019).

The increased aboveground yield and water productivity (WP) **(Table 4.15)** were associated with adding N, P, and K from inorganic and organic amendments. Nitrogen application affects maize grain yield by regulating; 1) N uptake, 2) radiation and water use efficiencies, 3) root distribution, 4) photosynthesis, 5) and grain filling (Su *et al*., 2020; Yue *et al*., 2022). Applying N through calcium superphosphate, urea, and pig manure significantly increased maize yield in a study conducted by Zhang *et al*. (2021). Soil fertility amendments improved WP by providing N, P, and K that control critical bio-physico-chemical functions in crops. For instance, P fertilization from the amendments could have stimulated root hydrotropism during intra-seasonal water shortages (Szulc *et al*., 2021), leading to higher WP. Treatments that contained organic amendments like CTCrGF, CTCrTiG, MTCrGF, and MTCrTiG could have altered soil hydraulic characteristics and enhanced the soil's physical environment (Parihar & Nayak, 2019), leading to improved water utilization. On the other hand, K from NPK fertilization could have increased water uptake and translocation within the plant resulting in higher WP.

Stover yield declined under MT during the LR21 cropping season and coincided with the low WP. A previous study also reported a reduced maize yield grown under conservation tillage in adequate rainfall conditions (Parihar & Nayak, 2019). The low maize grain yield observed under CTCrGL and MTCrGL was attributed to water stress caused by legume-cereal soil moisture competition during periods of moisture scarcity (Teixeira *et al*., 2014) at the grain filling stage during the SR20 season.

The observed higher maize performance under the different ISFM technologies was due to a combined effect of tillage and soil fertility amendments. The improved performance under CT could be ascribed to better root development due to improved soil porosity

(Cosentino *et al*., 2016) and rapid mineralization of plant nutrients. Kiboi *et al*. (2019) attributed the significantly high maize yield to quick nutrient release under conservation tillage. On the other hand, minimum tillage (MT) could have contributed to better maize performance by regulating plant photosynthetic capacity, hormonal changes, and grain filling (Yue *et al*., 2022). Other studies have linked high crop performance under MT to increased water retention and fertilizer responsiveness (Vazquez *et al*., 2019).

The reduced consumptive water use (Et) under CTCrGF, MTCrGF, CTCrGL, and CTCrTiG could be attributed to improved soil water conservation **(Table 4.13)** and canopy cover as indicated by the leaf area index (Table 4.9) under these treatments. A similar finding was reported by Li *et al*. (2010), who found lower Et and higher maize biomass production under combined inorganic fertilizer and animal manure treatment. Integration of all-inclusive organic amendments like CTCrGL and CTCrTiG could have improved water storage efficiency, leading to low consumptive use. This result agrees with the finding of Xu *et al*. (2023), who also reported lower consumptive water use under all-inclusive organic amendments.

Apart from CT and MT that had Nitrogen Nutrition Index (NNI) below 1, it was at a supra-optimal level (Li *et al*., 2022) in all the other treatments with values greater than 1 **(Figure 4.12).** This could be attributed to the addition of N through the fertility amendments and its protection against losses. The NNI positively relates with other crop growth parameters like chlorophyll content and LAI (Zhao *et al*., 2018), which are both affected by N nutrition. The NNI of summer maize ranged between 0.68 to 1.15 under various N treatments in another study (Zhao *et al*., 2018). The finding under CTCrGF and MTCrGF was similar to that of Liu *et al*. (2023), who also reported higher NNI under the combined application of inorganic fertilizer and manure. Particularly under MTCrGL and CTCrGL, intercropping maize with Dolichos could have increased NNI by improving resource use and rhizobia efficiency. The finding agrees with Latati *et al*. (2016), who found higher NNI value under maize-common bean intercrop.

CHAPTER SIX

SUMMARY OF OBJECTIVES, CONCLUSIONS, AND RECOMMENDATIONS

6.1 Introduction

This Chapter contains summary of the research objectives, conclusions, and recommendations arising from the study. These three subsections are aligned to the objectives, research hypotheses and the findings.

6.2 Summary of the Study Objectives

Informed by the need to improve crop productivity in an acidic Nitisol, this study was conducted in a Humic nitisol of Chuka Subcounty situated in Tharaka-Nithi County to assess the effects of integrated soil fertility management (ISFM) technologies on soil microbial biomass, , maize water productivity, and N and P dynamics. In addition to this, the study sought to validate Agricultural Production Systems sIMulator Model (APSIM) in simulating N mineralization as influenced by selected ISFM technologies. The specific objectives of the study were;

i. Determine the effects of selected ISFM technologies on soil microbial biomass N, C, and P.
ii. Evaluate the effects of selected ISFM technologies on N mineralization, partial factor productivity, and apparent N recovery.
iii. Simulate soil N mineralization under selected ISFM technologies, and
iv. Assess the response of soil phosphorus fractions, degree of saturation, maximum sorption capacity, use efficiency, and legacy to selected ISFM technologies.
v. Evaluate the effects of the selected ISFM technologies on maize yield, soil moisture content, and water productivity.

6.3 Conclusions

i. Integrated soil fertility management technologies significantly affected soil microbial C, N, and P thus the first null hypothesis was rejected. The microbial elements were highest in technologies that integrated organic amendments. However, the highest values were recorded under different technologies. The highest MBC was under CTCrGL (865.16 mg kg^{-1}) and MTCrGL (863.94 mg kg^{-1}), MBN peaked under MTCrTiG (120.59 mg kg^{-1}) and was highly improved by the sole organic amendments or combined with inorganic fertilizers. The CTCrGF (45.04 mg kg^{-1}) treatment greatly enhanced MBP.

ii. The selected integrated soil fertility management (ISFM) technologies significantly affected the quantity and pattern of N mineralization. The technologies also greatly improved N partial factor productivity (NPFP) and apparent N recovery (ANR). The second null hypothesis was also rejected. Averaged across the two seasons and sampling dates, MTCrGL, MTCrGF, CTCrGF, CTCrGL, CTCrTiR, MTCrTiG, CTCrTiG, and MTCrTiR resulted in the greatest mineralized N by 1.27, 1.05, 1.05, 0.93, 0.91, 0.74, 0.69, and 0.65 ug g^{-1}, respectively compared to the control that recorded an average of 0.20 ug g^{-1}. Application of CTCrGF and MTCrGF resulted in the highest apparent N recovery (ANR) of 5.11 and 5.75, respectively, in maize crop. The implementation of CTCrGF also led to the highest N partial factor productivity of 52.80 kg N ha^{-1}.

iii. Strong positive concurrence between observed and APSIM simulated NO_3-N only existed under CTCrTiG, CTCrTiR, MTCrF, and CTCrGF ($R^2 = 0.63, 0.58, 0.56$, and 0.54; $p = 0.02, 0.03, 0.03$, and 0.04, respectively) during SR20. Whereas, there was strong agreement between observed and simulated NH_4-N only under MTCrF ($R^2 = 0.56$; $p= 0.03$) and CTCrGL (R2 = 0.52; $p = 0.04$) during the LR21. The model did not accurately predict N mineralization under the rest of the selected ISFM technologies. Consequently, the third null hypothesis was not rejected. The Model mostly under-estimated mineralized N at the start of the season and over-estimated it in the later dates under most of the technologies.

iv. The selected ISFM technologies significantly affected quantities of soil P fractions, degree of saturation (DPS), maximum sorption capacity (S_{max}), P use efficiency (PUE), and legacy. The fourth null hypothesis was also rejected. The MTCrGF had the highest effect on and significantly increased resin-Pi, NaHCO3-Pi, and maximum P sorption (S_{max}) by 182, 76, and 52 mg P kg^{-1}. Also, NaOH-Pi and S_{max} concentrations were greatly higher under CTCrGF by 216 mg P kg^{-1} and

49 mg P kg^{-1}, respectively, than the control. Additionally, MTCrGF and CTCrGF had the lowest P bonding energy (0.04 L mg^{-1}). The CTCrGF had the highest P partial productivity factor (0.093 and 0.140 kg biomass kg^{-1} P) and P agronomic efficiency (0.080 and 0.073 kg biomass kg^{-1} P) during sort and long rainy seasons.

v. The selected ISFM technologies significantly explained the variations on maize yield, soil moisture content, and water productivity, thus the fifth null hypothesis was rejected. Grain yield was significantly higher under CTCrGF, MTCrF, CTCrF, MTCrGF, MTCrTiG, CTCrTiR, CTF, CTCrTiG, and CTCrTiR than the control in the SR2020 season by 95, 93, 93, 93, 92, 92, 92, 92 and 88%. During LR2021, CTCrGF recorded the highest grain yield, which was 74% higher than the control, while CTCrGL, MTCrGF, MTCrGL, CTF, MTCrF, CTCrF, MTF, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR, had higher yields than the control by 73, 71, 70, 69, 69, 66, 65, 64, 58, 55 and 49%. The control treatment (C) had lower SMC (52.88 mm averaged across the sampling period) throughout the sampling periods during the seasons compared to the other treatments namely; MTCrGF, MTCrGL, CTCrGF, CTCrGL, MTCrTiR, CTCrTiG, and MTCrTiG of 73.09, 71.01, 70.69, 70.06, 65.06, 64.52, and 61.15 mm, respectively, across the two seasons and sampling dates. The same treatments resulted in identical effect on water productivity.

6.4 Recommendations and areas of further studies

6.4.1 Recommendations

i. The use of CTCrGF, CTCrTiG, CTCrTiR, MTCrGF, MTCrTiG, and MTCrTiR should be promoted as medium (5 years duration) and long-term (above 5 years duration) technologies to improve soil biological fertility; microbial biomass C, N, and P.

ii. Based on the research findings, it is crucial for short-term and medium-term integrated soil fertility management (ISFM) studies to include evaluation of the effect of the technologies on microbial C, N, and P as quick and accurate assessment parameters.

iii. The utilization of MTCrTiG, CTCrTiG, CTCrGL, CTCrTiR, MTCrGF, CTCrGF, or MTCrTiR is recommended for enhanced N management due to their significant effects in improving mineralized N, NPFP, and ANR in a maize-based cropping system.
iv. There should be limited use of default (model inbuilt values) parameters during model initialization and parameterization to improve its accuracy in simulating N mineralization under the selected ISFM technologies. Incorporating actual measurements of Soil Organic Matter (SOM) module components, such as C: N ratio, total organic carbon (OC), fresh soil microbial biomass, their products (FBiom), and a fraction of SOM that is inert (FInert) should be included in the Model.
v. The ISFM technologies, especially CTCrGF and MTCrGF, should be promoted to manage P through improved P fractions, its sorption characteristics and PUE in Humic Nitisols.

6.4.2 Areas for Further Research

The following were identified as areas that require further research.

i. A long-term study that assesses the effects of the selected ISFM technologies on soil aggregate stability.
ii. Field assay to isolate and identify the specific microbes driving microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), and microbial biomass phosphorus (MBP).
iii. A long-term study to assess the impact of MTCrGL, MTCrTiG, CTCrTiG, CTCrGL, CTCrTiR, MTCrGF, CTCrGF, and MTCrTiR on nitrogen (N) residual effects.
iv. Conduct a cost-benefit analysis, and evaluate the sustainability of MTCrGL, MTCrTiG, CTCrTiG, CTCrGL, CTCrTiR, MTCrGF, CTCrGF, and MTCrTiR technologies.
v. A long-term study incorporating actual values of components within the SoilOrganicMatter module to further validate the accuracy of the APSIM model in simulating N mineralization. The study should include inputs with

different C:N ratios and modify the partitioning of C through the inclusion of an additional C pool or assigning different C pools based on their biochemical compositions.

vi. Assessment of the effect of the selected ISFM technologies on N and P dynamics and crop productivity in other soil types to enhance adoption of the technologies in different regions.

REFERENCES

Abbasi, M. K., & Khizar, A. (2012). Microbial biomass carbon and nitrogen transformations in a loam soil amended with organic – inorganic N sources and their effect on growth and N-uptake in maize. *Ecological Engineering*, *39*, 123–132. https://doi.org/10.1016/j.ecoleng.2011.12.027

Afreh, D., Zhang, J., Guan, D., Liu, K., Song, Z., Zheng, C., Deng, A., Feng, X., Zhang, X., Wu, Y., Huang, Q., & Zhang, W. (2018). Long-term fertilization on nitrogen use efficiency and greenhouse gas emissions in a double maize cropping system in subtropical China. *Soil and Tillage Research, 180,* 259–267. https://doi.org/10.1016/j.still.2018.03.016

Ahmed, W., Qaswar, M., Jing, H., Wenjun, D., Geng, S., Kailou, L., Ying, M., Ao, T., Mei, S., Chao, L., Yongmei, X., Ali, S., Normatov, Y., Mehmood, S., Khan, M. N., & Huimin, Z. (2020). Tillage practices improve rice yield and soil phosphorus fractions in two typical paddy soils. *Journal of Soils and Sediments*, *20*(2), 850–861. https://doi.org/10.1007/s11368-019-02468-3

Ajibade, S., Mupambwa, H. A., Manyevere, A., & Mnkeni, P. N. S. (2020). Influence of microbial inoculation of igneous rock phosphate-amended cow and pig manures on vermidegradation and nutrient release. *Agronomy, 10,* 1587–1597. https://doi.org/10.3390/agronomy10101587

Akponikpè, P. B. I., Gérard, B., Michels, K., & Bielders, C. (2010). Use of the APSIM model in long term simulation to support decision making regarding nitrogen management for pearl millet in the Sahel. *European Journal of Agronomy*, *32,* 144–154. https://doi.org/10.1016/j.eja.2009.09.005

Ali, M., Khanom, A., Nahar, K., Ali, Y., & Kalam, A. (2021). Effect of manure application on net nitrification rates, heavy metal concentrations and nitrifying archaea / bacteria in soils. *Bulletin of Environmental Contamination and Toxicology, 106,* 707–713. https://doi.org/10.1007/s00128-021-03112-y

Anil, A. S., Sharma, V. K., Jiménez-Ballesta, R., Parihar, C. M., Datta, S. P., Barman, M., Chobhe, K. A., Kumawat, C., Patra, A., & Jatav, S. S. (2022). Impact of long-term conservation agriculture practices on phosphorus dynamics under maize-based cropping systems in a sub-tropical soil. *Land*, *11*, 1488–1500. https://doi.org/10.3390/land11091488

Arce, M. I., Schiller, D. Von, Bengtsson, M. M., Hinze, C., Jung, H., Alves, R. J. E., Urich, T., Singer, G., & Nicol, G. W. (2018). Drying and rainfall shape the structure and functioning of nitrifying microbial communities in riverbed sediments. *Frontiers in Microbiology*, *9*, 1–17. https://doi.org/10.3389/fmicb.2018.02794

Arruda, B., Herrera, W. F. B., Rojas-García, J. C., Turner, C., & Pavinato, P. S. (2021). Cover crop species and mycorrhizal colonization on soil phosphorus dynamics. *Rhizosphere*, *19*, 100396. https://doi.org/10.1016/j.rhisph.2021.100396

Arruda, C. J. M., Ruiz Diaz, D., Hettiarachchi, G. M., Dubou Hansel, F., & Pavinato, P. S. (2019). Soil phosphorus fractions and legacy in a corn-soybean rotation on Mollisols in Kansas, USA. *Geoderma Regional*, *18*, e00228. https://doi.org/10.1016/j.geodrs.2019.e00228

Arslan, H., Gueryuz, G., & Kırmızı, S. (2010). Nitrogen mineralisation in the soil of indigenous oak and pine plantation forests in a Mediterranean environment. *European Journal of Soil Biology*, *46*, 11–17. https://doi.org/10.1016/j.ejsobi.2009.08.002

Asada, K., Kanda, T., Yamashita, N., Asano, M., & Eguchi, S. (2022). Interpreting stoichiometric homeostasis and flexibility of soil microbial biomass carbon, nitrogen, and phosphorus. *Ecological Modelling*, *470*, 110018. https://doi.org/https://doi.org/10.1016/j.ecolmodel.2022.110018

Asbon, P., Oloo, P., & Orangi, R. (2015). Effects of Tithonia diversifolia , farmyard manure and urea , and phosphate fertiliser application methods on maize yields in western Kenya. *Journal of Agriculture and Rural Development in the Tropics and Subtropics*, *116*, 1–9.

Ashraf, M. N., Cheng, H., Xiangru, X., Aziz, T., Lei, W., Waqas, M. A., Farooq, M., Xu, H., Zhang, W., & Minggang, X. (2022). Long-term manure application increased soil organic carbon and nitrogen mineralization through the accumulation of unprotected and physically protected carbon fractions. *Pedosphere, 17,* 34–49. https://doi.org/https://doi.org/10.1016/j.pedsph.2022.06.047

Asrade, A., Kulhánek, M., Černý, J., Sedlář, O., & Balík, J. (2022). Effects of long-term mineral fertilization on silage maize monoculture yield, phosphorus uptake and its dynamic in soil. *Field Crops Research, 280,* 108476. https://doi.org/https://doi.org/10.1016/j.fcr.2022.108476

Azeem, M., Hayat, R., Hussain, Q., Tahir, M. I., Imran, M., Abbas, Z., Sajid, M., Latif, A., & Irfan, M. (2019). Effects of biochar and NPK on soil microbial biomass and enzyme activity during 2 years of application in the arid region. *Arabian Journal of Geosciences*, *12,* 311–321. doi:10.1007/s12517-019-4482-1

Bai, J., Yu, Z., Yu, L., Wang, D., Guan, Y., Liu, X., Gu, C., & Cui, B. (2019). In-situ organic phosphorus mineralization in sediments in coastal wetlands with different flooding periods in the Yellow River Delta, China. *Science of the Total Environment, 682,* 417–425. https://doi.org/10.1016/j.scitotenv.2019.05.176

Bhattacharyya, P., Nayak, A. K., Shahid, M., Tripathi, R., Mohanty, S., Kumar, A., Raja, R., Panda, B. B., Lal, B., Gautam, P., Swain, C. K., Roy, K. S., & Dash, P. K. (2015). Effects of 42-year long-term fertilizer management on soil phosphorus availability, fractionation, adsorption–desorption isotherm and plant uptake in flooded tropical rice. *Crop Journal*, *3,* 387–395. https://doi.org/10.1016/j.cj.2015.03.009

Bicharanloo, B., Bagheri Shirvan, M., Keitel, C., & Dijkstra, F. A. (2022). Nitrogen and phosphorus availability have stronger effects on gross and net nitrogen mineralisation than wheat rhizodeposition. *Geoderma, 405,* 115440. https://doi.org/10.1016/j.geoderma.2021.115440

Biswas, S. S., Ghosh, A., Singhal, S. K., Biswas, D. R., Roy, T., Sarkar, A., & Das, D. (2019). Phosphorus enriched organic amendments can increase nitrogen use efficiency in wheat. *Communications in Soil Science and Plant Analysis, 50,* 1178–1191. https://doi.org/10.1080/00103624.2019.1604736

Bolo, P., Kihara, J., Mucheru-Muna, M., Mugendi, N., & Kinyua, M. (2023). Soil aggregation, organic carbon and microbial biomass as affected by tillage, residue management and cropping systems in tropical Ferralsols of Western Kenya. *East African Agricultural and Forestry Journal*, *87*, 9–36.

