EFFECTS OF ORGANIC AND INORGANIC INPUTS ON SOIL CHEMICAL PROPERTIES, ORGANIC CARBON FRACTIONS AND MAIZE YIELD IN MBEERE SOUTH SUB-COUNTY, KENYA

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DEDICATION

This thesis is a dedication to my family and supervisors for their encouragement, unending support, and value towards my education.

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ABSTRACT

Declining soil fertility affects farmers both globally and in Kenya. Small-scale farmers are experiencing declining agricultural productivity and land degradation due to nutrient and soil carbon depletion. Soil erosion, high temperatures, and poor farming practices are some of the factors that lead to low soil organic matter (SOM). This study investigated the effects of organic and inorganic inputs on soil chemical properties, organic fractions, and maize yield. The research was conducted on a long-term soil fertility field experiment established in 2004 in Kenya's relatively arid Mbeere South sub-county. A randomized complete block design was used for the experimental setup. The Integrated Soil Fertility Management (ISFM) treatments included 60 kg ha^{-1} nitrogen (N) from goat manure (GM60); 30 kg ha^{-1} inorganic N fertilizer (IF30); 60 kg ha^{-1} inorganic N fertilizer (IF60); GM30+IF30; 90 kg ha^{-1} inorganic N fertilizer (IF90); 60 kg ha^{-1} N from lantana (*Lantana camara*) (LC60); LC30+IF30; 60 kg ha^{-1} N from mucuna beans (*Mucuna pruriens*) (MP60); MP30+IF30; 60 kg ha^{-1} N from Mexican sunflower (*Tithonia diversifolia*) (TD60); TD30+IF30, as well as a control treatment. The carbon (C) compositions of ground soil samples and organic amendments were analyzed using ^{13}C solid-state nuclear magnetic resonance (NMR). The GM60, GM30+IF30, LC60, and TD60 treatments had much higher Alkyl and O-Alkyl C SOM functional groups than the control and other treatments. Analysis of variance (ANOVA) was performed on the data. The relationship of grain yields against soil N or soil C was evaluated using a bivariate Pearson Correlation to produce a correlation coefficient. Differences between treatment means were separated using the least significant difference (LSD) at p=0.05. The average soil C for the control was 7.47 mg kg^{-1} and ranged from 5.03 to 7.37, 9.57 to 18.77, and 7.03 to 14.50 mg kg^{-1} for inorganic fertilizers, organic fertilizers, and organic + inorganic fertilizers, respectively. The mean grain yield for the control was 0.56 Mg ha^{-1} and ranged from 1.51 to 1.99, 1.94 to 4.16, and 2.98 to 4.60 Mg ha^{-1} for inorganic fertilizers, organic fertilizers, and organic + inorganic fertilizers, respectively. The results showed that applying sole organic fertilizers or combined with inorganic fertilizers increase maize yield and promotes soil C sequestration potential. The increase was attributed to high Alkyl and O-Alkyl C SOM functional groups. It is crucial to consider and understand the C fraction content of organic inputs when selecting the most appropriate management techniques to enhance soil fertility and maintain or increase crop yields. The findings of this study have practical implications for smallholder farmers, as they can adopt and make informed decisions regarding suitable and sustainable soil management options to improve soil and crop productivity in their areas. Additionally, this research contributes valuable knowledge on local strategies for dealing with climate variability, further benefiting farmers in the study areas.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANOVA	Analysis of Variance
ASL	Above Sea Level
C	Carbon
FAO	Food Agricultural Organisation
ISFM	Integrated Soil Fertility Management
LSD	Least Significance Difference
N	Nitrogen
NMR	Nuclear Magnetic Resonance
SAS	Statistical Analysis Software
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
TDR	Time Domain Reflectometry

CHAPTER 1

INTRODUCTION

1.1 Background

Maintaining soil fertility is critical to sustaining food security under the prevailing climate variability and increasing population. Conversely, deteriorating soil fertility reduces crop yields and increases the threat of food insecurity. Continuous cultivation and low soil replenishment are the leading causes of declining soil fertility (Shisanya et al., 2009). These unsustainable farming practices have resulted in soil degradation and reduced crop productivity. The innovation of integrated soil fertility management (ISFM) techniques that employ a judicious implementation of organic and inorganic nutrients offers potential solutions to ameliorate soil infertility and boost or sustain crop yields. In most semi-arid environments and Sub-Saharan Africa's small-scale farming systems, where soil fertility is declining (Badalucco et al., 2010), locally accessible organic inputs have been used to boost the organic matter content in soil and thus improve soil fertility (Kiboi et al., 2018).

The magnitude of deteriorating soil fertility corresponds to soil organic matter loss. Soil organic matter (SOM) significantly impacts the chemical, biological, and physical characteristics of soils, which in turn affect how productive they are (Mrabet, 2002). Hence the need to emphasize that the loss of nutrients and removal of organic matter through cultivation adversely affects agricultural production (Stolte et al., 2009). SOM is a significant source of soil organic carbon (SOC), phosphorous, nitrogen, and other macro and micronutrients. Soil organic carbon enhances nutrient transformation. The nitrogen cycle functions mainly on the energy derived from the carbon cycle, thus the importance of the C:N ratio. The depletion of soil carbon is affected by the characteristics of the local farming system.

Numerous studies show that compared to conventional farming, conservation farming (using soil organic inputs) results in soil with a considerably higher soil carbon stock. For example, Chivenge et al., (2007) reported conservation farming with soil organic inputs increases soil carbon stocks. It highlighted the need to tailor practices based on soil texture, emphasizing residue retention for coarse textured soils and reduced tillage for fine textured soils to optimize soil carbon content and agroecosystem sustainability. The study, conducted in Zimbabwe, portrayed similar characteristics to Mbeere South. It suggested that the