Bolo, P., Kihara, J., Mucheru-Muna, M., Njeru, E. M., Kinyua, M., & Sommer, R. (2021). Application of residue, inorganic fertilizer and lime affect phosphorus solubilizing microorganisms and microbial biomass under different tillage and cropping systems in a Ferralsol. *Geoderma*, *390*, 114962. https://doi.org/10.1016/j.geoderma.2021.114962

Bouwman, A. F., Beusen, A. H. W., & Billen, G. (2009). Human alteration of the global nitrogen and phosphorus soil balances for the period 1970-2050. *Global Biogeochemical Cycles*, *23*, 1–16. https://doi.org/10.1029/2009GB003576

Bravo, C., Torrent, J., Giráldez, J. V., González, P., & Ordóñez, R. (2006). Long-term effect of tillage on phosphorus forms and sorption in a Vertisol of southern Spain. *European Journal of Agronomy*, *25*, 264–269. https://doi.org/10.1016/j.eja.2006.06.003

Brennan, J., Hackett, R., Mccabe, T., Grant, J., Fortune, R. A., & Forristal, P. D. (2014). The effect of tillage system and residue management on grain yield and nitrogen use efficiency in winter wheat in a cool Atlantic climate. *European Journal of Agronomy*, *54*, 61–69. https://doi.org/10.1016/j.eja.2013.11.009

Brookes, P. C., & Powlson, D. S. (1981). Preventing phosphorus losses during perchloric acid digestion of sodium bicarbonate soil extracts. *Journal of the Science of Food and Agriculture*, *32*(7), 671–674. https://doi.org/10.1002/jsfa.2740320707

Brown, H., Huth, N., & Holzworth, D. (2018). Crop model improvement in APSIM: Using wheat as a case study. *European Journal of Agronomy*, *May 2017*, 0–1.

https://doi.org/10.1016/j.eja.2018.02.002

Brunetti, G., Traversa, A., De Mastro, F., & Cocozza, C. (2019). Short term effects of synergistic inorganic and organic fertilization on soil properties and yield and quality of plum tomato. *Scientia Horticulturae*, *252*(August 2018), 342–347. https://doi.org/10.1016/j.scienta.2019.04.002

Büchi, L., Wendling, M., Amossé, C., Necpalova, M., & Charles, R. (2018). Importance of cover crops in alleviating negative effects of reduced soil tillage and promoting soil fertility in a winter wheat cropping system. *Agriculture, Ecosystems and Environment*, *256*, 92–104. https://doi.org/10.1016/j.agee.2018.01.005

Cabrera, M. L. (2016). Legacy effect of fertilization and tillage systems on nitrogen mineralization and microbial communities. *Soil Fertility and Plant Nutrition in the Tropics and Subtropics*, *80*, 1262–1271. https://doi.org/10.2136/sssaj2016.03.0070

Campos, M., Antonangelo, J. A., & Alleoni, L. R. F. (2016). Phosphorus sorption index in humid tropical soils. *Soil and Tillage Research*, *156*, 110–118. https://doi.org/10.1016/j.still.2015.09.020

Cao, D., Lan, Y., Liu, Z., Yang, X., Liu, S., He, T., Wang, D., & Meng, J. (2020). Responses of organic and inorganic phosphorus fractions in brown earth to successive maize stover and biochar application : a 5-year field experiment in Northeast China. *Journal of Soils and Sediments*, *10*, 1614–7480. https://doi.org/https://doi.org/10.1007/s11368-019-02508-y

Cao, N., Zhi, M., Zhao, W., Pang, J., Hu, W., Zhou, Z., & Meng, Y. (2022). Straw retention combined with phosphorus fertilizer promotes soil phosphorus availability by enhancing soil P-related enzymes and the abundance of phoC and phoD genes. *Soil and Tillage Research*, *220*, 105390. https://doi.org/https://doi.org/10.1016/j.still.2022.105390

Cardarelli, M., Chami, A. El, Iovieno, P., Rouphael, Y., Bonini, P., & Colla, G. (2023). Organic fertilizer sources distinctively modulate productivity, quality, mineral composition, and soil enzyme activity of greenhouse lettuce grown in degraded soil. *Agronomy*, *13*, 194–210. https://doi.org/https://doi.org/10.3390/agronomy13010194

Caspersen, S., & Bergstrand, K. J. (2020). Phosphorus restriction influences P efficiency and ornamental quality of poinsettia and chrysanthemum. *Scientia Horticulturae*, *23*, 109316. https://doi.org/10.1016/j.scienta.2020.109316

Cassity-Duffey, K., Cabrera, M., Gaskin, J., Franklin, D., Kissel, D., & Saha, U. (2020). Nitrogen mineralization from organic materials and fertilizers: Predicting N release. *Soil Science Society of America Journal*, *84*, 522–533. https://doi.org/10.1002/saj2.20037

Chaki, A. K., Gaydon, D. S., Dalal, R. C., Bellotti, W. D., Gathala, M. K., Hossain, A., & Menzies, N. W. (2022). How we used APSIM to simulate conservation agriculture practices in the rice-wheat system of the Eastern Gangetic Plains. *Field Crops Research*, *275*, 108344. https://doi.org/10.1016/j.fcr.2021.108344

Chalhoub, M., Garnier, P., Coquet, Y., Mary, B., Lafolie, F., & Houot, S. (2013). Increased nitrogen availability in soil after repeated compost applications: Use of the PASTIS model to separate short and long-term effects. *Soil Biology and Biochemistry*, *65*, 144–157. https://doi.org/10.1016/j.soilbio.2013.05.023

Chen, A., Zhang, W., Sheng, R., Liu, Y., Hou, H., Liu, F., Ma, G., Wei, W., & Qin, H. (2021). Long-term partial replacement of mineral fertilizer with in situ crop residues ensures continued rice yields and soil fertility: A case study of a 27-year field experiment in subtropical China. *Science of The Total Environment*, *787*, 147523. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.147523

Chen, C., & Xiao, W. (2023). The global positive effect of phosphorus addition on soil microbial biomass. *Soil Biology and Biochemistry*, *176*, 108882. https://doi.org/https://doi.org/10.1016/j.soilbio.2022.108882

Chen, G., Yuan, J., Chen, H., Zhao, X., Wang, S., Zhu, Y., & Wang, Y. (2022). Animal manures promoted soil phosphorus transformation via affecting soil microbial community in paddy soil. *Science of The Total Environment*, *831*, 154917. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.154917

Chen, H., Dai, Z., Veach, A. M., Zheng, J., Xu, J., & Schadt, C. W. (2020). Global meta-analyses show that conservation tillage practices promote soil fungal and bacterial biomass. *Agriculture, Ecosystems and Environment*, *293*, 106841. https://doi.org/10.1016/j.agee.2020.106841

Chen, H., Hu, W., Wang, Y., Zhang, P., Zhou, Y., Yang, L.-T., Li, Y., Chen, L.-S., & Guo, J. (2023). Declined photosynthetic nitrogen use efficiency under ammonium nutrition is related to photosynthetic electron transport chain disruption in citrus plants. *Scientia Horticulturae*, *308*, 111594. https://doi.org/https://doi.org/10.1016/j.scienta.2022.111594

Chen, X., Yan, X., Wang, M., Cai, Y., Weng, X., Su, D., Guo, J., Wang, W., Hou, Y., Ye, D., Zhang, S., Liu, D., Tong, L., Xu, X., Zhou, S., Wu, L., & Zhang, F. (2022). Long-term excessive phosphorus fertilization alters soil phosphorus fractions in the acidic soil of pomelo orchards. *Soil and Tillage Research*, *215*, 105214. https://doi.org/https://doi.org/10.1016/j.still.2021.105214

Chen, Z., Xu, Y., He, Y., Zhou, X., Fan, J., Yu, H., & Ding, W. (2018). Nitrogen fertilization stimulated soil heterotrophic but not autotrophic respiration in cropland soils: A greater role of organic over inorganic fertilizer. *Soil Biology and Biochemistry*, *116*, 253–264. https://doi.org/10.1016/j.soilbio.2017.10.029

Cheptoek, R., Nsar, J., Ochieng, I., Maitra, S., Heydarzadeh, S., & Gitari, H. (2022). Role of minjingu rock phosphate and nitrogen fertilizer in improving phosphorus and nitrogen use efficiency in maize: A Kenyan Case Study. *International Journal of Bioresource Science*, *9*, 9–19. https://doi.org/10.30954/2347-9655.01.2022.2

Cheptoek, R. P., Gitari, H. I., Mochoge, B., Kisaka, O. M., Otieno, E., Maitra, S., Nasar, J., & Seleiman, M. F. (2021). Maize productivity, economic returns and phosphorus use efficiency as influenced by lime, minjingu rock phosphate and NPK inorganic fertilizer. *International Journal of Bioresource Science, 08*, 47–60. https://doi.org/10.30954/2347-9655.01.2021.7

Cichota, R., Vogeler, I., Sharp, J., Verburg, K., Huth, N., Holzworth, D., Dalgliesh, N., & Snow, V. (2021). A protocol to build soil descriptions for APSIM simulations. *MethodsX*, *8*, 101566. https://doi.org/10.1016/j.mex.2021.101566

Cook, S., Gichuki, F., & Turral, H. (2018). Water productivity: Measuring and mapping in benchmark basins, basin focal project working paper no. 2, estimation at plot, farm and basin scale (Issue 2).

Cosentino, S. L., Patanè, C., Sanzone, E., Testa, G., & Scordia, D. (2016). Leaf gas exchange , water status and radiation use efficiency of giant reed (*Arundo donax* L.) in a changing soil nitrogen fertilization and soil water availability in a semi-arid Mediterranean area. *European Journal of Agronomy*, *72*, 56–69. https://doi.org/10.1016/j.eja.2015.09.011

Costa, D., Pomeroy, J. W., Brown, T., Baulch, H., Elliott, J., & Macrae, M. (2021). Advances in the simulation of nutrient dynamics in cold climate agricultural basins: Developing new nitrogen and phosphorus modules for the Cold Regions Hydrological Modelling Platform. *Journal of Hydrology*, *603*, 126901. https://doi.org/https://doi.org/10.1016/j.jhydrol.2021.126901

Costa, N. R., Crusciol, C. A. C., Trivelin, P. C. O., Pariz, C. M., Costa, C., Castilhos, A. M., Souza, D. M., Bossolani, J. W., Andreotti, M., Meirelles, P. R. L., Moretti, L. G., & Mariano, E. (2021). Recovery of 15N fertilizer in intercropped maize, grass and legume and residual effect in black oat under tropical conditions. *Agriculture, Ecosystems & Environment*, *310*, 107226. https://doi.org/https://doi.org/10.1016/j.agee.2020.107226

Dahunsi, O. S., Oranusi, S., & Efeovbokhan, E. V. (2017). Anaerobic mono-digestion of Tithonia diversifolia (Wild Mexican sunflower). *Energy Conversion and Management*, *148*, 128–145. https://doi.org/10.1016/j.enconman.2017.05.056

Dai, X., Guo, Q., Song, D., Zhou, W., Liu, G., Liang, G., He, P., Sun, G., Yuan, F., & Liu, Z. (2021). Long-term mineral fertilizer substitution by organic fertilizer and the effect on the abundance and community structure of ammonia-oxidizing archaea and bacteria in paddy soil of south China. *European Journal of Soil Biology*, *103*, 103288. https://doi.org/10.1016/j.ejsobi.2021.103288

Damon, P. M., Bowden, B., Rose, T., & Rengel, Z. (2014). Crop residue contributions to phosphorus pools in agricultural soils: A review. *Soil Biology and Biochemistry*, *74*, 127–137. https://doi.org/10.1016/j.soilbio.2014.03.003

Das, S., Liptzin, D., & Maharjan, B. (2023). Long-term manure application improves soil health and stabilizes carbon in continuous maize production system. *Geoderma*, *430*, 116338. https://doi.org/https://doi.org/10.1016/j.geoderma.2023.116338

Debicka, M., Kocowicz, A., Weber, J., & Jamroz, E. (2016). Organic matter effects on phosphorus sorption in sandy soils. *Archives of Agronomy and Soil Science*, *62*, 840–855. https://doi.org/10.1080/03650340.2015.1083981

Ding, L., & Su, J. (2018). Increased microbial functional diversity under long-term organic and integrated fertilization in a paddy soil. *Applied Microbiology and Biotechnology*, *102*, 1969–1982. https://doi.org/doi.org/10.1007/s00253-017-8704-8

Duncan, E. G., Sullivan, C. A. O., Roper, M. M., Biggs, J. S., & Peoples, M. B. (2018). Influence of co-application of nitrogen with phosphorus, potassium and sulphur on the apparent efficiency of nitrogen fertiliser use , grain yield and protein content of wheat: Review. *Field Crops Research*, *226*, 56–65. https://doi.org/10.1016/j.fcr.2018.07.010

Dunne, K. S., Holden, N. M., & Daly, K. (2021). A management framework for phosphorus use on agricultural soils using sorption criteria and soil test P. *Journal of Environmental Management*, *299*, 113665. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.113665

Dwivedi, B. S., Meena, M. C., & Datta, S. (2019). Effect of phosphorus fertilization and microbial inoculants on yield, phosphorus use-efficiency and available phosphorus in maize (Zea mays) - wheat (Triticum aestivum) cropping system. *Indian Journal of Agricultural Sciences, 89,* 806–812. doi:10.1007/s12517-019-4482-1

Eger, A., Yoo, K., Almond, P. C., Boitt, G., Larsen, I. J., Condron, L. M., Wang, X., & Mudd, S. M. (2018). Does soil erosion rejuvenate the soil phosphorus inventory? *Geoderma*, *332*, 45–59. https://doi.org/10.1016/j.geoderma.2018.06.021

Endris, S. (2019). Combined Application of phosphorus fertilizer with Tithonia biomass improves grain yield and agronomic phosphorus use efficiency of hybrid maize. *International Journal of Agronomy*, *2019*, 1–19. https://doi.org/https://doi.org/10.1155/2019/6167384

Fang, Q., Ma, L., Yu, Q., Ahuja, L. R., Malone, R. W., & Hoogenboom, G. (2010). Irrigation strategies to improve the water use efficiency of wheat–maize double cropping systems in North China Plain. *Agricultural Water Management, 97*, 1164–1173. https://doi.org/10.1016/j.agwat.2009.02.012

Fern, G., Plaza-bonilla, D., & Lampurlan, J. (2021). Nitrogen fertilization strategies for improved Mediterranean rainfed wheat and barley performance and water and nitrogen use efficiency. *European Journal of Agronomy*, *124*, 126238 Contents. https://doi.org/10.1016/j.eja.2021.126238

Fink, J. R., Inda, A. V., Bayer, C., Torrent, J., & Barrón, V. (2014). Mineralogy and phosphorus adsorption in soils of south and central-west Brazil under conventional and no-tillage systems. *Acta Scientiarum - Agronomy*, *36,* 379–387. https://doi.org/10.4025/actasciagron.v36i3.17937

Fink, J. R., Inda, A. V., Bavaresco, J., Barrón, V., Torrent, J., & Bayer, C. (2016). Phosphorus adsorption and desorption in undisturbed samples from subtropical soils under conventional tillage or no-tillage. *Journal of Plant Nutrition and Soil Science, 179,* 198–205. https://doi.org/10.1002/jpln.201500017

Fujita, K., Miyabara, Y., & Kunito, T. (2019). Microbial biomass and ecoenzymatic stoichiometries vary in response to nutrient availability in an arable soil. *European Journal of Soil Biology*, *91*, 1–8. https://doi.org/10.1016/j.ejsobi.2018.12.005

Gaffney, J., Anderson, J., Franks, C., Collinson, S., MacRobert, J., Woldemariam, W., & Albertsen, M. (2016). Robust seed systems, emerging technologies, and hybrid crops for Africa. *Global Food Security*, *9*, 36–44. https://doi.org/10.1016/j.gfs.2016.06.001

Gaind, S., & Pandey, A. K. (2006). Microbial biomass, P-nutrition, and enzymatic activities of wheat soil in response to phosphorus enriched organic and inorganic manures. *Journal of Environmental Science and Health Part B*, *2*, 177–187. https://doi.org/10.1080/03601230500365044

Gao, Y., Duan, A., Qiu, X., Sun, J., & Zhang, J. (2010). Distribution and use efficiency of photosynthetically active radiation in strip intercropping of maize and soybean. *Agronomy Journal*, *102*, 1149–1157. https://doi.org/10.2134/agronj2009.0409

Gao, Y., Liang, A., Zhang, Y., Mclaughlin, N., Zhang, S., Chen, X., Zheng, H., & Fan, R. (2021). Dynamics of Microbial biomass, nitrogen mineralization and crop uptake in response to placement of maize residue returned to chinese mollisols over the maize growing season. *Atmosphere*, *12*, 1166. https://doi.org/ttps://doi.org/10.3390/atmos12091166

Gautam, S., Tiwari, U., Sapkota, B., Sharma, B., Parajuli, S., Pandit, N. R., Gaihre, Y. K., & Dhakal, K. (2022). Field evaluation of slow-release nitrogen fertilizers and real-time nitrogen management tools to improve grain yield and nitrogen use efficiency of spring maize in Nepal. *Heliyon*, *8*, e09566. https://doi.org/https://doi.org/10.1016/j.heliyon.2022.e09566

Gaydon, D. S., Balwinder-Singh, Wang, E., Poulton, P. L., Ahmad, B., Ahmed, F., Akhter, S., Ali, I., Amarasingha, R., Chaki, A. K., Chen, C., Choudhury, B. U., Darai, R., Das, A., Hochman, Z., Horan, H., Hosang, E. Y., Kumar, P. V., Khan, A. S. M. M. R., … Roth, C. H. (2017). Evaluation of the APSIM model in cropping systems of Asia. *Field Crops Research, 204*, 52–75. https://doi.org/10.1016/j.fcr.2016.12.015

Geng, Y., Id, G. C., Wang, L., & Wang, S. (2019). Effects of equal chemical fertilizer substitutions with organic manure on yield , dry matter, and nitrogen uptake of spring maize and soil nitrogen distribution. *PLoS ONE, 14*, 1–16. https://doi.org/doi.org/10.1371/journal.pone.0219512

Ghosh, A., Bhattacharyya, R., Aggarwal, B. K., P., M., D.K., S., Geeta, S., R., A., Ravi, S., C., S., & 1Division. (2018). Long-term fertilization effects on 13^C natural abundance, soil aggregation, and deep soil organic carbon sequestration in an Alfiso. *Land Degradation & Development*, *30*, 391–405. https://doi.org/10.1002/ldr.3229

Ghosh, A., Singh, A. B., Kumar, R. V, Manna, M. C., Bhattacharyya, R., Mahmudur, M., Sharma, P., Rajput, P. S., & Misra, S. (2020). Soil enzymes and microbial elemental stoichiometry as bio-indicators of soil quality in diverse cropping systems and nutrient management practices of Indian Vertisols. *Applied Soil Ecology*, *145*, 103304. https://doi.org/10.1016/j.apsoil.2019.06.007

Gomez-Munoz, B., Larsen, J. D., Bekiaris, G., Scheutz, C., Bruun, S., Nielsen, S., & Jensen, L. S. (2017). Nitrogen mineralisation and greenhouse gas emission from the soil application of sludge from reed bed mineralisation systems. *Journal of Environmental Management*, *203*, 59–67. https://doi.org/10.1016/j.jenvman.2017.07.042

Gong, X., Dang, K., Lv, S., Zhao, G., Wang, H., & Feng, B. (2021). Interspecific competition and nitrogen application alter soil ecoenzymatic stoichiometry, microbial nutrient status, and improve grain yield in broomcorn millet / mung bean intercropping systems. *Field Crops Research*, *270*, 108–227. https://doi.org/10.1016/j.fcr.2021.108227

Guo, J., Feng, H., Roberge, G., Feng, L., Pan, C., McNie, P., & Yu, Y. (2022). The negative effect of Chinese fir (*Cunninghamia lanceolata*) monoculture plantations on soil physicochemical properties, microbial biomass, fungal communities, and enzymatic activities. *Forest Ecology and Management, 519,* 120297. https://doi.org/https://doi.org/10.1016/j.foreco.2022.120297

Guo, L., Wang, C., & Shen, R. F. (2022). Stronger effects of maize rhizosphere than phosphorus fertilization on phosphatase activity and phosphorus-mineralizing-related bacteria in acidic soils. *Rhizosphere*, *23*, 100555. https://doi.org/https://doi.org/10.1016/j.rhisph.2022.100555

Habtegebrial, K., Singh, B. R., & Haile, M. (2007). Impact of tillage and nitrogen fertilization on yield , nitrogen use efficiency of tef (*Eragrostis tef* (Zucc.) Trotter) and soil properties. *Soil & Tillage Research*, *94*, 55–63. https://doi.org/10.1016/j.still.2006.07.002

Hammad, H. M., Abbas, F., Ahmad, A., Farhad, W., Anothai, J., & Hoogenboom, G. (2018). Predicting water and nitrogen requirements for maize under semi-arid conditions using the CSM-CERES-Maize model. *European Journal of Agronomy, 100*, 56–66. https://doi.org/10.1016/j.eja.2017.10.008

Han, J., Dong, Y., & Zhang, M. (2021). Chemical fertilizer reduction with organic fertilizer effectively improve soil fertility and microbial community from newly cultivated land in the Loess Plateau of China. *Applied Soil Ecology*, *165*, 103966. https://doi.org/https://doi.org/10.1016/j.apsoil.2021.103966

Haruna, S. I., Ritchey, E., Mosley, C., & Ku, S. (2023). Effects of cover crops on soil hydraulic properties during commodity crop growing season. *Soil Use and Management*, *39*, 218–231. https://doi.org/10.1111/sum.12803

Hassen, S. (2018). The effect of farmyard manure on the continued and discontinued use of inorganic fertilizer in Ethiopia: An ordered probit analysis. *Land Use Policy, 72*, 523–532. https://doi.org/10.1016/j.landusepol.2018.01.002

He, D., Wang, E., Wang, J., & Robertson, M. J. (2017). Agricultural and Forest Meteorology Data requirement for effective calibration of process-based crop models. *Agricultural and Forest Meteorology*, *234*, 136–148.

https://doi.org/10.1016/j.agrformet.2016.12.015

He, Y., Ding, N., Shi, J., Wu, M., Liao, H., & Xu, J. (2013). Profiling of microbial PLFAs: Implications for interspecific interactions due to intercropping which increase phosphorus uptake in phosphorus limited acidic soils. *Soil Biology and Biochemistry*, *57*, 625–634. https://doi.org/10.1016/j.soilbio.2012.07.027

Hedley, M. J., Stewart, J. W. B., & Chauhan, B. S. (1982). Changes in inorganic and organic soil phosphorus fractions induced by cultivation practices and by laboratory incubations. *Soil Science Society of America Journal*, *46*(5), 970–976. https://doi.org/10.2136/sssaj1982.03615995004600050017x

Hinsinger, P., Betencourt, E., Bernard, L., Brauman, A., Plassard, C., Shen, J., Tang, X., & Zhang, F. (2011). P for two, sharing a scarce resource: Soil phosphorus acquisition in the rhizosphere of intercropped species. *Plant Physiology*, *156*, 1078–1086. https://doi.org/10.1104/pp.111.175331

Holzworth, D., Huth, N. I., Fainges, J., Brown, H., Zurcher, E., Cichota, R., Verrall, S., Herrmann, N. I., Zheng, B., & Snow, V. (2018). APSIM Next Generation: Overcoming challenges in modernising a farming systems model. *Environmental Modelling and Software*, *103*, 43–51. https://doi.org/10.1016/j.envsoft.2018.02.002

Holzworth, D. P., Huth, N. I., DeVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., Chenu, K., van Oosterom, E. J., Snow, V., Murphy, C., Moore, A. D., Brown, H., Whish, J. P., Verrall, S., Fainges, J., Bell, L. W., Peake, A. S., Poulton, P. L., Hochman, Z., Keating, B. A. (2014). APSIM - Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling and Software*, *62*, 327–350. https://doi.org/10.1016/j.envsoft.2014.07.009

Hu, Q., Liu, T., Ding, H., Li, C., Tan, W., Yu, M., Liu, J., & Cao, C. (2023). Effects of nitrogen fertilizer on soil microbial residues and their contribution to soil organic carbon and total nitrogen in a rice-wheat system. *Applied Soil Ecology*, *181*, 104648. https://doi.org/https://doi.org/10.1016/j.apsoil.2022.104648

Hua, W., Luo, P., An, N., Cai, F., Zhang, S., Chen, K., Yang, J., & Han, X. (2020). Manure application increased crop yields by promoting nitrogen use efficiency in the soils of 40-year soybean-maize rotation. *Scientific Reports*, *10*, 1–10. https://doi.org/10.1038/s41598-020-71932-9

Huang, Y., Wang, Q., Zhang, W., Zhu, P., Xiao, Q., Wang, C., Wu, L., Tian, Y., Xu, M., & Gunina, A. (2021). Stoichiometric imbalance of soil carbon and nutrients drives microbial community structure under long-term fertilization. *Applied Soil Ecology*, *168*, 104119. https://doi.org/10.1016/j.apsoil.2021.104119

Huiling, L., Fuyun, G., Hao, S., Peng, Z., Yaying, L., & Huaiying, Y. (2022). Nitrogen distribution and soil microbial community characteristics in a legume-cereal intercropping system: *Agronomy*, *12*, 1900. https://doi.org/https://doi.org/10.3390/agronomy12081900

Hunter, M. C., Smith, R. G., Schipanski, M. E., Atwood, L. W., & Mortensen, D. A. (2017). *Agriculture in 2050 : Recalibrating Targets for Sustainable Intensification*. *67*, 386–391. https://doi.org/10.1093/biosci/bix010

Imani Wa Rusaati, B., Kang, J.-W., Gendusa, P. A., Bisimwa, P. B., Kasali, J. L., Rolly, N. K., Park, J., Rehema, E. M., Masumbuko Ndabaga, C., Kaboyi, G. I., Nankafu, O. N., & Chirimwami, A. B. (2020). Influence of the application of *Tithonia diversifolia* and phosphate rocks on the performances of rainfed rice. *Korean Journal of Agricultural Science*, *5*, 403–414. https://doi.org/10.7744/kjoas.20200029

Israr, M., Suk, H., Ashraful, M., Ji, H., Das, S., & Joo, P. (2019). Short-term effects of different green manure amendments on the composition of main microbial groups and microbial activity of a submerged rice cropping system. *Applied Soil Ecology*, *In press*, 103400. https://doi.org/10.1016/j.apsoil.2019.103400

Jaetzold, R., Schmidt, H., Hornetz, B., & Shisanya, C. (2007). *Farm management Handbook of Kenya. Natural conditions and farm management information. Part C-East Kenya. Subpart C1 - Eastern Province: Vol. II.*

Jalpa, L., Mylavarapu, R. S., Hochmuth, G., Wright, A., & Santen, E. Van. (2021). Recovery efficiency of applied and residual nitrogen fertilizer in tomatoes grown on sandy soils using the 15 N technique. *Scientia Horticulturae*, *278*, 109861. https://doi.org/10.1016/j.scienta.2020.109861

Jenkinson, D. S., & Polvlson, D. S. (1974). The effects of biocidal treatments metabolism in soil: Fumigation with chloroform. *Soil Biology and Biochemistry*, *8*, 167–177.

Jha, P., Hati, K. M., Dalal, R. C., Dang, Y. P., Kopittke, P. M., & Menzies, N. W. (2020). Soil carbon and nitrogen dynamics in a Vertisol following 50 years of no- tillage, crop stubble retention and nitrogen fertilization. *Geoderma*, *358*, 113996. https://doi.org/10.1016/j.geoderma.2019.113996

Jia, T., Liang, X., Guo, T., Wu, T., & Chai, B. (2022). Bacterial community succession and influencing factors for *Imperata cylindrica* litter decomposition in a copper tailings area of China. *Science of The Total Environment*, *815*, 152908. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.152908

Jia, X., Zhong, Y., Liu, J., Zhu, G., Shangguan, Z., & Yan, W. (2020). Effects of nitrogen enrichment on soil microbial characteristics: From biomass to enzyme activities. *Geoderma*, *366*, 114256. https://doi.org/10.1016/j.geoderma.2020.114256

Joan, R., Jos, B., & Xavier, S. F. (2017). Phosphorus mobilization in low-P arable soils may involve soil organic C depletion. *Https://Doi.Org/10.1016/j.Soilbio.2017.06.015*, *113*, 250–259. https://doi.org/10.1016/j.soilbio.2017.06.015

Johnson, M. V. V., Kiniry, J. R., & Burson, B. L. (2010). Ceptometer deployment method affects measurement of fraction of intercepted photosynthetically active radiation. *Agronomy Journal*, *102*, 1132–1137. https://doi.org/10.2134/agronj2009.0478

Jones, D. L., Cooledge, E. C., Hoyle, F. C., Griffiths, R. I., & Murphy, D. V. (2019). pH and exchangeable aluminum are major regulators of microbial energy flow and carbon use efficiency in soil microbial communities. *Soil Biology and Biochemistry*, *138*, 0–4. https://doi.org/10.1016/j.soilbio.2019.107584

Jug, D., Boris, Đ., Birkás, M., Brozovi, B., Lipiec, J., Vukadinovi, V., & Jug, I. (2019). Effect of conservation tillage on crop productivity and nitrogen use efficiency. *Soil & Tillage Research*, *194*, 104327 Contents. https://doi.org/10.1016/j.still.2019.104327

Kabiri, V., Raiesi, F., & Ali, M. (2017). Tillage effects on soil microbial biomass, SOM mineralization and enzyme activity in a semi-arid Calcixerepts. *Agriculture, Ecosystems and Environment*, *232*, 73–84. https://doi.org/10.1016/j.agee.2016.07.022

Kagabo, D. M., Stroosnijder, L., Visser, S. M., & Moore, D. (2013). Soil erosion, soil fertility and crop yield on slow-forming terraces in the highlands of Buberuka, Rwanda. *Soil & Tillage Research*, *128*, 23–29. https://doi.org/10.1016/j.still.2012.11.002

Kakraliya, S. K., Singh, U., Bohra, A., Choudhary, K. K., Kumar, S., & Meena, R. S. (2018). Nitrogen and Legumes: A Meta-analysis. In R. Meena, A. Das, G. Yadav, & R. Lal (Eds.), *Legumes for Soil Health and Sustainable Management* (eds, pp. 978–981). Springer.

Kaur, A., Bedi, S., Gill, G., & Kumar, M. (2012). Effect of nitrogen fertilizers on radiation use efficiency, Crop growth and yield in some maize (*Zea mays* L.) genotypes. *Maydica*, *57*, 75–82. https://journals-crea.4science.it/index.php/maydica/article/view/692

Kaur, G., & Reddy, M. S. (2015). Effects of phosphate-solubilizing bacteria, rock phosphate and chemical fertilizers on maize-wheat cropping cycle and economics. *Pedosphere*, *25*, 428–437. https://doi.org/10.1016/S1002-0160(15)30010-2

Ke, J., He, R., Hou, P., Ding, C., Ding, Y., & Wang, S. (2018). Combined controlled-released nitrogen fertilizers and deep placement e ff ects of N leaching, rice yield and N recovery in machine-transplanted rice. *Agriculture, Ecosystems and*

Environment, *265,* 402–412. https://doi.org/10.1016/j.agee.2018.06.023

Khaembah, E. N., Cichota, R., & Vogeler, I. (2021). Simulation of management strategies to mitigate nitrogen losses from crop rotations in Southland, New Zealand. *Journal of the Science of Food and Agriculture*, *101*, 4241–4249. https://doi.org/10.1002/jsfa.11063

Kheyrodin, H., & Antoun, H. (2011). Tillage and manure effect on soil physical and chemical properties and on carbon and nitrogen mineralization potentials. *African Journal of Biotechnology*, *10,* 9824–9830. doi:10.5897/AJB09.1025

Kiboi, M. N., Ngetich, F. K., Muriuki, A., Adamtey, N., & Mugendi, D. (2020). The response of soil physicochemical properties to tillage and soil fertility resources in Central Highlands of Kenya. *Italian Journal of Agronomy*, *15,* 71–87. https://doi.org/10.4081/ija.2020.1381

Kiboi, M. N., Ngetich, K. F., Diels, J., Mucheru-Muna, M., Mugwe, J., & Mugendi, D. N. (2017). Minimum tillage, tied ridging and mulching for better maize yield and yield stability in the Central Highlands of Kenya. *Soil and Tillage Research*, *170,* 157–166. https://doi.org/10.1016/j.still.2017.04.001

Kiboi, M. N., Ngetich, K. F., Fliessbach, A., Muriuki, A., & Mugendi, D. N. (2019). Soil fertility inputs and tillage influence on maize crop performance and soil water content in the Central Highlands of Kenya. *Agricultural Water Management*, *217,* 316–331. https://doi.org/10.1016/j.agwat.2019.03.014

Kiboi, M. N., Ngetich, K. F., Mugendi, D. N., Muriuki, A., Adamtey, N., & Fliessbach, A. (2018). Microbial biomass and acid phosphomonoesterase activity in soils of the Central Highlands of Kenya. *Geoderma Regional*, *15,* 1–10. https://doi.org/10.1016/j.geodrs.2018.e00193

Kooch, Y., Ehsani, S., & Akbarinia, M. (2019). Stoichiometry of microbial indicators shows clearly more soil responses to land cover changes than absolute microbial activities. *Ecological Engineering*, *131,* 99–106.

https://doi.org/10.1016/j.ecoleng.2019.03.009

Kramer, A. W., Doane, T. A., Horwath, W. R., & Van Kessel, C. (2002). Short-term nitrogen-15 recovery vs. long-term total soil N gains in conventional and alternative cropping systems. *Soil Biology and Biochemistry*, *34*, 43–50. https://doi.org/10.1016/S0038-0717(01)00149-3

Lal, R. (2020). Soil organic matter and water retention. *Agronomy Journal*, *112*, 3265–3277. https://doi.org/10.1002/agj2.20282

Lambano, B. G., Beyene, S., & Abera, G. (2022). Phosphorus sorption characteristics as influenced by major soil units in southern Ethiopia. *Journal of Plant Nutrition and Soil Science*, 486–494. https://doi.org/10.1002/jpln.202200026

Latati, M., Bargaz, A., Belarbi, B., & Lazali, M. (2016). The intercropping common bean with maize improves the rhizobial efficiency , resource use and grain yield under low phosphorus availability. *European Journal of Agronomy, 72,* 80–90. https://doi.org/10.1016/j.eja.2015.09.015

Lazicki, P., Geisseler, D., & Lloyd, M. (2020). Nitrogen mineralization from organic amendments is variable but predictable. *Journal of Environmental Quality*, *49,* 483–495. https://doi.org/10.1002/jeq2.20030

Lemaire, G., Jeuffroy, M. H., & Gastal, F. (2008). Diagnosis tool for plant and crop N status in vegetative stage. Theory and practices for crop N management. *European Journal of Agronomy*, *28,* 614–624. https://doi.org/10.1016/j.eja.2008.01.005

Li, B., Bicknell, K. B., & Renwick, A. (2019). Peak phosphorus, demand trends and implications for the sustainable management of phosphorus in China. *Resources, Conservation and Recycling, 146,* 316–328. https://doi.org/10.1016/j.resconrec.2019.03.033

Li, F., Yu, J., Nong, M., Kang, S., & Zhang, J. (2010). Partial root-zone irrigation enhanced soil enzyme activities and water use of maize under different ratios of inorganic to organic nitrogen fertilizers. *Agricultural Water Management*, *97*, 231–239. https://doi.org/10.1016/j.agwat.2009.09.014

Li, H., & Zhang, X. (2017). A spatial explicit assessment of food security in Africa based on simulated crop production and distribution. *Journal of Cleaner Production*, *147*, 628–636. https://doi.org/10.1016/j.jclepro.2017.01.124

Li, H., Zhang, X., Zhang, X., & Wu, Y. (2018). Utilization benefit of cultivated land and land institution reforms: Economy, society and ecology. *Habitat International*, *77*, 64–70. https://doi.org/10.1016/j.habitatint.2017.12.006

Li, L., & Li, S. (2014). Nitrogen mineralization from animal manures and its relation to organic N fractions. *Journal of Integrative Agriculture*, *13*, 2040–2048. https://doi.org/10.1016/S2095-3119(14)60769-3

Li, N., Lei, W., Sheng, M., Long, J., & Han, Z. (2022). Straw amendment and soil tillage alter soil organic carbon chemical composition and are associated with microbial community structure. *European Journal of Soil Biology*, *110*, 103406. https://doi.org/https://doi.org/10.1016/j.ejsobi.2022.103406

Li, R. H., Li, X. B., Li, G. Q., & Wen, W. Y. (2014). Simulation of soil nitrogen storage of the typical steppe with the DNDC model: A case study in Inner Mongolia, China. *Ecological Indicators*, *41*, 155–164. https://doi.org/10.1016/j.ecolind.2014.01.043

Li, S., Jiang, X., Wang, X., & Wright, A. L. (2015). Tillage effects on soil nitrification and the dynamic changes in nitrifying microorganisms in a subtropical rice-based ecosystem : A long-term field study. *Soil & Tillage Research*, *150*, 132–138. https://doi.org/10.1016/j.still.2015.02.005

Li, W., Liu, Q., Xie, L., & Yin, C. (2023). Interspecific plant-plant interactions increase the soil microbial network stability, shift keystone microbial taxa, and enhance their functions in mixed stands. *Forest Ecology and Management*, *533*, 120851. https://doi.org/https://doi.org/10.1016/j.foreco.2023.120851

Li, X., Ata-UI-Karim, S. T., Li, Y., Yuan, F., Miao, Y., Yoichiro, K., Cheng, T., Tang, L., Tian, X., Liu, X., Tian, Y., Zhu, Y., Cao, W., & Cao, Q. (2022). Advances in the estimations and applications of critical nitrogen dilution curve and nitrogen nutrition index of major cereal crops. A review. *Computers and Electronics in Agriculture*, *197*, 106998. https://doi.org/https://doi.org/10.1016/j.compag.2022.106998

Li, Y., Zhang, Q., Cai, Y., Yang, Q., & Chang, S. X. (2020). Minimum tillage and residue retention increase soil microbial population size and diversity: Implications for conservation tillage. *Science of the Total Environment*, *716*, 137164. https://doi.org/10.1016/j.scitotenv.2020.137164

Lian, J., Wang, H., Deng, Y., Xu, M., Liu, S., Zhou, B., Jangid, K., & Duan, Y. (2022). Impact of long-term application of manure and inorganic fertilizers on common soil bacteria in different soil types. *Agriculture, Ecosystems & Environment*, *337*, 108044. https://doi.org/https://doi.org/10.1016/j.agee.2022.108044

Liang, G., Sun, P., & Waring, B. G. (2022). Nitrogen agronomic efficiency under nitrogen fertilization does not change over time in the long term: Evidence from 477 global studies. *Soil and Tillage Research*, *223*, 105468. https://doi.org/https://doi.org/10.1016/j.still.2022.105468

Liang, J., He, Z., & Shi, W. (2020). Cotton/mung bean intercropping improves crop productivity, water use efficiency, nitrogen uptake, and economic benefits in the arid area of Northwest China. *Agricultural Water Management*, *240*, 106277. https://doi.org/10.1016/j.agwat.2020.106277

Liang, Z., Jin, X., Zhai, P., Zhao, Y., Cai, J., Li, S., Yang, S., Li, C., & Li, C. (2022). Combination of organic fertilizer and slow-release fertilizer increases pineapple yields, agronomic efficiency and reduces greenhouse gas emissions under reduced fertilization conditions in tropical areas. *Journal of Cleaner Production*, *343*, 131054. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.131054

Liao, D., Zhang, C., Lambers, H., & Zhang, F. (2021). Changes in soil phosphorus fractions in response to long-term phosphate fertilization under sole cropping and intercropping of maize and faba bean on a calcareous soil. *Plant and Soil*, *463*, 589–600. https://doi.org/10.1007/s11104-021-04915-y

Liao, D., Zhang, C., Lambers, H., & Zhang, F. (2022). Adding intercropped maize and faba bean root residues increases phosphorus bioavailability in a calcareous soil due to organic phosphorus mineralization. *Plant and Soil*, *476*, 201–218. https://doi.org/10.1007/s11104-022-05309-4

Liao, D., Zhang, C., Li, H., Lambers, H., & Zhang, F. (2020). Changes in soil phosphorus fractions following sole cropped and intercropped maize and faba bean grown on calcareous soil. *Plant and Soil*, *448*, 587–601. https://doi.org/10.1007/s11104-020-04460-0

Liao, X., Zhao, J., Yi, Q., Li, J., Li, Z., Wu, S., Zhang, W., & Wang, K. (2023). Metagenomic insights into the effects of organic and inorganic agricultural managements on soil phosphorus cycling. *Agriculture, Ecosystems & Environment*, *343*, 108281. https://doi.org/https://doi.org/10.1016/j.agee.2022.108281

Liu, P., Guo, X., Zhou, D., Zhang, Q., Ren, X., Wang, R., Wang, X., Chen, X., & Li, J. (2023). Quantify the effect of manure fertilizer addition and optimal nitrogen input on rainfed wheat yield and nitrogen requirement using nitrogen nutrition index. *Agriculture, Ecosystems & Environment*, *345*, 108319. https://doi.org/https://doi.org/10.1016/j.agee.2022.108319

Liu, X. A., Jan, K., Groenigen, V., Dijkstra, P., & Hungate, B. A. (2017). Increased plant uptake of native soil nitrogen following fertilizer addition – not a priming effect ? *Applied Soil Ecology*, *114*, 105–110. https://doi.org/10.1016/j.apsoil.2017.03.011

Liu, X., Dong, W., Jia, S., Liu, Q., Li, Y., Hossain, E., Liu, E., & Kuzyakov, Y. (2021). Transformations of N derived from straw under long-term conventional and no-tillage soils: A 15 N labelling study. *Science of the Total Environment*, *786*, 147428. https://doi.org/10.1016/j.scitotenv.2021.147428

Liu, Z., Rong, Q., Zhou, W., & Liang, G. (2017). Effects of inorganic and organic amendment on soil chemical properties , enzyme activities , microbial community and soil quality in yellow clayey soil. *PLOSONE |*, *6*, 1–20. https://doi.org/10.1371/journal.pone.0172767

Lopes, L. D., & Fernandes, M. F. (2020). Changes in microbial community structure and physiological profile in a kaolinitic tropical soil under different conservation agricultural practices. *Applied Soil Ecology*, *152*, 103545. https://doi.org/10.1016/j.apsoil.2020.103545

Ludwig, B. (2019). Short-Term effect of nitrogen intensification on aggregate size distribution, microbial biomass and enzyme activities in a semi-arid soil under different crop types. *Pedosphere: An International Journal*, *29*, 483–491. https://doi.org/10.1016/S1002-0160(19)60802-7

Luo, G., Li, L., Friman, V., Guo, J., Guo, S., & Shen, Q. (2018). Organic amendments increase crop yields by improving microbe-mediated soil functioning of agroecosystems: A meta-analysis. *Soil Biology and Biochemistry*, *124*, 105–115. https://doi.org/10.1016/j.soilbio.2018.06.002

Luo, H., Yu, J., Li, R., Gu, J.-D., Luo, L., Zhang, Y., He, Y., Xiao, Y., Deng, S., Zhang, Y., Zhang, S., Wang, L., He, J., Deng, O., & Lan, T. (2022). Microbial biomass C:N:P as a better indicator than soil and ecoenzymatic C:N:P for microbial nutrient limitation and C dynamics in Zoige Plateau peatland soils. *International Biodeterioration & Biodegradation*, *175*, 105492. https://doi.org/https://doi.org/10.1016/j.ibiod.2022.105492

Luo, Z., Wang, E., Fillery, I. R. P., Macdonald, L. M., Huth, N., & Baldock, J. (2014). Modelling soil carbon and nitrogen dynamics using measurable and conceptual soil organic matter pools in APSIM. *Agriculture, Ecosystems and Environment*, *186*, 94–104. https://doi.org/10.1016/j.agee.2014.01.019

Ma, Q., Wen, Y., Ma, J., Macdonald, A., Hill, P. W., Chadwick, D. R., Wu, L., & Jones, D. L. (2020). Long-term farmyard manure application affects soil organic phosphorus cycling: A combined metagenomic and 33P/14C labelling study. *Soil*

Biology and Biochemistry, *149*, 107959. https://doi.org/https://doi.org/10.1016/j.soilbio.2020.107959

Ma, Q., Wu, L., Wang, J., Ma, J., Zheng, N., Hill, P. W., Chadwick, D. R., & Jones, D. L. (2018). Fertilizer regime changes the competitive uptake of organic nitrogen by wheat and soil microorganisms: An in-situ uptake test using 13^{C}, 15^{N} labelling, and 13^{C}-PLFA analysis. *Soil Biology and Biochemistry*, *125*, 319–327. https://doi.org/10.1016/j.soilbio.2018.08.009

Macdonald, G. K., Bennett, E. M., Potter, P. A., & Ramankutty, N. (2011). Agronomic phosphorus imbalances across the world' s croplands. *PNAS*, *108*, 3086–3091. https://doi.org/10.1073/pnas.1010808108

Maharjan, M., Maranguit, D., & Kuzyakov, Y. (2018). Phosphorus fractions in subtropical soils depending on land use. *European Journal of Soil Biology*, *87*, 17–24. https://doi.org/10.1016/j.ejsobi.2018.04.002

Mahmood, M., Tian, Y., Ma, Q., Hui, X., Elrys, A. S., Ahmed, W., Mehmood, S., & Wang, Z. (2021). Changes in phosphorus fractions in response to long-term nitrogen fertilization in loess plateau of China. *Field Crops Research*, *270*, 108207. https://doi.org/10.1016/j.fcr.2021.108207

Mahmoud, E., Ibrahim, M., & El-rahman, L. A. (2018). Effects of biochar and phosphorus fertilizers on phosphorus fractions , wheat yield and microbial biomass carbon in vertic torrifluvents. *Communications in Soil Science and Plant Analysis*, *00*, 1–11. https://doi.org/10.1080/00103624.2018.1563103

Mahmud, K., Makaju, S., Ibrahim, R., & Missaoui, A. (2020). Current progress in nitrogen fixing plants and microbiome research. *Plants*, *9*, 1–17. https://doi.org/10.3390/plants9010097

Mangalassery, S., Kalaivanan, D., & Philip, P. S. (2019). Effect of inorganic fertilisers and organic amendments on soil aggregation and biochemical characteristics in a weathered tropical soil. *Soil & Tillage Research*, *187*, 144–151.

https://doi.org/10.1016/j.still.2018.12.008

Månsson, K. F., & Falkengren-Grerup, U. (2003). The effect of nitrogen deposition on nitrification, carbon and nitrogen mineralisation and litter C:N ratios in oak (*Quercus robur* L.) forests. *Forest Ecology and Management*, *179*, 455–467. https://doi.org/10.1016/S0378-1127(02)00535-2

Margenot, A. J., Paul, B. K., Sommer, R. R., Pulleman, M. M., Parikh, S. J., Jackson, L. E., & Fonte, S. J. (2016). Can conservation agriculture improve phosphorus (P) availability in weathered soils ? Effects of tillage and residue management on soil P status after 9 years in a Kenyan Oxisol. *Soil & Tillage Research*, *166*, 157–166. https://doi.org/10.1016/j.still.2016.09.003

Martínez, J. M., Galantini, J. A., Duval, M. E., & López, F. M. (2017). Tillage effects on labile pools of soil organic nitrogen in a semi-humid climate of Argentina: A long-term field study. *Soil & Tillage Research*, *169*, 71–80. https://doi.org/10.1016/j.still.2017.02.001

Marumoto, T. (1984). Mineralization of C and N from microbial biomass in paddy soil. *Plant and Soil*, *76*, 165–173. http://www.jstor.org/stable/42934497

Massawe, P., Mtei, K., Munishi, L., & Ndakidemi, P. (2016). Effect of Rhizobium and intercropping systems on soil nutrients and biological nitrogen fixation as influenced by legumes (*Phaseolus vulgaris* and *Dolichos lablab*). *Life Sciences and Bio-Engineering*, *5*, 135–149. https://doi.org/http://dx.doi.org/10.20546/ijcmas.2016.510.016

Meena, M. D., & Biswas, D. R. (2015). Effect of rock phosphate enriched compost and chemical fertilizers on microbial biomass phosphorus and phosphorus fractions. *African Journal of Microbiology Research*, *9*, 1519–1526. https://doi.org/10.5897/AJMR2014.6957

Mi, W., Sun, Y., Xia, S., Zhao, H., Mi, W., & Brookes, P. C. (2018). Effect of inorganic fertilizers with organic amendments on soil chemical properties and rice yield in a low-productivity paddy soil. *Geoderma*, *320*(August 2016), 23–29. https://doi.org/10.1016/j.geoderma.2018.01.016

Moe, K., Htwe, A. Z., Thi, T., Thu, P., & Kajihara, Y. (2019). Effects on NPK status, growth , dry matter and yield of rice (*Oryza sativa*) by organic fertilizers applied in field condition. *Agriculture, 9,* 1–25. https://doi.org/10.7744/ kjoas.20200029

Received:

Mohanty, M., Probert, M. E., Reddy, K. S., Dalal, R. C., Mishra, A. K., Rao, A. S., Singh, M., & Menzies, N. W. (2012). Simulating soybean – wheat cropping system: APSIM model parameterization and validation. *Agriculture, Ecosystems and Environment, 152,* 68–78. https://doi.org/10.1016/j.agee.2012.02.013

Mohanty, M., Reddy, K. S., Probert, M. E., Dalal, R. C., Rao, A. S., & Menzies, N. W. (2011). Modelling N mineralization from green manure and farmyard manure from a laboratory incubation study. *Ecological Modelling*, *222*, 719–726. https://doi.org/10.1016/j.ecolmodel.2010.10.027

Mohanty, S., Nayak, A. K., Kumar, A., Tripathi, R., Shahid, M., Bhattacharyya, P., Raja, R., & Panda, B. B. (2013). Carbon and nitrogen mineralization kinetics in soil of rice e rice system under long term application of chemical fertilizers and farmyard manure. *European Journal of Soil Biology*, *58*, 113–121. https://doi.org/10.1016/j.ejsobi.2013.07.004

Mohanty, S., Santra, G. H., Rout, P. P., & Mishra, S. (2021). Combined effect of rock phosphate with single super phosphate on yield and phosphorus use efficiency under maize-groundnut cropping sequence in Alfisols of Odisha. *Journal of Environmental Biology, 42,* 1046–1052.

Moharana, P. C., & Biswas, D. R. (2018). Use of mineralization kinetics to estimate the potentially mineralizable nitrogen of rock phosphate-enriched composts-amended soil. *Journal of Plant Nutrition*, *41*, 1333–1344. https://doi.org/10.1080/01904167.2018.1452942

Mooshammer, M., Wanek, W., Zechmeister-boltenstern, S., & Richter, A. (2014). Stoichiometric imbalances between terrestrial decomposer communities and their resources : mechanisms and implications of microbial adaptations to their resources. *Frontiers in Microbiology, 5,* 1–10. https://doi.org/10.3389/fmicb.2014.00022

Morugán-Coronado, A., Pérez-Rodríguez, P., Insolia, E., Soto-Gómez, D., Fernández-Calviño, D., & Zornoza, R. (2022). The impact of crop diversification, tillage and fertilization type on soil total microbial, fungal and bacterial abundance: A worldwide meta-analysis of agricultural sites. *Agriculture, Ecosystems & Environment, 329,* 107867. https://doi.org/https://doi.org/10.1016/j.agee.2022.107867

Mubarak, A., Gali, E. A., Mohamed, A., Steffens, D., & Awadelkarim, A. (2010). Nitrogen mineralization from five manures as influenced by chemical composition and soil type. *Communications in Soil Science and Plant Analysis*, *41*, 37–41. https://doi.org/10.1080/00103624.2010.495802

Mueller, S. M., & Vyn, T. J. (2018). Field Crops Research Physiological constraints to realizing maize grain yield recovery with silking-stage nitrogen fertilizer applications. 228, 102–109. https://doi.org/10.1016/j.fcr.2018.08.025

Mugi-Ngenga, E., Bastiaans, L., Zingore, S., Anten, N. P. R., & Giller, K. E. (2022). The role of nitrogen fixation and crop N dynamics on performance and legacy effects of maize-grain legumes intercrops on smallholder farms in Tanzania. *European Journal of Agronomy*, *141*, 126617. https://doi.org/https://doi.org/10.1016/j.eja.2022.126617

Munir, P., Isselstein, J., Rötter, R. P., & Kayser, M. (2018). Nitrogen management in crop rotations after the break-up of grassland : Insights from modelling. *Agriculture, Ecosystems and Environment, 259,* 28–44. https://doi.org/10.1016/j.agee.2018.02.009

Mupangwa, W., Dimes, J., Walker, S., & Twomlow, S. (2011). Measuring and simulating maize (*Zea mays* L.) yield responses to reduced tillage and mulching under semi-arid conditions. *Agricultural Sciences, 2,* 167–174. https://doi.org/10.4236/as.2011.23023

Mussarat, M., Ali, H., Muhammad, D., Mian, I. A., Khan, S., Adnan, M., Fahad, S., Wahid, F., Dawar, K., Ali, S., Zia, A., Ahmad, M., Khan, S., Shah, W. A., Romman, M., & Parvez, R. (2021). Comparing the phosphorus use efficiency of pre-treated (organically) rock phosphate with soluble P fertilizers in maize under calcareous soils. *PeerJ, 10,* 1–20. https://doi.org/10.7717/peerj.11452

Musyoka, M. W., Adamtey, N., Muriuki, A. W., Bautze, D., Karanja, E. N., Fiaboe, K. K. M., & Cadisch, G. (2018). Nitrogen leaching losses and balances in conventional and organic farming systems of Central Highlands of Kenya. *Nutrient Cycling in Agroecosystems*, *114*, 237–260. https://doi.org/10.1007/s10705-019-10002-7

Musyoka, M. W., Adamtey, N., Muriuki, A. W., & Cadisch, G. (2017). Effect of organic and conventional farming systems on nitrogen use efficiency of potato, maize and vegetables in the Central highlands of Kenya. *European Journal of Agronomy, 86,* 24–36. https://doi.org/10.1016/j.eja.2017.02.005

Nafi, E., Webber, H., Danso, I., Naab, J. B., Frei, M., & Gaiser, T. (2019). Soil tillage, residue management and site interactions affecting nitrogen use efficiency in maize and cotton in the Sudan Savanna of Africa. *Field Crops Research*, *244*, 107629. https://doi.org/10.1016/j.fcr.2019.107629

Naher, U. A., & Biswas, J. C. (2021). Bio-organic fertilizer: A green technology to reduce synthetic N and P fertilizer for rice production. *Frontiers in Plant Science, 12*, 1–14. https://doi.org/10.3389/fpls.2021.602052

Nobile, C. M., Bravin, M. N., Becquer, T., & Paillat, J. M. (2020). Phosphorus sorption and availability in an andosol after a decade of organic or mineral fertilizer applications: Importance of pH and organic carbon modifications in soil as compared to phosphorus accumulation. *Chemosphere, 239,* 124709. https://doi.org/10.1016/j.chemosphere.2019.124709

Noirot-Cosson, P. E., Dhaouadi, K., Etievant, V., Vaudour, E., & Houot, S. (2017). Parameterisation of the NCSOIL model to simulate C and N short-term mineralisation of exogenous organic matter in different soils. *Soil Biology and Biochemistry*, *104*, 128–140. https://doi.org/10.1016/j.soilbio.2016.10.015

Nordblom, T., Gurusinghe, S., Erbacher, A., & Weston, L. A. (2023). Opportunities and Challenges for Cover Cropping in Sustainable Agriculture Systems in Southern Australia. *Agriculture (Switzerland)*, *13*, 688–698. https://doi.org/10.3390/agriculture13030688

Nunes, R. de S., de Sousa, D. M. G., Goedert, W. J., de Oliveira, L. E. Z., Pavinato, P. S., & Pinheiro, T. D. (2020). Distribution of soil phosphorus fractions as a function of long-term soil tillage and phosphate fertilization management. *Frontiers in Earth Science*, *8*, 1–12. https://doi.org/10.3389/feart.2020.00350

Nyawade, S. O., Karanja, N. N., Gachene, C. K. K., & Gitari, H. I. (2019). Intercropping optimizes soil temperature and increases crop water productivity and radiation use efficiency of rainfed potato. *American Journal of Potato Research*, *96*, 457–471. https://doi.org/https://doi.org/10.1007/s12230-019-09737-4

Nyawade, S. O., Karanja, N. N., Gachene, C. K. K., Gitari, H. I., Schulte-Geldermann, E., & Parker, M. (2020). Optimizing soil nitrogen balance in a potato cropping system through legume intercropping. *Nutrient Cycling in Agroecosystems*, *117*, 43–59. https://doi.org/10.1007/s10705-020-10054-0

Nyawade, S. O., Karanja, N. N., Gachene, C. K. K., Gitari, H. I., Schulte-Geldermann, E., & Parker, M. L. (2019). Short-term dynamics of soil organic matter fractions and microbial activity in smallholder potato-legume intercropping systems. *Applied Soil Ecology*, *142*, 123–135. https://doi.org/10.1016/j.apsoil.2019.04.015

Obour, A. K., Mikha, M. M., Holman, J. D., & Stahlman, P. W. (2017). Changes in soil surface chemistry after fifty years of tillage and nitrogen fertilization. *Geoderma*, *308*, 46–53. https://doi.org/10.1016/j.geoderma.2017.08.020

Oduor, N., Kiboi, M. N., Muriuki, A., Adamtey, N., Musafiri, C. M., & Ngetich, F. K. (2021). Soil management strategies enhanced crop yield, soil moisture, and water productivity in Nitisols of the Upper Eastern Kenya. *Environmental Challenges*, *5*(, 100375. https://doi.org/10.1016/j.envc.2021.100375

Ogbazghi, Z. M., Tesfamariam, E. H., & Annandale, J. G. (2016). Modelling N mineralisation from sludge-amended soils across agro-ecological zones: A case study from South Africa. *Ecological Modelling*, *322*, 19–30. https://doi.org/10.1016/j.ecolmodel.2015.11.019

Okalebo, G. & W. (2002). Laboratory methods of soil and plant analysis: a working manual. *Researchgate.Net*, 128.

Okeyo, A. I., Mucheru-muna, M., Mugwe, J., & Ngetich, K. F. (2014). Effects of selected soil and water conservation technologies on nutrient losses and maize yields in the central highlands of Kenya. *Agricultural Water Management*, *137*, 52–58. https://doi.org/DOI: 10.1016/j.agwat.2014.01.014

Oliveira, J. F., de Oliveira, J. C. S., Ruiz, D. B., de Cesare Barbosa, G. M., & Filho, J. T. (2022). Changes in carbon and phosphorus storages and humic substances in a Ferralsol, after tillage and animal manures applications. *Soil and Tillage Research*, *220*, 105358. https://doi.org/https://doi.org/10.1016/j.still.2022.105358

Oliveira, M. F., Barreto-Garcia, P. A. B., da Conceição Júnior, V., Monroe, P. H. M., Gomes, V. de S., & Sousa, J. P. (2022). Changes in microbial biomass and activity of tropical soil submitted to successive Eucalyptus rotations in the semi-arid region of Brazil. *Geoderma Regional*, *29*, e00492. https://doi.org/https://doi.org/10.1016/j.geodrs.2022.e00492

Ordoñez-morales, K. D., Cadena-zapata, M., & Zermeño-gonz, A. (2019). Effect of tillage systems on physical properties of a clay loam soil under Oats. *Agriculture*, *9*, 62. https://doi.org/10.3390/agriculture9030062

Otieno, E., Kipchirchir, F., Kiboi, M. N., & Muriuki, A. (2021). Tillage system and integrated soil fertility inputs improve smallholder farmers' soil fertility and maize productivity in the Central Highlands of Kenya. *Journal of Agriculture and Rural Development in the Tropics and Subtropics, 122,* 159–171. https://doi.org/https://doi.org/10.17170/kobra-202107134319

Otieno, E. O., Mburu, D. M., Ngetich, F. K., Kiboi, M. N., Fliessbach, A., & Lenga, F. K. (2023). Effects of different soil management strategies on fertility and crop productivity in acidic nitisols of Central Highlands of Kenya. *Environmental Challenges, 11,* 100683 Contents. https://doi.org/10.1016/j.envc.2023.100683

Pakhshan, A. D., Maulood, M., & Amin, S. A. (2013). Effect of phosphorus fertilizers on growth and physiological phosphorus use efficiency of three soy bean cultivars. *Journal of Agriculture and Veterinary Science*, *3*, 32–36.

Palmero, F., Fernandez, J. A., Garcia, F. O., Haro, R. J., Prasad, P. V. V., Salvagiotti, F., & Ciampitti, I. A. (2022). A quantitative review into the contributions of biological nitrogen fixation to agricultural systems by grain legumes. *European Journal of Agronomy, 136,* 126514. https://doi.org/https://doi.org/10.1016/j.eja.2022.126514

Panagos, P., Köningner, J., Ballabio, C., Liakos, L., Muntwyler, A., Borrelli, P., & Lugato, E. (2022). Improving the phosphorus budget of European agricultural soils. *Science of the Total Environment*, *853,* 158706. https://doi.org/10.1016/j.scitotenv.2022.158706

Pandiaraj, T., Selvaraj, S., & Ramu, N. (2015). Effects of crop residue management and nitrogen fertilizer on soil nitrogen and carbon content and productivity of wheat (*Triticum aestivum* L.) in two cropping systems. *Journal of Agriculture, Science and Technology*, *17,* 249–260.

Pang, J., Ryan, M. H., Lambers, H., & Siddique, K. H. (2018). Phosphorus acquisition and utilisation in crop legumes under global change. *Current Opinion in Plant Biology*, *45*, 248–254. https://doi.org/10.1016/j.pbi.2018.05.012

Parihar, C. M., & Nayak, H. S. (2019). Soil water dynamics, water productivity and radiation use efficiency of maize under multi-year conservation agriculture during contrasting rainfall events. *Field Crops Research*, *241*, 107570. https://doi.org/10.1016/j.fcr.2019.107570

Parker, G. G. (2020). Tamm review: Leaf Area Index (LAI) is both a determinant and a consequence of important processes in vegetation canopies. *Forest Ecology and Management*, *477*(August). https://doi.org/10.1016/j.foreco.2020.118496

Pavinato, P. S., Dao, T. H., & Rosolem, C. A. (2010). Tillage and phosphorus management effects on enzyme-labile bioactive phosphorus availability in Cerrado Oxisols. *Geoderma*, *156*, 207–215. https://doi.org/10.1016/j.geoderma.2010.02.019

Pavinato, P. S., Merlin, A., & Rosolem, C. A. (2009). Phosphorus fractions in Brazilian Cerrado soils as affected by tillage. *Soil and Tillage Research*, *105*, 149–155. https://doi.org/https://doi.org/10.1016/j.still.2009.07.001

Pavinato, P. S., Rodrigues, M., Soltangheisi, A., Sartor, L. R., & Withers, P. J. A. (2017). Effects of cover crops and phosphorus sources on maize yield, phosphorus uptake, and phosphorus use efficiency. *Agronomy Journal*, *109*, 1039–1047. https://doi.org/10.2134/agronj2016.06.0323

Pecci, L., Grove, J., Miguez, F., & Poffenbarger, H. (2021). Long-term no-till increases soil nitrogen mineralization but does not affect optimal corn nitrogen fertilization practices relative to inversion tillage. *Soil & Tillage Research*, *213*, 105080. https://doi.org/10.1016/j.still.2021.105080

Peng, Y., Duan, Y., Huo, W., Xu, M., Yang, X., Wang, X., Wang, B., Blackwell, M. S. A., & Feng, G. (2021). Soil microbial biomass phosphorus can serve as an index to reflect soil phosphorus fertility. *Biology and Fertility of Soils*, *57*, 671. https://doi.org/10.1007/s00374-021-01563-3

Pereira, L. S., Cordery, I., & Iacovides, I. (2012). Improved indicators of water use performance and productivity for sustainable water conservation and saving. *Agricultural Water Management*, *108*, 39–51.

https://doi.org/10.1016/j.agwat.2011.08.022

Pizzeghello, D., Berti, A., Nardi, S., & Morari, F. (2016). Relationship between soil test phosphorus and phosphorus release to solution in three soils after long-term mineral and manure application. *Agriculture, Ecosystems and Environment*, *233*, 214–223. https://doi.org/10.1016/j.agee.2016.09.015

Pradhan, S., Ghosh, A., Nema, A., Ram, S., & Pal, Y. (2021). Changes in soil phosphorus forms in a long-term cropping system as influenced by fertilization and tillage. *Archives of Agronomy and Soil Science*, *67*, 822–835. https://doi.org/10.1080/03650340.2020.1759800

Pradhan, S. N., Ghosh, A. K., Seema, Ram, S., Pal, Y., & Pradhan, C. (2021). Changes in degree of phosphorus saturation and risk of P loss upon twelve years of manuring and reduced tillage. *Geoderma*, *404*, 115277. https://doi.org/https://doi.org/10.1016/j.geoderma.2021.115277

Qarni, A., Billah, M., Hussain, K., Shah, S. H., Ahmed, W., Alam, S., Sheikh, A. A., Jafri, L., Munir, A., Malik, K. M., & Khan, N. (2021). Isolation and characterization of phosphate solubilizing microbes from rock phosphate mines and their potential effect for sustainable agriculture. *Sustainability*, *13*, 21–51. https://doi.org/https://doi.org/10.3390/su13042151

Qaswar, M., Ahmed, W., Huang, J., Liu, K., Zhang, L., Han, T., Du, J., Ali, S., Ur-rahimM, H., Huang, Q., & Zhang, H. (2022). Interaction of soil microbial communities and phosphorus fractions under long-term fertilization in paddy soil. *Journal of Integrative Agriculture*, *21*, 2134–2144. https://doi.org/https://doi.org/10.1016/S2095-3119(21)63733-4

Qiong, W., Zhen-han, Q. I. N., Wei-wei, Z., Yan-hua, C., Ping, Z. H. U., Chang, P., Shu-xiang, Z., & Colinet, G. (2022). Effect of long-term fertilization on phosphorus fractions in different soil layers and their quantitative relationships with soil properties. *Journal of Integrative Agriculture*, *21*, 2720–2733. https://doi.org/10.1016/j.jia.2022.07.018

Radanielson, A. M., Gaydon, D. S., Li, T., Angeles, O., & Roth, C. H. (2018). Modeling salinity effect on rice growth and grain yield with ORYZA v3 and APSIM-Oryza. *European Journal of Agronomy, 100,* 44–55. https://doi.org/10.1016/j.eja.2018.01.015

Rahman, J. M. M., Rahman, S., Uddin, S., Mumu, N. J., Biswas, C., Jahiruddin, M., Müller, C., & Zaman, M. (2022). Crop residue interactions with fertilizer rate enhances volatilization loss and reduces nitrogen use efficiency in irrigated maize and potato. *Archives of Agronomy and Soil Science, 69,* 1833–1845. https://doi.org/10.1080/03650340.2022.2117303

Raiesi, F., & Kabiri, V. (2017). Carbon and nitrogen mineralization kinetics as affected by tillage systems in a calcareous loam soil. *Ecological Engineering, 106,* 24–34. https://doi.org/https://doi.org/10.1016/j.ecoleng.2017.05.023

Ram, G., Prescher, A., Nendel, C., Ewert, F., Miltin, C., Gaiser, T., & Seidel, S. J. (2018). Approaches to model the impact of tillage implements on soil physical and nutrient properties in different agro-ecosystem models. *Soil & Tillage Research, 180,* 210–221. https://doi.org/10.1016/j.still.2018.03.009

Rao, A. C. S., Smith, J. L., Parr, J. F., & Papendick, R. I. (1992). Considerations in estimating Nitrogen Recovery Efficiency by the difference and isotopic dilution methods. *Fertilizer Research, 33,* 209–217. https://doi.org/10.1007/BF01050876

Raymond, N., Kopittke, P. M., Wang, E., Lester, D., & Bell, M. J. (2021). Does the APSIM model capture soil phosphorus dynamics? A case study with Vertisols. *Field Crops Research, 273,* 108302. https://doi.org/https://doi.org/10.1016/j.fcr.2021.108302

Raza, S., Chen, Z., Ahmed, M., Afzal, M. R., Aziz, T., & Zhou, J. (2019). Dicyandiamide application improved nitrogen use efficiency and decreased nitrogen losses in wheat-maize crop rotation in Loess Plateau. *Archives of Agronomy and Soil Science, 65,* 450–464. https://doi.org/10.1080/03650340.2018.1506584

Rechberger, M. V., Zehetner, F., & Gerzabek, M. H. (2021). Phosphate sorption-desorption properties in volcanic topsoils along a chronosequence and a climatic gradient on the Galápagos Islands. *Journal of Plant Nutrition and Soil Science*, *184*, 479–491. https://doi.org/10.1002/jpln.202000488

Ren, F., Sun, N., Xu, M., Zhang, X., Wu, L., & Xu, M. (2019). Changes in soil microbial biomass with manure application in cropping systems : A meta-analysis. *Soil & Tillage Research*, *194*, 104291. https://doi.org/10.1016/j.still.2019.06.008

Roberts, T. L., & Johnston, A. E. (2015). Phosphorus use efficiency and management in agriculture. *Resources, Conservation & Recycling*, *105*, 275–281. https://doi.org/10.1016/j.resconrec.2015.09.013

Roohi, M., Arif, M. S., Yasmeen, T., Riaz, M., Rizwan, M., Shahzad, S. M., Ali, S., & Bragazza, L. (2020). Effects of cropping system and fertilization regime on soil phosphorous are mediated by rhizosphere-microbial processes in a semi-arid agroecosystem. *Journal of Environmental Management*, *271*, 111033. https://doi.org/10.1016/j.jenvman.2020.111033

Rothé, M., Darnaudery, M., & Thuriès, L. (2019). Organic fertilizers, green manures and mixtures of the two revealed their potential as substitutes for inorganic fertilizers used in pineapple cropping. *Scientia Horticulturae*, *257*, 108691. https://doi.org/10.1016/j.scienta.2019.108691

Rudisill, M. A., Turco, R. F., & Hoagland, L. A. (2016). Fertility practices and rhizosphere effects alter ammonia oxidizer community structure and potential nitri fi cation activity in pepper production soils. *Applied Soil Ecology*, *99*, 70–77. https://doi.org/10.1016/j.apsoil.2015.10.011

Ryan, J., Estefan, G., & Rashid, A. (2001). Soil and Plant Analysis Laboratory Manual. *Soil and Plant Analysis Laboratory Manual*, *1991*, 5–12. http://www.icarda.org/publications/lab_manual/read.htm

Sabahi, H., Veisi, H., & Soufizadeh, S. (2010). Effect of fertilization fystems on foil ficrobial biomass and fineral nitrogen during Canola (*Brassica napus* L.) development stages. *Communications in Soil Science and Plant Analysis*, 37–41. https://doi.org/10.1080/00103624.2010.489132

Salvagiotti, F., Prystupa, P., Ferraris, G., Couretot, L., Magnano, L., Dignani, D., Hernán, F., & Bgutiérrez-boemoem, G. (2017). N : P : S stoichiometry in grains and physiological attributes associated with grain yield in maize as affected by phosphorus and sulfur nutrition. *Field Crops Research*, *203*, 128–138. https://doi.org/10.1016/j.fcr.2016.12.019

Saputra, D. D., Sari, R. R., Sari, I. N., Suprayogo, D., & van Noordwijk, M. (2023). Water repellency by volcanic ash interacting with organic matter: Incubation response and effect on infiltration. *Geoderma*, *436*, 116535. https://doi.org/https://doi.org/10.1016/j.geoderma.2023.116535

Sarabia, M., Cornejo, P., Azcón, R., Carreón-Abud, Y., & Larsen, J. (2017). Mineral phosphorus fertilization modulates interactions between maize, rhizosphere yeasts and arbuscular mycorrhizal fungi. *Rhizosphere*, *4*, 89–93. https://doi.org/10.1016/j.rhisph.2017.09.001

Sawyer, J. E., Woli, K. P., Barker, D. W., & Pantoja, J. L. (2017). Stover removal impact on corn plant biomass, nitrogen, and use effi ciency. *Agronomy, Soil & Environmental Quality*, *109*, 802–810. https://doi.org/10.2134/agronj2016.11.0672

Selles, F., Kochhann, R. A., Denardin, J. E., Zentner, R. P., & Faganello, A. (1997). Distribution of phosphorus fractions in a Brazilian Oxisol under different tillage systems. *Soil & Tillage Research*, *44*, 23–34.

Shafqat, M. N., & Pierzynski, G. M. (2010). Long-term effects of tillage and manure applications on soil phosphorus fractions. *Communications in Soil Science and Plant Analysis*, *41*, 1084–1097. https://doi.org/10.1080/00103621003687174

Shafqat, M. N., & Pierzynski, G. M. (2013). The effect of various sources and dose of phosphorus on residual soil test phosphorus in different soils. *Catena*, *105*, 21–28.

https://doi.org/10.1016/j.catena.2013.01.003

Sharma, S., Kaur, S., Choudhary, O. P., & Singh, M. (2022). Tillage, green manure and residue retention improves aggregate-associated phosphorus fractions under rice–wheat cropping. *Scientific Reports*, *12*, 1–13. https://doi.org/10.1038/s41598-022-11106-x

Shen, J., Yuan, L., Zhang, J., Li, H., Bai, Z., Chen, X., Zhang, W., & Zhang, F. (2011). Phosphorus dynamics: From soil to plant. *Plant Physiology*, *156*, 997–1005. https://doi.org/10.1104/pp.111.175232

Shi, D., Huang, Q., Liu, Z., Liu, T., Su, Z., Guo, S., Bai, F., Sun, S., Lin, X., Li, T., & Yang, X. (2022). Radiation use efficiency and biomass production of maize under optimal growth conditions in Northeast China. *Science of The Total Environment*, *836*, 155574. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.155574

Shi, Y., & Ziadi, N. (2015). Soil Phosphorus Fractions Change in Winter in a Corn-Soybean Rotation with Tillage and Phosphorus Fertilization. *Pedosphere*, *25*, 1–11. https://doi.org/10.1016/S1002-0160(14)60071-0

Shi, Y., Ziadi, N., Hamel, C., Bélanger, G., Abdi, D., Lajeunesse, J., Lafond, J., Lalande, R., & Shang, J. (2020). Soil microbial biomass, activity and community structure as affected by mineral phosphorus fertilization in grasslands. *Applied Soil Ecology*, *146*, 103391. https://doi.org/10.1016/j.apsoil.2019.103391

Shi, Z., Wei, F., Wan, R., Li, Y., Wang, Y., An, W., Qin, K., Dai, G., Cao, Y., Chen, X., Wang, X., & Yang, L. (2022). Comprehensive evaluation of nitrogen use efficiency of different Lycium barbarum L. cultivars under nitrogen stress. *Scientia Horticulturae*, *295*, 110807. https://doi.org/https://doi.org/10.1016/j.scienta.2021.110807

Shrestha, P., Gautam, R., & Ashwath, N. (2019). Effects of agronomic treatments on functional diversity of soil microbial community and microbial activity in a revegetated coal mine spoil. *Geoderma*, *338*, 40–47.

https://doi.org/10.1016/j.geoderma.2018.11.038

Singh, G., Walia, S. S., & Singh, S. (2017). Effect of integrated nutrient management on agroclimatic environment and yield of baby corn (*Zea mays* L.) in Punjab , India., *No. 4 Journal of Agrometeorology*, *19*, 9–12.

Skudra, I., & Ruza, A. (2017). Effect of nitrogen and sulphur fertilization on chlorophyll content in winter wheat. *Rural Sustainability Research, 37,* 23–55. https://doi.org/10.1515/plua-2017-0004

Smith, C. J., MacDonald, B. C. T., Xing, H., Denmead, O. T., Wang, E., McLachlan, G., Tuomi, S., Turner, D., & Chen, D. (2019). Measurements and APSIM modelling of soil C and N dynamics. *Soil Research*, *58*, 41–61. https://doi.org/10.1071/SR19021

Soltangheisi, A., Rodrigues, M., Coelho, M. J. A., Gasperini, A. M., Sartor, L. R., & Pavinato, P. S. (2018). Changes in soil phosphorus lability promoted by phosphate sources and cover crops. *Soil and Tillage Research, 179,* 20–28. https://doi.org/10.1016/j.still.2018.01.006

Somavilla, A., Caner, L., Bortoluzzi, E. C., Santanna, M. A., & Rheinheimer dos Santos, D. (2021). P-legacy effect of soluble fertilizer added with limestone and phosphate rock on grassland soil in subtropical climate region. *Soil and Tillage Research*, *211*, 105021. https://doi.org/10.1016/j.still.2021.105021

Song, C., Kyei, C., Zhang, X., Wang, W., Wang, L., Gan, Y., Yong, T., Chang, X., Wang, Y., & Yang, W. (2021). Mycorrhizosphere bacteria and plant-plant interactions facilitate maize P acquisition in an intercropping system. *Journal of Cleaner Production, 314,* 127993. https://doi.org/10.1016/j.jclepro.2021.127993

Song, D., Dai, X., Guo, T., Cui, J., Zhou, W., Huang, S., Shen, J., Liang, G., He, P., Wang, X., & Zhang, S. (2022). Organic amendment regulates soil microbial biomass and activity in wheat-maize and wheat-soybean rotation systems. *Agriculture, Ecosystems & Environment*, *333*, 107974. https://doi.org/https://doi.org/10.1016/j.agee.2022.107974

Song, L., Wang, J., Pan, J., Yan, Y., & Niu, S. (2022). Chronic nitrogen enrichment decreases soil gross nitrogen mineralization by acidification in topsoil but by carbon limitation in subsoil. *Geoderma*, *428,* 116159. https://doi.org/https://doi.org/10.1016/j.geoderma.2022.116159

Song, Q., Ouyang, M., & Yang, Q. (2016). Degradation of litter quality and decline of soil nitrogen mineralization after moso bamboo (*Phyllostachys pubscens*) expansion to neighboring broadleaved forest in subtropical China. *Plant and Soil*, *404*, 113–124. https://doi.org/10.1007/s11104-016-2835-z

Soufizadeh, S., Munaro, E., McLean, G., Massignam, A., van Oosterom, E. J., Chapman, S. C., Messina, C., Cooper, M., & Hammer, G. L. (2018). Modelling the nitrogen dynamics of maize crops – Enhancing the APSIM maize model. *European Journal of Agronomy*, *100*, 118–131. https://doi.org/10.1016/j.eja.2017.12.007

Spohn, M., Zavišić, A., Nassal, P., Bergkemper, F., Schulz, S., Marhan, S., Schloter, M., Kandeler, E., & Polle, A. (2018). Temporal variations of phosphorus uptake by soil microbial biomass and young beech trees in two forest soils with contrasting phosphorus stocks. *Soil Biology and Biochemistry*, *117*, 191–202. https://doi.org/10.1016/j.soilbio.2017.10.019

Su, W., Ahmad, S., Ahmad, I., & Han, Q. (2020). Nitrogen fertilization affects maize grain yield through regulating nitrogen uptake, radiation and water use efficiency, photosynthesis and root distribution. *PeerJ*, *8*, 1–21. https://doi.org/10.7717/peerj.10291

Sun, D., Yang, X., Wang, C., Hao, X., Hong, J., & Lin, X. (2019). Dynamics of available and enzymatically hydrolysable soil phosphorus fractions during repeated freeze-thaw cycles. *Geoderma*, *345*, 1–4. https://doi.org/10.1016/j.geoderma.2019.03.009

Sun, Q., Wang, R., Wang, Y., Du, L., Zhao, M., Gao, X., & Hu, Y. (2018). Temperature sensitivity of soil respiration to nitrogen and phosphorous fertilization: Does soil initial fertility matter? *Geoderma*, *325*, 172–182. https://doi.org/10.1016/j.geoderma.2018.04.001

Sun, W., Villamil, M. B., Behnke, G. D., & Margenot, A. J. (2022). Long-term effects of crop rotation and nitrogen fertilization on phosphorus cycling and balances in loess-derived Mollisols. *Geoderma, 420,* 115829. https://doi.org/https://doi.org/10.1016/j.geoderma.2022.115829

Susanne, J. M. M., & Tabatabai, K. M. A. (2017). Soil microbial biomass carbon and nitrogen as affected by cropping systems. *Biology and Fertility of Soils*, *31,* 200–210. https://doi.org/10.1007/s003740050646

Szulc, P., Bocianowski, J., Nowosad, K., Bujak, H., Zielewicz, W., & Stachowiak, B. (2021). Effects of NP fertilizer placement depth by year interaction on the number of maize (*Zea mays* L.) plants after emergence using the additive main effects and multiplicative interaction model. *Agronomy*, *11*, 1543–1569.

Tang, H. (2021). Effect of different short - term tillage management on nitrogen - fixing bacteria community in a double - cropping paddy field of southern China. *Journal of Basic Microbiology*, *61*, 241–252. https://doi.org/10.1002/jobm.202000608

Tang, H., Cheng, K., Shi, L., Li, C., Wen, L., Li, W., Sun, M., Sun, G., & Long, Z. (2022). Effects of long-term organic matter application on soil carbon accumulation and nitrogen use efficiency in a double-cropping rice field. *Environmental Research*, *213*, 113700. https://doi.org/https://doi.org/10.1016/j.envres.2022.113700

Tang, X., Zhang, C., & Yu, Y. (2020). Intercropping legumes and cereals increases phosphorus use efficiency; a meta-analysis. *Plant Soil*, *460*, 89–104.

Tao, R., Wakelin, S. A., Liang, Y., & Chu, G. (2017). Response of ammonia-oxidizing archaea and bacteria in calcareous soil to mineral and organic fertilizer application and their relative contribution to nitrification. *Soil Biology and Biochemistry*, *114,* 20–30. https://doi.org/10.1016/j.soilbio.2017.06.027

Tapiwa, L., Nyari, P., & Mnkeni, S. (2018). Vermicomposting manure- paper mixture with igneous rock phosphate enhances biodegradation , phosphorus bioavailability and reduces heavy metal concentrations. *Heliyon*, *4*, e00749.

https://doi.org/10.1016/j.heliyon.2018.e00749

Tariq, A., Sardans, J., Peñuelas, J., Zhang, Z., Graciano, C., Zeng, F., Olatunji, O. A., Ullah, A., & Pan, K. (2022). Intercropping of leguminous and non-leguminous desert plant species does not facilitate phosphorus mineralization and plant nutrition. *Cells*, *11*, 998–1110. https://doi.org/10.3390/cells11060998

Tasmeea, T., Roy, B. B., Chowdhury, R. B., Hossain, M. M., & Sujauddin, M. (2021). Urban metabolism of phosphorus in the food production-consumption system of Bangladesh. *Journal of Environmental Management*, *292*, 112715. https://doi.org/10.1016/j.jenvman.2021.112715

Tayyab, M., Id, W. I., Arafat, Y., Pang, Z., & Zhang, C. (2018). Effect of sugarcane straw and goat manure on soil nutrient transformation and bacterial communities. *Sustainability*, *10*, 1–21. https://doi.org/10.3390/su10072361

Teixeira, E. I., George, M., Herreman, T., Brown, H., Fletcher, A., Chakwizira, E., Ruiter, J. De, Maley, S., & Noble, A. (2014). The impact of water and nitrogen limitation on maize biomass and resource-use efficiencies for radiation , water and nitrogen. *Field Crops Research*, *168*, 109–118. https://doi.org/10.1016/j.fcr.2014.08.002

Thapa, V. R., Ghimire, R., Paye, W. S., & VanLeeuwen, D. (2023). Soil organic carbon and nitrogen responses to occasional tillage in a continuous no-tillage system. *Soil and Tillage Research*, *227*, 105619. https://doi.org/https://doi.org/10.1016/j.still.2022.105619

Thomas, M., Job, P., Souza, J. L., Oliveira, J. R., Thomas, M., & Job, P. (2022). Changes in inorganic phosphorus fractions in weathered soils under long-term intensive cultivation and irrigation under long-term intensive cultivation and irrigation. *Archives of Agronomy and Soil Science*, *00*, 1–16. https://doi.org/10.1080/03650340.2022.2070160

Tian, J., Pausch, J., Yu, G., Blagodatskaya, E., & Kuzyakov, Y. (2016). Aggregate size and glucose level affect priming sources : A three- source-partitioning study. *Soil*

Biology and Biochemistry, *97*, 199–210. https://doi.org/10.1016/j.soilbio.2016.03.013

Tiecher, T., Gomes, M. V., Ambrosini, V. G., Amorim, M. B., & Bayer, C. (2018). Assessing linkage between soil phosphorus forms in contrasting tillage systems by path analysis. *Soil and Tillage Research*, *175*, 276–280. https://doi.org/10.1016/j.still.2017.09.015

Tongma, S., & Kobayashi, K. (2019). Allelopathic activity of Mexican sunflower (*Tithonia diversifolia*) in soil Materials and Methods. *Weed Science*, *46*, 432–437.

Umar, W., Ayub, M. A., Rehman, M. Z. ur, Ahmad, H. R., Farooqi, Z. U. R., Shahzad, A., Rehman, U., Mustafa, A., & Nadeem, M. (2020). Nitrogen and phosphorus use efficiency in agroecosystems bt - resources use efficiency in agriculture. In S. Kumar, R. S. Meena, & M. K. Jhariya (Eds.), *Resources Use Efficiency in Agriculture* (eds, pp. 213–257). Springer Singapore. https://doi.org/10.1007/978-981-15-6953-1_7

USAID. (2014). Kenya: Nutrition Profile. In *United States Agency for International Development* (Issue June 2014).

Uwah, D. F., & Eyo, V. E. (2014). Effects of number and rate of goat manure application on soil properties , growth and yield of sweet maize (*Zea mays* L . *saccharata Strut*). *Sustainable Agriculture Research*, *3*, 75–83. https://doi.org/10.5539/sar.v3n4p75

Vanlauwe, B., Descheemaeker, K., Giller, K. E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., & Zingore, S. (2015). Integrated soil fertility management in sub-Saharan Africa: Unravelling local adaptation. *Soil*, *1*, 491–508. https://doi.org/10.5194/soil-1-491-2015

Vazquez, E., Benito, M., Espejo, R., & Teutscherova, N. (2019). Effects of no-tillage and liming amendment combination on soil carbon and nitrogen mineralization. *European Journal of Soil Biology*, *93*, 103090. https://doi.org/10.1016/j.ejsobi.2019.103090

Venterea, R. T., Clough, T. J., Coulter, J. A., Souza, E. F. C., Breuillin-Sessoms, F., Spokas, K. A., Sadowsky, M. J., Gupta, S. K., & Bronson, K. F. (2021). Temperature alters dicyandiamide (DCD) efficacy for multiple reactive nitrogen species in urea-amended soils: Experiments and modeling. *Soil Biology and Biochemistry*, *160*, 108341. https://doi.org/10.1016/j.soilbio.2021.108341

Vogeler, I., Cichota, R., Thomsen, I. K., Bruun, S., Stoumann, L., & Pullens, J. W. M. (2019). Estimating nitrogen release from Brassica catch crop residues-Comparison of different approaches within the APSIM model. *Soil & Tillage Research*, *195*, 104358. https://doi.org/10.1016/j.still.2019.104358

Wallenstein, M. D., & Hall, E. K. (2012). A trait-based framework for predicting when and where microbial adaptation to climate change will affect ecosystem functioning. *Biogeochemistry*, 35–47. https://doi.org/10.1007/s10533-011-9641-8

Wan, P., He, R., Wang, P., & Cao, A. (2022). Implementation of different forest management methods in a natural forest: Changes in soil microbial biomass and enzyme activities. *Forest Ecology and Management*, *520*, 120409. https://doi.org/https://doi.org/10.1016/j.foreco.2022.120409

Wang, C., Liu, D., & Bai, E. (2018). Decreasing soil microbial diversity is associated with decreasing microbial biomass under nitrogen addition. *Soil Biology and Biochemistry*, *120*, 126–133. https://doi.org/10.1016/j.soilbio.2018.02.003

Wang, C., Qu, L., Yang, L., Liu, D., Morrissey, E., Miao, R., Liu, Z., Wang, Q., Fang, Y., & Bai, E. (2020). Large-scale importance of microbial carbon use efficiency and necromass to soil.pdf. *Blobal Change Biology*, *27*, 2039–2048. https://doi.org/DOI: 10.1111/gcb.15550

Wang, G., Huang, W., Zhou, G., Mayes, M. A., & Zhou, J. (2020). Modeling the processes of soil moisture in regulating microbial and carbon-nitrogen cycling. *Journal of Hydrology*, *585*, 124777. https://doi.org/10.1016/j.jhydrol.2020.124777

Wang, H., Wu, L., Cheng, M., Fan, J., Zhang, F., Zou, Y., Wai, H., Gao, Z., & Wang, X.

(2018). Coupling effects of water and fertilizer on yield , water and fertilizer use efficiency of drip-fertigated cotton in northern Xinjiang , China. *Field Crops Research*, *219*, 169–179. https://doi.org/10.1016/j.fcr.2018.02.002

Wang, H., Yang, A., Yang, G., Zhao, H., Xie, F., Zhang, H., Wang, H., & Ao, X. (2021). Screening and identification of soybean varieties with high phosphorus efficiency at seedling stage. *Oil Crop Science*, *6*, 41–49. https://doi.org/10.1016/j.ocsci.2021.03.001

Wang, J., Chadwick, D. R., Cheng, Y., & Yan, X. (2018). Global analysis of agricultural soil denitrification in response to fertilizer nitrogen. *Science of the Total Environment*, *616–617*, 908–917. https://doi.org/10.1016/j.scitotenv.2017.10.229

Wang, K., Ren, T., Yan, J., Zhu, D., Liao, S., Zhang, Y., Lu, Z., Cong, R., Li, X., & Lu, J. (2022). Straw returning mediates soil microbial biomass carbon and phosphorus turnover to enhance soil phosphorus availability in a rice-oilseed rape rotation with different soil phosphorus levels. *Agriculture, Ecosystems & Environment*, *335*, 107991. https://doi.org/https://doi.org/10.1016/j.agee.2022.107991

Wang, Q., Sun, D., Hao, H., Zhao, X., & Hao, W. (2015). Photosynthetically active radiation determining yields for an intercrop of maize with cabbage. *European Journal of Agronomy*, *69*, 32–40. https://doi.org/10.1016/j.eja.2015.05.004

Wang, X., Deng, X., Pu, T., Song, C., Yong, T., Yang, F., Sun, X., Liu, W., Yan, Y., Du, J., Liu, J., Su, K., & Yang, W. (2017). Contribution of interspecific interactions and phosphorus application to increasing soil phosphorus availability in relay intercropping systems. *Field Crops Research*, *204*, 12–22. https://doi.org/10.1016/j.fcr.2016.12.020

Wang, X., Fan, J., Xing, Y., Xu, G., Wang, H., Deng, J., Wang, Y., Zhang, F., Li, P., & Li, Z. (2019). The Effects of Mulch and Nitrogen Fertilizer on the Soil Environment of Crop Plants. In *Advances in Agronomy* (1st ed., Vol. 153). Elsevier Inc. https://doi.org/10.1016/bs.agron.2018.08.003

Wang, Y., Li, C., Tu, C., Hoyt, G. D., DeForest, J. L., & Hu, S. (2017). Long-term no-tillage and organic input management enhanced the diversity and stability of soil microbial community. *Science of the Total Environment*, *609*, 341–347. https://doi.org/10.1016/j.scitotenv.2017.07.053

Wang, Y., Zhang, Y., Zhang, H., Yang, Z., Zhu, Q., Yan, B., Fei, J., Rong, X., Peng, J., & Luo, G. (2022). Intercropping-driven nitrogen trade-off enhances maize productivity in a long-term experiment. *Field Crops Research*, *287*, 108671. https://doi.org/https://doi.org/10.1016/j.fcr.2022.108671

Wang, Z., Zhao, M., Yan, Z., Yang, Y., Niklas, K. J., Huang, H., Donko Mipam, T., He, X., Hu, H., & Joseph Wright, S. (2022). Global patterns and predictors of soil microbial biomass carbon, nitrogen, and phosphorus in terrestrial ecosystems. *CATENA*, *211*, 106037. https://doi.org/https://doi.org/10.1016/j.catena.2022.106037

Wanjiku, K. J., Biber-Freudenberger, L., Lamers, J. P. A., Stellmacher, T., & Borgemeister, C. (2019). Soil fertility and biodiversity on organic and conventional smallholder farms in Kenya. *Applied Soil Ecology*, *134*, 85–97. https://doi.org/10.1016/j.apsoil.2018.10.020

Wei, L., Chen, S., Cui, J., Ping, H., Yuan, C., & Chen, Q. (2022). A meta-analysis of arable soil phosphorus pools response to manure application as influenced by manure types, soil properties, and climate. *Journal of Environmental Management*, *313*, 115006. https://doi.org/https://doi.org/10.1016/j.jenvman.2022.115006

Wei, Y., Zhao, Y., Shi, M., Cao, Z., Lu, Q., & Yang, T. (2017). Effect of organic acids production and bacterial community on the possible mechanism of phosphorus solubilization during composting with enriched phosphate-solubilizing bacteria inoculation. *Bioresource Technology*, *2*, 20–37. https://doi.org/10.1016/j.biortech.2017.09.092

Werner, F., Mueller, C. W., Thieme, J., Gianoncelli, A., Höschen, C., & Prietzel, J. (2017). Micro-scale heterogeneity of soil phosphorus depends on soil substrate and depth. In *Scienntific Reports* (Vol. 7). https://doi.org/10.1038/s41598-017-03537-8

Willy, D. K., Muyanga, M., Mbuvi, J., & Jayne, T. (2019). The effect of land use change on soil fertility parameters in densely populated areas of Kenya. *Geoderma*, *343*, 254–262. https://doi.org/10.1016/j.geoderma.2019.02.033

Wu, H., Cai, A., Xing, T., Huai, S., Zhu, P., Xu, M., & Lu, C. (2021). Fertilization enhances mineralization of soil carbon and nitrogen pools by regulating the bacterial community and biomass. *Journal of Soils and Sediments*, *21*, 1633–1643. https://doi.org/10.1007/s11368-020-02865-z

Wu, Q., Zhou, W., Chen, D., Cai, A., Ao, J., & Huang, Z. (2020). Optimizing soil and fertilizer phosphorus management according to the yield response and phosphorus use efficiency of sugarcane in Southern China. *Journal of Soil Science and Plant Nutrition, 20,* 1655–1664.

Wu, W., Wu, J., Liu, X., Chen, X., Wu, Y., & Yu, S. (2017). Inorganic phosphorus fertilizer ameliorates maize growth by reducing metal uptake, improving soil enzyme activity and microbial community structure. *Ecotoxicology and Environmental Safety*, *143*, 322–329. https://doi.org/10.1016/j.ecoenv.2017.05.039

Wu, Y., He, D., Wang, E., Liu, X., Huth, N. I., Zhao, Z., Gong, W., Yang, F., Wang, X., Yong, T., Liu, J., Liu, W., Du, J., Pu, T., Liu, C., Yu, L., van der Werf, W., & Yang, W. (2021). Modelling soybean and maize growth and grain yield in strip intercropping systems with different row configurations. *Field Crops Research*, *265*, 108122. https://doi.org/10.1016/j.fcr.2021.108122

Wyngaard, N., Echeverria, H. E., Sainz-Roazas, H. R., & Divito, G. A. (2012). Fertilization and tillage effects on soil properties and maize yield in a Southern Pampas Argiudoll. *Soil & Tillage Research*, *119*, 22–30. https://doi.org/10.1016/j.still.2011.12.002

Xiao, S., Ye, Y., Xiao, D., Chen, W., & Zhang, W. (2019). Effects of tillage on soil N availability , aggregate size , and microbial biomass in a subtropical karst region.

Soil & Tillage Research, *192*, 187–195. https://doi.org/10.1016/j.still.2019.05.006

Xie, C., Yan, L., Liang, A., Jiang, R., Man, Z., & Che, S. (2022). Seasonal and spatial characterisation of soil properties, nitrification and denitrification at the urban river-riparian interface with permeable revetments. *Applied Soil Ecology*, *173*, 104372. https://doi.org/https://doi.org/10.1016/j.apsoil.2021.104372

Xin, X., Qin, S., Zhang, J., Zhu, A., Yang, W., & Zhang, X. (2017). Yield, phosphorus use efficiency and balance response to substituting longterm chemical fertilizer use with organic manure in a wheat-maize system. *Field Crops Research*, *208*, 27–33. https://doi.org/10.1016/j.fcr.2017.03.011

Xu, G., Ren, Y., Yue, M., Lv, Y., Chen, X., & Hui, H. (2022). Phosphorus sorption capacity in soils from freshwater restored coastal wetlands increased with restoration age. *Geoderma*, *422*, 115926. https://doi.org/https://doi.org/10.1016/j.geoderma.2022.115926

Xu, H., Zhang, H., Fan, Y., Wang, R., Cui, R., Liu, X., Chu, S., Jiao, Y., Zhang, X., & Zhang, D. (2022). The purple acid phosphatase GmPAP17 predominantly enhances phosphorus use efficiency in soybean. *Plant Science*, *320*, 111283. https://doi.org/https://doi.org/10.1016/j.plantsci.2022.111283

Xu, P., Gao, Y., Cui, Z., Wu, B., Yan, B., Wang, Y., Wen, M., Wang, H., Ma, X., & Wen, Z. (2023). Application of organic fertilizers optimizes water consumption characteristics and improves seed yield of Oilseed Flax in semi-arid areas of the Loess Plateau. *Agronomy*, *13*, 1755. https://doi.org/10.3390/agronomy13071755

Xu, S., & Arai, Y. (2022). Competitive sorption and accumulation of organic phosphorus in phosphate-rich soils and sediments. In D. L. B. T.-A. in A. Sparks (Ed.), *Advances in Agronomy* (eds, Vol. 173, pp. 337–374). Academic Press. https://doi.org/https://doi.org/10.1016/bs.agron.2022.02.006

Xu, Y., & Qiu, W. (2018). Effects of wheat/faba bean intercropping on soil nitrogen transformation processes. *Journal of Soils and Sediments*, *19*, 724–1734.

Xu, Z., Li, C., Zhang, C., Yu, Y., van der Werf, W., & Zhang, F. (2020). Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use; A meta-analysis. *Field Crops Research*, *246*, 107661. https://doi.org/10.1016/j.fcr.2019.107661

Yan, S., Wu, Y., Fan, J., Zhang, F., Guo, J., Zheng, J., Wu, L., & Lu, J. (2022). Quantifying nutrient stoichiometry and radiation use efficiency of two maize cultivars under various water and fertilizer management practices in northwest China. *Agricultural Water Management*, *271*, 107772. https://doi.org/https://doi.org/10.1016/j.agwat.2022.107772

Yan, X., Wei, Z., Hong, Q., Lu, Z., & Wu, J. (2017). Phosphorus fractions and sorption characteristics in a subtropical paddy soil as influenced by fertilizer sources. *Geoderma*, *295*, 80–85. https://doi.org/10.1016/j.geoderma.2017.02.012

Yan, Y., Wang, C., Zhang, J., Sun, Y., Xu, X., Zhu, N., Cai, Y., Xu, D., Wang, X., Xin, X., & Chen, J. (2022). Response of soil microbial biomass C, N, and P and microbial quotient to agriculture and agricultural abandonment in a meadow steppe of northeast China. *Soil and Tillage Research*, *223*, 105475. https://doi.org/https://doi.org/10.1016/j.still.2022.105475

Yang, F., Liao, D., Wu, X., Gao, R., Fan, Y., Raza, M. A., Wang, X., Yong, T., Liu, W., Liu, J., Du, J., Shu, K., & Yang, W. (2017). Effect of aboveground and belowground interactions on the intercrop yields in maize-soybean relay intercropping systems. *Field Crops Research*, *203*, 16–23. https://doi.org/10.1016/j.fcr.2016.12.007

Yang, H., Li, J., Wu, G., Huang, X., & Fan, G. (2023). Maize straw mulching with no-tillage increases fertile spike and grain yield of dryland wheat by regulating root-soil interaction and nitrogen nutrition. *Soil and Tillage Research*, *228*, 105652. https://doi.org/https://doi.org/10.1016/j.still.2023.105652

Yang, H., Wu, G., Mo, P., Chen, S., Wang, S., Xiao, Y., Wen, T., Guo, X., & Fan, G. (2020). The combined effects of maize straw mulch and no-tillage on grain yield and water and nitrogen use efficiency of dry-land winter wheat (*Triticum aestivum*

L.). *Soil & Tillage Research, 197*, 104485 Contents. https://doi.org/10.1016/j.still.2019.104485

Yang, J., Yang, W., Wang, F., Zhang, L., Zhou, B., Sarfraz, R., & Xing, S. (2020). Driving factors of soluble organic nitrogen dynamics in paddy soils: Structure equation modeling analysis. *Pedosphere, 30*, 801–809. https://doi.org/10.1016/S1002-0160(18)60032-3

Yang, L., Muhammad, I., Chi, Y. X., Liu, Y. X., Wang, G. Y., Wang, Y., & Zhou, X. B. (2022). Straw return and nitrogen fertilization regulate soil greenhouse gas emissions and global warming potential in dual maize cropping system. *Science of The Total Environment*, *853*, 158370. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.158370

Yang, X., Chen, X., & Yang, X. (2019). Effect of organic matter on phosphorus adsorption and desorption in a black soil from Northeast China. *Soil and Tillage Research*, *187*, 85–91. https://doi.org/10.1016/j.still.2018.11.016

Yang, X., Li, Z., & Cheng, C. (2017). Effect of conservation tillage practices on soil phosphorus nutrition in an apple orchard. *Horticultural Plant Journal*, *2*, 331–337. https://doi.org/10.1016/j.hpj.2016.11.005

Yang, X., Zheng, L., Yang, Q., Wang, Z., Cui, S., & Shen, Y. (2018). Modelling the effects of conservation tillage on crop water productivity, soil water dynamics and evapotranspiration of a maize-winter wheat-soybean rotation system on the Loess Plateau of China using APSIM. *Agricultural Systems*, *166*, 111–123. https://doi.org/10.1016/j.agsy.2018.08.005

Yang, Y., Dou, Y., Wang, B., Wang, Y., Liang, C., An, S., Soromotin, A., & Kuzyakov, Y. (2022). Increasing contribution of microbial residues to soil organic carbon in grassland restoration chronosequence. *Soil Biology and Biochemistry*, *170*, 108688. https://doi.org/https://doi.org/10.1016/j.soilbio.2022.108688

Yang, Z., Zhang, Y., Wang, Y., Zhang, H., Zhu, Q., Yan, B., Fei, J., Xiangmin, R., Peng, J., & Luo, G. (2022). Intercropping regulation of soil phosphorus composition and microbially-driven dynamics facilitates maize phosphorus uptake and productivity improvement. *Field Crops Research*, *287*, 108666. https://doi.org/https://doi.org/10.1016/j.fcr.2022.108666

Yousaf, M., Bashir, S., Raza, H., Shah, A. N., Iqbal, J., Arif, M., Bukhari, M. A., Muhammad, S., Hashim, S., Alkahtani, J., Alwahibi, M. S., & Hu, C. (2021). Role of nitrogen and magnesium for growth, yield and nutritional quality of radish. *Saudi Journal of Biological Sciences*, *28*, 3021–3030. https://doi.org/10.1016/j.sjbs.2021.02.043

Yu, X., Keitel, C., & Dijkstra, F. A. (2021). Global analysis of phosphorus fertilizer use efficiency in cereal crops. *Global Food Security*, *29*, 100545. https://doi.org/10.1016/j.gfs.2021.100545

Yu, X., Keitel, C., Zhang, Y., Wangeci, A. N., & Dijkstra, F. A. (2022). Global meta-analysis of nitrogen fertilizer use efficiency in rice, wheat and maize. *Agriculture, Ecosystems & Environment*, *338*, 108089. https://doi.org/https://doi.org/10.1016/j.agee.2022.108089

Yue, K., Li, L., Xie, J., Wang, L., Liu, Y., & Anwar, S. (2022). Tillage and nitrogen supply affects maize yield by regulating photosynthetic capacity, hormonal changes and grain filling in the Loess Plateau. *Soil and Tillage Research*, *218*, 105317. https://doi.org/https://doi.org/10.1016/j.still.2022.105317

Zafar, M., Abbasi, M. K., & Khaliq, A. (2013). Effect of different phosphorus sources on the growth, yield, energy content andp hosphorus utilization efficiency in maize at Rawalakot Azad Jammu and. *Journal of Plant Nutrition*, *5*, 37–41. https://doi.org/10.1080/01904167.2013.819892

Zhai, L., Xu, P., Zhang, Z., Wei, B., Jia, X., & Zhang, L. (2019). Improvements in grain yield and nitrogen use efficiency of summer maize by optimizing tillage practice and nitrogen application rate. *Crop Economics, Production, and Management*, *11*, 1–11. https://doi.org/10.2134/agronj2018.05.0347

Zhang, B., Hu, Y., Hill, R. L., Wu, S., & Song, X. (2021). Combined effects of biomaterial amendments and rainwater harvesting on soil moisture, structure and apple roots in a rainfed apple orchard on the Loess Plateau, China. *Agricultural Water Management*, *248*, 106776. https://doi.org/https://doi.org/10.1016/j.agwat.2021.106776

Zhang, H., Deng, Q., Hui, D., Wu, J., Xiong, X., Zhao, J., Zhao, M., Chu, G., Zhou, G., & Zhang, D. (2019). Recovery in soil carbon stock but reduction in carbon stabilization after 56-year forest restoration in degraded tropical lands. *Forest Ecology and Management*, *441*(December 2018), 1–8. https://doi.org/10.1016/j.foreco.2019.03.037

Zhang, H., Hobbie, E. A., Feng, P., Zhou, Z., Niu, L., Duan, W., Hao, J., & Hu, K. (2021). Responses of soil organic carbon and crop yields to 33-year mineral fertilizer and straw additions under different tillage systems. *Soil and Tillage Research*, *209*, 104943. https://doi.org/https://doi.org/10.1016/j.still.2021.104943

Zhang, K., Li, Y., Wei, H., Zhang, L., Li, F.-M., & Zhang, F. (2022). Conservation tillage or plastic film mulching? A comprehensive global meta-analysis based on maize yield and nitrogen use efficiency. *Science of The Total Environment*, *831*, 154869. https://doi.org/https://doi.org/10.1016/j.scitotenv.2022.154869

Zhang, L., Hu, Y., Han, F., Wu, Y., Tian, D., Su, M., Wang, S., Li, Z., & Hu, S. (2019). Influences of multiple clay minerals on the phosphorus transport driven by Aspergillus niger. *Applied Clay Science*, *177*, 12–18. https://doi.org/10.1016/j.clay.2019.04.026

Zhang, M., Zhang, X., Zhang, L., Zeng, L., Liu, Y., Wang, X., He, P., Li, S., Liang, G., Zhou, W., & Ai, C. (2021). The stronger impact of inorganic nitrogen fertilization on soil bacterial community than organic fertilization in short-term condition. *Geoderma*, *382*, 114752. https://doi.org/https://doi.org/10.1016/j.geoderma.2020.114752

Zhang, X., Li, Q., Gao, J., Hu, Y., Song, M., & Yue, Y. (2020). Effects of rainfall amount and frequency on soil nitrogen mineralization in Zoigê alpine wetland. *European Journal of Soil Biology*, *97*, 103170. https://doi.org/10.1016/j.ejsobi.2020.103170

Zhang, X., Zhu, A., Xin, X., Yang, W., Zhang, J., & Ding, S. (2018). Tillage and residue management for long-term wheat-maize cropping in the North China Plain : I. Crop yield and integrated soil fertility index. *Field Crops Research*, *221*, 157–165. https://doi.org/https://doi.org/10.1016/j.fcr.2018.02.025

Zhang, Y., Jin, Y., Xu, J., He, H., Tao, Y., Yang, Z., & Bai, Y. (2022). Effects of exogenous N and endogenous nutrients on alpine tundra litter decomposition in an area of high nitrogen deposition. *Science of The Total Environment*, *805*, 150388. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.150388

Zhang, Y., Li, C., Wang, Y., Hu, Y., Christie, P., Zhang, J., & Li, X. (2016). Maize yield and soil fertility with combined use of compost and inorganic fertilizers on a calcareous soil on the North China Plain. *Soil & Tillage Research*, *155*, 85–94. https://doi.org/10.1016/j.still.2015.08.006

Zhang, Y., Yan, J., Rong, X., Han, Y., Yang, Z., Hou, K., Zhao, H., & Hu, W. (2021). Responses of maize yield, nitrogen and phosphorus runoff losses and soil properties to biochar and organic fertilizer application in a light-loamy fluvo-aquic soil. *Agriculture, Ecosystems and Environment*, *314*, 107433. https://doi.org/10.1016/j.agee.2021.107433

Zhang, Y., Zhang, H., Liu, Q., Duan, L., & Zhou, Q. (2023). Total nitrogen and community turnover determine phosphorus use efficiency of phytoplankton along nutrient gradients in plateau lakes. *Journal of Environmental Sciences*, *124*, 699–711. https://doi.org/https://doi.org/10.1016/j.jes.2022.02.005

Zhao, B., Ata-ul-karim, S. T., Duan, A., Liu, Z., Wang, X., Xiao, J., Liu, Z., Qin, A., Ning, D., Zhang, W., & Lian, Y. (2018). Determination of critical nitrogen concentration and dilution curve based on leaf area index for summer maize. *Field Crops Research*, *228*, 195–203. https://doi.org/10.1016/j.fcr.2018.09.005

Zhao, B., Ata-ul-karim, S. T., Liu, Z., Zhang, J., & Xiao, J. (2018). Simple assessment of nitrogen nutrition index in summer maize by using chlorophyll meter readings. *Frontier in Plant Science, 9,* 1–13. https://doi.org/10.3389/fpls.2018.00011

Zhao, Z., Gao, S., Lu, C., LI, X., Li, F., & Wang, T. (2021). Effects of different tillage and fertilization management practices on soil organic carbon and aggregates under the rice–wheat rotation system. *Soil and Tillage Research, 212,* 105071. https://doi.org/https://doi.org/10.1016/j.still.2021.105071

Zheng, L., Chen, H., Wang, Y., Mao, Q., Zheng, M., Su, Y., Xiao, K., Wang, K., & Li, D. (2020). Responses of soil microbial resource limitation to multiple fertilization strategies. *Soil & Tillage Research, 196,* 104474. https://doi.org/10.1016/j.still.2019.104474

Zheng, W., Zhang, M., Liu, Z., Zhou, H., Lu, H., Zhang, W., Yang, Y., Li, C., & Chen, B. (2016). Combining controlled-release urea and normal urea to improve the nitrogen use efficiency and yield under wheat-maize double cropping system. *Field Crops Research, 13,* 292=320. https://doi.org/10.1016/j.fcr.2016.08.004

Zhihui, W. E. N., Jianbo, S., Blackwell, M., Haigang, L. I., Bingqiang, Z., & Huimin, Y. (2016). Combined applications of nitrogen and phosphorus fertilizers with manure increase maize yield and nutrient uptake via stimulating root growth in a long-term experiment. *Pedosphere: An International Journal, 26,* 62–73. https://doi.org/10.1016/S1002-0160(15)60023-6

Zhu, C., Wang, J., Li, Q., Wang, L., Tang, G., Cui, B., & Bai, J. (2021). Integration of CW-MFC and anaerobic granular sludge to explore the intensified ammonification-nitrification-denitrification processes for nitrogen removal. *Chemosphere, 278,* 130428. https://doi.org/10.1016/j.chemosphere.2021.130428

Zhu, X., Jackson, R. D., DeLucia, E. H., Tiedje, J. M., & Liang, C. (2020). The soil microbial carbon pump: From conceptual insights to empirical assessments. *Global Change Biology, 26,* 6032–6039. https://doi.org/10.1111/gcb.15319

Zhu, X., Xie, H., Masters, M. D., Rui, Y., Luo, Y., He, H., Zhang, X., & Liang, C. (2023). Microorganisms, their residues, and soil carbon storage under a continuous maize cropping system with eight years of variable residue retention. *Applied Soil Ecology*, *187*, 104846. https://doi.org/https://doi.org/10.1016/j.apsoil.2023.104846

Zhu, Z., Bai, Y., Lv, M., Tian, G., Zhang, X., Jia, Z., Jiang, Y., & Ge, S. (2020). Soil fertility, microbial biomass, and microbial functional diversity responses to four years fertilization in an apple orchard in north china. *Horticultural Plant Journal*, *3*, 0–12. https://doi.org/10.1016/j.hpj.2020.06.003

Zou, W., Lang, M., Zhang, L., Liu, B., & Chen, X. (2022). Ammonia-oxidizing bacteria rather than ammonia-oxidizing archaea dominate nitrification in a nitrogen-fertilized calcareous soil. *Science of The Total Environment*, *811*, 151402. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.151402

Zuber, S. M., & Villamil, M. B. (2016). Meta-analysis approach to assess effect of tillage on microbial biomass and enzyme activities. *Soil Biology and Biochemistry*, *97*, 176–187. https://doi.org/10.1016/j.soilbio.2016.03.011

APPENDICES

Appendix I: Dates for Field Management Operations Carried Out during SR20 Cropping Season

Treatment	Tillage method	Tillage date	Sowing date	Inorganic fertilizer application	Organic fertilizer application	Mulching
C	Conventional	10/10/2020	15/10/2020	-	-	-
CTF	Conventional	10/10/2020	15/10/2020	15/10/2020	-	-
CTCrF	Conventional	10/10/2020	15/10/2020	15/10/2020	-	29/10/2020
CTCrGF	Conventional	10/10/2020	15/10/2020	15/10/2020	10/10/2020	29/10/2020
CTCrGL	Conventional	10/10/2020	15/10/2020	-	10/10/2020	29/10/2020
CTCrTiG	Conventional	10/10/2020	15/10/2020	-	10/10/2020	29/10/2020
CTCrTiR	Conventional	10/10/2020	15/10/2020	-	10/10/2020	29/10/2020
MT	Minimum	10/10/2020	15/10/2020	-	-	-
MTF	Minimum	10/10/2020	15/10/2020	15/10/2020	-	-
MTCrF	Minimum	10/10/2020	15/10/2020	15/10/2020	-	29/10/2020
MTCrGF	Minimum	10/10/2020	15/10/2020	15/10/2020	10/10/2020	29/10/2020
MTCrGL	Minimum	10/10/2020	15/10/2020	-	10/10/2020	29/10/2020
MTCrTiG	Minimum	10/10/2020	15/10/2020	-	10/10/2020	29/10/2020
MTCrTiR	Minimum	10/10/2020	15/10/2020	-	10/10/2020	29/10/2020

Appendix II: Dates for Field Management Operations Carried out during LR21 Cropping Season

Treatment	Tillage method	Tillage date	Sowing date	Inorganic fertilizer application	Organic fertilizer application	Mulching
C	Conventional	08/03/2021	18/03/2021	-	-	-
CTF	Conventional	08/03/2021	18/03/2021	18/03/2021	-	-
CTCrF	Conventional	08/03/2021	18/03/2021	18/03/2021	-	03/04/2021
CTCrGF	Conventional	08/03/2021	18/03/2021	18/03/2021	08/03/2021	03/04/2021
CTCrGL	Conventional	08/03/2021	18/03/2021	-	08/03/2021	03/04/2021
CTCrTiG	Conventional	08/03/2021	18/03/2021	-	08/03/2021	03/04/2021
CTCrTiR	Conventional	08/03/2021	18/03/2021	-	08/03/2021	03/04/2021
MT	Minimum	08/03/2021	18/03/2021	-	-	-
MTF	Minimum	08/03/2021	18/03/2021	18/03/2021	-	-
MTCrF	Minimum	08/03/2021	18/03/2021	18/03/2021	-	03/04/2021
MTCrGF	Minimum	08/03/2021	18/03/2021	18/03/2021	08/03/2021	03/04/2021
MTCrGL	Minimum	08/03/2021	18/03/2021	-	08/03/2021	03/04/2021
MTCrTiG	Minimum	08/03/2021	18/03/2021	-	08/03/2021	03/04/2021
MTCrTiR	Minimum	08/03/2021	18/03/2021	-	08/03/2021	03/04/2021

Appendix III: Observed and Simulated NH4-N (kg ha-1) under Different Treatments over Time during the SR20 Cropping System

Treatment		Days after planting							
		0	**15**	**30**	**45**	**60**	**75**	**90**	**105**
MTCrGF	Observed	0.2	4.1	0.3	0.1	0.0	0.1	0.1	0.1
	Simulated	0.1	0.9	1.1	1.2	0.9	0.8	0.8	0.6
	Change	-0.1	-3.2	0.8	1.1	0.9	0.7	0.7	0.5
CTCrGF	Observed	0.2	4.0	0.1	0.1	0.0	0.2	0.1	0.1
	Simulated	0.1	0.9	1.1	1.2	0.9	0.8	0.8	0.6
	Change	-0.1	-3.1	1.0	1.1	0.9	0.6	0.7	0.5
MTCrF	Observed	0.1	2.7	0.1	0.0	0.0	0.0	0.0	0.0
	Simulated	0.1	0.9	1.1	1.2	0.9	0.8	0.8	0.6
	Change	0.0	-1.8	1.0	1.2	0.9	0.8	0.8	0.6
MTCrGL	Observed	0.2	6.0	0.0	0.0	0.0	0.1	0.1	0.0
	Simulated	0.1	0.9	1.1	1.2	0.9	0.8	0.8	0.6
	Change	-0.1	-5.1	1.1	1.2	0.9	0.7	0.7	0.6
CTF	Observed	0.1	4.3	0.1	0.0	0.0	0.0	0.1	0.0
	Simulated	0.2	1.0	1.1	1.2	0.9	0.8	0.8	0.6
	Change	0.1	-3.3	1.0	1.2	0.9	0.8	0.7	0.6
CTCrF	Observed	0.1	2.5	0.1	0.1	0.0	0.1	0.1	0.1
	Simulated	0.1	0.1	0.2	0.4	0.8	0.1	0.7	0.7
	Change	0.0	-2.4	0.1	0.3	0.8	0.0	0.6	0.6
CTCrTiG	Observed	0.1	1.8	0.0	0.0	0.0	0.0	0.1	0.0
	Simulated	0.1	0.9	1.1	1.2	0.9	0.8	0.8	0.6
	Change	0.0	-0.9	1.1	1.2	0.9	0.8	0.7	0.6
CTCrGL	Observed	0.2	0.6	0.0	0.0	0.0	0.1	0.1	0.0
	Simulated	0.1	0.9	1.1	1.2	0.9	0.8	0.8	0.6
	Change	-0.1	0.3	1.1	1.2	0.9	0.7	0.7	0.6

CTCrTiR	Observed	0.0	4.3	0.1	0.1	0.0	0.0	0.1	0.0
	Simulated	0.1	0.9	1.1	1.2	0.9	0.8	0.8	0.6
	Change	0.1	-3.4	1.0	1.1	0.9	0.8	0.7	0.6
MTCrTiR	Observed	0.2	0.6	0.2	0.0	0.0	0.1	0.1	0.0
	Simulated	0.1	0.9	1.1	1.2	0.9	0.8	0.8	0.6
	Change	-0.1	0.3	0.9	1.2	0.9	0.7	0.7	0.6
MTF	Observed	0.1	6.7	0.2	0.1	0.0	0.1	0.1	0.1
	Simulated	0.2	1.0	1.1	1.2	0.9	0.8	0.8	0.6
	Change	0.1	-5.7	0.9	1.1	0.9	0.7	0.7	0.5
MTCrTiG	Observed	0.1	1.0	0.0	0.0	0.0	0.1	0.0	0.1
	Simulated	0.1	0.9	1.1	1.2	0.9	0.8	0.8	0.6
	Change	0.0	-0.1	1.1	1.2	0.9	0.7	0.8	0.5
MT	Observed	0.1	1.7	0.1	0.1	0.0	0.1	0.1	0.0
	Simulated	0.1	1.0	1.1	1.2	0.9	0.8	0.8	0.6
	Change	0.0	-0.7	1.0	1.1	0.9	0.7	0.7	0.6
C	Observed	0.0	0.1	0.1	0.0	0.0	0.1	0.0	0.0
	Simulated	0.1	1.0	1.1	1.2	0.9	0.8	0.8	0.6
	Change	0.1	0.9	1.0	1.2	0.9	0.7	0.8	0.6

Appendix IV: Observed and Simulated NO3-N (kg ha-1) under Different Treatments over Time during the SR20 Cropping System

Treatment		Days after planting							
		0	15	30	45	60	75	90	105
MTCrGF	Observed	0.1	0.5	0.1	0.1	0.2	0.1	2.2	1.1
	Simulated	0.0	0.6	2.0	2.9	4.8	5.0	6.7	8.1
	Change	-0.1	0.1	1.9	2.8	4.6	4.9	4.5	7.0
CTCrGF	Observed	0.2	0.4	0.1	0.3	0.1	0.2	1.6	1.5
	Simulated	1.0	0.6	2.0	2.9	4.8	5.0	6.7	8.1
	Change	0.8	0.2	1.9	2.6	4.7	4.8	5.1	6.6
MTCrF	Observed	0.3	0.2	0.2	0.2	0.2	0.2	1.2	1.2
	Simulated	0.0	0.6	2.0	2.9	4.8	5.0	6.7	8.0
	Change	-0.3	0.4	1.8	2.7	4.6	4.8	5.5	6.8
MTCrGL	Observed	0.1	0.6	0.1	0.2	0.1	0.2	1.1	2.1
	Simulated	0.0	0.6	2.0	2.9	4.8	5.0	6.7	8.0
	Change	-0.1	0.0	1.9	2.7	4.7	4.8	5.6	5.9
CTF	Observed	0.5	0.1	0.1	0.1	0.3	0.2	0.7	0.3
	Simulated	0.5	1.0	2.5	3.2	5.0	5.2	6.8	8.2
	Change	0.0	0.9	2.4	3.1	4.7	5.0	6.1	7.9
CTCrF	Observed	0.2	0.1	0.1	0.0	0.0	0.2	2.1	1.4
	Simulated	0.0	0.0	0.0	0.1	1.3	0.0	0.9	2.4
	Change	-0.2	-0.1	-0.1	0.1	1.3	-0.2	-1.2	1.0
CTCrTiG	Observed	0.1	0.2	0.3	0.2	0.0	0.6	1.3	1.2
	Simulated	0.0	0.6	2.0	2.9	4.8	5.1	6.7	8.1
	Change	-0.1	0.4	1.7	2.7	4.8	4.5	5.4	6.9
CTCrGL	Observed	0.4	0.2	0.2	0.1	0.1	1.4	0.9	0.7
	Simulated	0.0	0.6	2.0	2.9	4.8	5.1	6.7	8.1
	Change	-0.4	0.4	1.8	2.8	4.7	3.7	5.8	7.4

CTCrTiR	Observed	0.3	0.3	0.0	0.3	0.2	0.3	1.0	1.4
	Simulated	0.0	0.6	2.0	2.9	4.8	5.0	6.7	8.0
	Change	-0.3	0.3	2.0	2.6	4.6	4.7	5.7	6.6
MTCrTiR	Observed	0.2	0.1	0.2	0.2	0.0	0.1	0.4	1.7
	Simulated	0.0	0.6	2.0	2.9	4.8	5.0	6.7	8.0
	Change	-0.2	0.5	1.8	2.7	4.8	4.9	6.3	6.3
MTF	Observed	0.5	0.5	0.2	0.3	0.1	0.2	0.6	2.3
	Simulated	0.5	0.9	2.1	3.1	4.9	5.2	6.8	8.1
	Change	0.0	0.4	1.9	2.8	4.8	5.0	6.2	5.8
MTCrTiG	Observed	0.2	0.1	0.1	0.1	0.1	0.1	0.3	0.3
	Simulated	0.0	0.6	2.0	2.9	4.8	5.0	6.7	8.0
	Change	-0.2	0.5	1.9	2.8	4.7	4.9	6.4	7.7
MT	Observed	0.2	0.1	0.1	0.0	0.2	0.2	0.1	0.1
	Simulated	0.2	0.9	2.3	3.1	4.9	5.1	6.8	8.1
	Change	0.0	0.8	2.2	3.1	4.7	4.9	6.7	8.0
C	Observed	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
	Simulated	0.1	0.8	2.3	3.1	4.9	5.1	6.7	8.1
	Change	0.1	0.7	2.2	3.0	4.8	5.0	6.6	8.0

Appendix V: Observed and Simulated NH4-N (kg ha-1) under Different Treatments over Time during the LR21 Cropping System

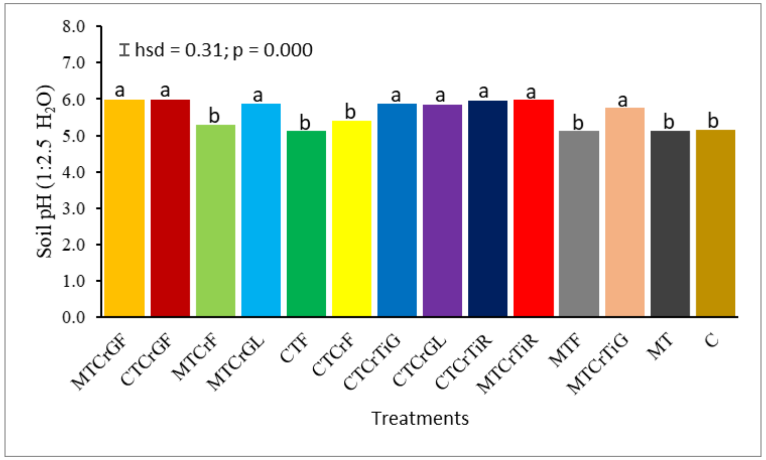
Treatment		**Days after planting**							
		0	**15**	**30**	**45**	**60**	**75**	**90**	**105**
MTCrGF	Observed	1.4	0.2	0.2	0.1	0.4	0.4	0.2	0.2
	Simulated	0.1	0.6	1.3	1.7	1.7	1.6	1.1	0.7
	Change	-1.3	0.4	1.1	1.6	1.3	1.2	0.9	0.5
CTCrGF	Observed	1.1	0.1	0.4	0.1	0.5	0.3	0.4	0.2
	Simulated	0.1	0.6	1.2	1.5	1.6	1.5	1.1	0.7
	Change	-1.0	0.5	0.8	1.4	1.1	1.2	0.7	0.5
MTCrF	Observed	1.3	0.5	0.2	0.2	0.2	0.2	0.2	0.1
	Simulated	0.1	0.6	1.1	1.4	1.5	1.4	1.0	0.6
	Change	-1.2	0.1	0.9	1.2	1.3	1.2	0.8	0.5
MTCrGL	Observed	1.7	0.4	0.3	0.3	0.3	0.2	0.1	0.1
	Simulated	0.2	0.7	1.3	1.6	1.6	1.6	1.1	0.7
	Change	-1.5	0.3	1.0	1.3	1.3	1.4	1.0	0.6
CTF	Observed	1.1	0.6	0.4	0.2	0.1	1.7	0.1	0.1
	Simulated	1.1	1.2	1.3	1.3	1.3	1.2	0.9	0.6
	Change	0.0	0.6	0.9	1.1	1.2	-0.5	0.8	0.5
CTCrF	Observed	2.5	0.4	0.4	0.2	0.1	0.2	0.2	0.1
	Simulated	1.1	0.7	0.2	0.2	0.1	1.1	1.1	0.8
	Change	-1.4	0.3	-0.2	0.0	0.0	0.9	0.9	0.7
CTCrTiG	Observed	0.9	0.4	0.4	0.2	0.2	0.3	0.3	0.1
	Simulated	0.1	0.6	1.2	1.5	1.6	1.5	1.1	0.7
	Change	-0.8	0.2	0.8	1.3	1.4	1.2	0.8	0.6
CTCrGL	Observed	1.8	0.6	0.3	0.3	0.1	0.2	0.1	0.2
	Simulated	0.3	0.7	1.3	1.6	1.7	1.6	1.1	0.7
	Change	-1.5	0.1	1.0	1.3	1.6	1.4	1.0	0.5

CTCrTiR	Observed	1.2	0.2	0.3	0.2	0.1	0.4	0.1	0.2
	Simulated	0.1	0.6	1.2	1.5	1.5	1.5	1.0	0.7
	Change	-1.1	0.4	0.9	1.3	1.4	1.1	0.9	0.5
MTCrTiR	Observed	1.3	0.3	0.4	0.2	0.3	0.1	0.1	0.1
	Simulated	0.1	0.6	1.2	1.5	1.5	1.5	1.0	0.7
	Change	-1.2	0.3	0.8	1.3	1.2	1.4	0.9	0.6
MTF	Observed	1.0	0.7	0.2	0.2	0.3	0.2	0.6	0.2
	Simulated	0.9	1.1	1.3	1.3	1.3	1.2	0.9	0.6
	Change	-0.1	0.4	1.1	1.1	1.0	1.0	0.3	0.4
MTCrTiG	Observed	1.0	0.3	0.3	0.2	0.3	0.3	0.1	0.1
	Simulated	0.1	0.6	1.2	1.5	1.5	1.4	1.0	0.6
	Change	-0.9	0.3	0.9	1.3	1.2	1.1	0.9	0.5
MT	Observed	0.8	0.5	0.1	0.1	0.3	0.2	0.2	0.2
	Simulated	0.7	1.0	1.3	1.3	1.3	1.2	0.9	0.6
	Change	-0.1	0.5	1.2	1.2	1.0	1.0	0.7	0.4
C	Observed	0.3	0.3	0.2	0.1	0.1	0.1	0.1	0.0
	Simulated	0.3	1.0	1.2	1.3	1.3	1.2	0.9	0.6
	Change	0.0	0.7	1.0	1.2	1.2	1.1	0.8	0.6

Appendix VI: Observed and Simulated NO3-N (kg ha-1) under Different Treatments over Time during the LR21 Cropping System

Treat*		Days after planting							
		0	**15**	**30**	**45**	**60**	**75**	**90**	**105**
MTCrGF	Observed	7.1	3.1	0.5	1.6	0.7	0.8	0.2	0.3
	Simulated	7.0	0.3	1.1	2.4	4.7	5.8	8.2	9.9
	Change	-0.1	-2.8	0.6	0.8	4.0	5.0	8.0	9.6
CTCrGF	Observed	4.1	1.6	1.2	2.0	0.3	3.6	0.3	0.4
	Simulated	3.7	0.3	1.0	2.3	4.4	5.4	7.6	9.3
	Change	-0.4	-1.3	-0.2	0.3	4.1	1.8	7.3	8.9
MTCrF	Observed	2.3	2.5	1.1	0.6	0.5	0.2	0.5	0.1
	Simulated	2.2	0.2	0.9	2.1	4.1	5.0	7.2	8.7
	Change	-0.1	-2.3	-0.2	1.5	3.6	4.8	6.7	8.6
MTCrGL	Observed	5.5	2.5	2.0	0.9	0.7	0.4	0.3	0.2
	Simulated	5.5	0.3	1.0	2.4	4.6	5.6	7.9	9.6
	Change	0.0	-2.2	-1.0	1.5	3.9	5.2	7.6	9.4
CTF	Observed	3.5	2.6	2.9	0.7	0.8	0.2	0.2	0.3
	Simulated	3.6	5.2	2.7	2.9	4.8	5.3	7.3	8.7
	Change	0.1	2.6	-0.2	2.2	4.0	5.1	7.1	8.4
CTCrF	Observed	5.6	1.7	1.5	0.9	0.2	0.6	0.5	0.4
	Simulated	5.7	0.3	0.0	0.0	0.0	0.7	2.7	4.4
	Change	0.1	-1.4	-1.5	-0.9	-0.2	0.1	2.2	4.0
CTCrTiG	Observed	4.5	0.5	0.8	0.5	0.9	0.4	0.1	0.3
	Simulated	3.9	0.3	1.0	2.3	4.4	5.4	7.7	9.3
	Change	-0.6	-0.2	0.2	1.8	3.5	5.0	7.6	9.0
CTCrGL	Observed	5.9	2.9	1.8	1.7	0.6	0.5	0.3	0.3
	Simulated	5.9	0.3	1.0	2.4	4.6	5.6	8.0	9.7
	Change	0.0	-2.6	-0.8	0.7	4.0	5.1	7.7	9.4

CTCrTiR	Observed	3.1	1.3	0.3	1.4	1.2	0.2	0.3	0.2
	Simulated	2.7	0.2	0.9	2.2	4.2	5.2	7.4	9.0
	Change	-0.4	-1.1	0.6	0.8	3.0	5.0	7.1	8.8
MTCrTiR	Observed	3.7	0.6	1.4	0.7	1.6	0.4	0.9	0.2
	Simulated	3.5	0.3	0.9	2.2	4.2	5.2	7.4	9.0
	Change	-0.2	-0.3	-0.5	1.5	2.6	4.8	6.5	8.8
MTF	Observed	4.9	1.1	2.0	1.0	0.5	0.1	0.6	0.4
	Simulated	5.0	6.4	3.1	3.1	4.9	5.4	7.4	8.9
	Change	0.1	5.3	1.1	2.1	4.4	5.3	6.8	8.5
MTCrTiG	Observed	2.7	1.7	2.5	1.2	1.3	0.3	0.6	0.3
	Simulated	2.3	0.2	0.9	2.1	4.2	5.1	7.3	8.8
	Change	-0.4	-1.5	-1.6	0.9	2.9	4.8	6.7	8.5
MT	Observed	3.9	0.6	0.3	0.3	0.1	0.2	0.1	0.1
	Simulated	4.0	5.3	2.8	3.0	4.8	5.3	7.3	8.7
	Change	0.1	4.7	2.5	2.7	4.7	5.1	7.2	8.6
C	Observed	1.3	0.2	0.4	0.2	0.2	0.0	0.1	0.2
	Simulated	1.3	2.3	2.0	2.6	4.4	5.0	6.9	8.3
	Change	0.0	2.1	1.6	2.4	4.2	5.0	6.8	8.1



8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
Soil pH (1:2.5 H_2O)
hsd = 0.31; p = 0.000
a
a
b
a
b
b
a
a
a
a
b
a
b
b
MTCrGF
CTCrGF
MTCrF
MTCrGL
CTF
CTCrF
CTCrTiG
CTCrGL
CTCrTiR
MTCrTiR
MTF
MTCrTiG
MT
C
Treatments

Appendix VII: Soil pH (1:2.5 soil: H2O) under Different Treatments at the End of the Study

Means with the same superscript letter(s) denote no significant difference at $p < 0.05$; C = Control, CTF = conventional tillage + inorganic fertilizer, CTCrF = conventional tillage + maize residues + inorganic fertilizer, CTCrGF = conventional tillage + maize residues + inorganic fertilizer + goat manure, CTCrTiR = conventional tillage + maize residues + Tithonia diversifolia + rock phosphate, CTCrGL = conventional tillage + maize residues+ goat manure + Dolichos lablab, CTCrTiG = conventional tillage + maize residues + Tithonia diversifolia + goat manure, MT = minimum tillage, MTF = minimum tillage + inorganic fertilizer, MTCrF = minimum tillage + maize residues + inorganic fertilizer, MTCrGF = minimum tillage + maize residues + inorganic fertilizer + goat manure, MTCrTiR = minimum tillage + maize residues + Tithonia diversifolia + rock phosphate, MTCrGL = minimum tillage + maize residues+ goat manure + Dolichos lablab, MTCrTiG = minimum tillage + maize residues + Tithonia diversifolia + goat manure, hsd = honestly significant difference pooled error bar.

Appendix VIII: Correlation Coefficients of Relationships between Different P Fractions

.P fractions	Resin-Pi	NaHCO$_3$-Pi	NaHCO$_3$-Po	NaOH-Pi	NaOH-Po	Sonic NaOH-Pi	Sonic NaOH-Po	HCl-Pi	Residual-P
Resin-Pi	1.00	0.83***	0.25	0.75***	0.07	0.75***	0.70***	0.60***	0.36***
NaHCO$_3$-Pi	0.83***	1.00	0.21	0.87***	-0.03	0.74***	0.56***	0.33*$^{\text{٢}}$	0.26
NaHCO$_3$-Po	0.25	0.21	1.00	0.22	0.04	0.16	0.16	0.18	-0.01
NaOH-Pi	0.75***	0.87***	0.22	1.00	-0.13	0.77***	0.40**††	0.32*$^{\text{٢٢}}$	0.13
NaOH-Po	0.07	-0.03	0.04	-0.13	1.00	0.00	0.15	0.23	0.14
Sonic NaOH-Pi	0.75***	0.74***	0.16	0.77***	0.00	1.00	0.48***	0.44***	0.23
Sonic NaOH-Po	0.70***	0.56***	0.16	0.40**††	0.15	0.48***	1.00	0.58***	0.29*$^{\text{٢٢٢}}$
HCl-Pi	0.60***	0.33*$^{\text{٢}}$	0.18	0.32*$^{\text{٢٢}}$	0.23	0.44***	0.58***	1.00	0.25
Residual-P	0.36**†††	0.26	-0.01	0.13	0.14	0.23	0.29	0.25	1.00

NaHCO$_3$-Pi = sodium bicarbonate-extractable inorganic P, NaHCO$_3$-Po = sodium bicarbonate-extractable organic P, NaOH-P = sodium hydroxide-extractable Fe.Al-P, and HCl-Pi= hydrochloric acid-extractable Mg.Ca-P. *$^{\text{٢}}$ p = 0.0122, *$^{\text{٢٢}}$ p = 0.0163, *$^{\text{٢٢٢}}$ p = 0.0282, **†† p = 0.0023, **††† p = 0.0060.

Appendix IX: Correlation Coefficients of Relationships between Sorption Characteristics, PPF, and PAE

Parameters	**S_{max}**	**DPS**	**k**	**PPF**	**PAE**
S_{max}	1.00	0.26	-0.51***	0.10	0.10
DPS	0.26	1.00	-0.12	-0.45**	-0.45**
k	-0.51***	-0.12	1.00	-0.06	-0.06
PPF	0.10	-0.45**	-0.06	1.00	1.00***
PAE	0.10	-0.45**	-0.06	1.00***	1.00

S_{max} = Maximum sorption capacity, DPS = Degrees of phosphorus saturation, k = bonding energy, PPF = partial productivity factors, PAE = phosphorus agronomic use efficiency. ** p = 0.0012, *** p = 0.0001.

Appendix X: First Publication

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Effects of different soil management strategies on fertility and crop productivity in acidic nitisols of Central Highlands of Kenya

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ABSTRACT

Managing soil fertility, especially nitrogen (N) and phosphorus (P), to sustain increased crop productivity is a complex challenge, especially in cultivated Nitisols. Experiments were conducted over eleven (11) cropping seasons in the acidic Nitisols to assess the impact of soil management strategies on soil N, P, and crop productivity. Fourteen treatments were laid out in a Randomized Complete Block Design. The treatments include; control (C), conventional tillage + inorganic fertilizer (CTF), conventional tillage + maize residues + inorganic fertilizer (CTCrF), conventional tillage + maize residues + inorganic fertilizer + goat manure (CTCrGF), conventional tillage + maize residues + *Tithonia diversifolia* + rock phosphate (CTCrTiR), conventional tillage + maize residues+ goat manure + *Dolichos lablab* (CTCrGL), conventional tillage + maize residues + *Tithonia diversifolia* + goat manure (CTCrTiG), minimum tillage (MT; no amendments), minimum tillage + inorganic fertilizer (MTF), minimum tillage + maize residues + inorganic fertilizer (MTCrF), minimum tillage + maize residues + inorganic fertilizer + goat manure (MTCrGF), minimum tillage + maize residues + *Tithonia diversifolia* + rock phosphate (MTCrTiR), minimum tillage + maize residues+ goat manure + *Dolichos lablab* (MTCrGL), and minimum tillage + maize residues + *Tithonia diversifolia* + goat manure (MTCrTiG). Available P was significantly higher by 51, 48, 43, 38, 37, 36 and 27% under MTCrGF, CTCrGF, MTCrF, CTF, CTCrF, MTCrGL, and CTCrTiG than the control. Available soil N was significantly higher (59, 59, 59, 57, 57, 57, 55, 55, 55, 50, and 50%) under MTCrGL, CTCrGL, CTCrTiR, MTCrTiR, MTCrF, CTCrTiG, MTF, CTCrGF, CTF, MTCrTiG and MTCrGF compared to the control. Grain radiation use efficiency was significantly higher under CTCrGF, MTCrF, CTCrTiR, CTF, MTCrTiG, CTCrF, MTCrGF, CTCrTiG, and MTCrTiR than the control by 95, 93, 93, 93, 92, 92, 92, 91 and 88% during the SR2020 cropping season. In the LR2021 season, it was significantly higher under CTCrGL, MTCrGL, CTCrGF, CTF, MTCrGF, CTCrF, MTF, MTCrF, MTCrTiG, MTCrTiR, CTCrTiG and CTCrTiR than the control by 80, 79, 78, 77, 77, 74, 73, 72, 70, 67, 66 and 62%. Grain yield was significantly higher under CTCrGF, MTCrF, CTCrF, MTCrGF, MTCrTiG, CTCrTiR, CTF, CTCrTiG, and CTCrTiR than the control in the SR2020 season by 95, 93, 93, 93, 92, 92, 92, 92 and 88%. During LR2021, CTCrGF recorded the highest grain yield, which was 74% higher than the control, while CTCrGL, MTCrGF, MTCrGL, CTF, MTCrF, CTCrF, MTF, MTCrTiG, CTCrTiG, MTCrTiR, and CTCrTiR, had higher yields than the control by 73, 71, 70, 69, 69, 66, 65, 64, 58, 55 and 49%. Overall, CTCrGF, CTCrGL, MTCrGF, and MTCrGL had a comparative advantage regarding soil fertility and crop productivity in acidic Nitisols, strongly illustrating the concept of 'complementarity' in integrated soil fertility management.

1. Introduction

Declining soil fertility, primarily nitrogen (N) and phosphorus (P) is the most serious problem facing crop productivity in Kenya and sub-Saharan Africa (SSA) at large. Overreliance on rainfed agriculture by smallholder farmers and degraded soil fertility greatly contribute to the low crop productivity in SSA. As a result, cereal production in SSA is less than 2.0 t ha^{-1} compared to 5.0 and 8.0 t ha^{-1} in Asia and Latin America (Epule & Bryant, 2015). It is estimated that farmers under rainfed agriculture risk a reduction in crop yields by 50% in the next 30-35 years if

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Appendix XI: Second Publication

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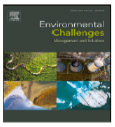

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Erick O. Otieno[a,b,*], David M. Mburu[a], Felix K. Ngetich[c,d], Milka N. Kiboi[d,e], Andreas Fliessbach[f], Florence K. Lenga[a]

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Influence of soil fertility management technologies on phosphorus fractions, sorption characteristics, and use efficiency in humic Nitisols of Upper Eastern Kenya

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ABSTRACT

Fractions of phosphorus (P) and its sorption characteristics are affected by different soil fertility (FM) technologies which ultimately affect crop growth and productivity. However, the response of P fractions and sorption characteristics to soil fertility technologies that integrate diverse amendments is still poorly understood in acidic Nitisols. A randomized complete block design was layout in an acidic Nitisol to determine fractions of P, its sorption characteristics and use efficiencies in acidic Nitisols under various FM technologies in field conditions. The use of minimum tillage + maize residue + inorganic fertilizer + goat manure (MTCrGF) had the highest impact on and significantly increased resin-Pi, NaHCO$_3$-Pi, and maximum P sorption (S_{max}) by 182, 76, and 52 mg P kg^{-1}. Moreover, NaOH-Pi and S_{max} concentrations were higher under conventional tillage + maize residue + inorganic fertilizer + goat manure (CTCrGF) by 216 mg P kg^{-1} and 49 mg P kg^{-1} than the control. MTCrGF and CTCrGF also had the lowest P bonding energy (0.04 L mg^{-1}). CTCrGF had the highest P partial productivity factor (0.093 and 0.140 kg biomass kg^{-1} P) and P agronomic efficiency (0.080 and 0.073 kg biomass kg^{-1} P) during the two cropping seasons. The results demonstrate the positive influence of combining multiple P sources on soil P fractions, sorption characteristics, and use efficiencies. Notably, combining either conventional or minimum tillage with maize straw and applying integrated manure and inorganic fertilizer (MTCrGF or CTCrGF) can increase the labile P concentrations and reduce the potential depletion of the non-renewable rock phosphate and the use of inorganic phosphatic fertilizers for agricultural production.

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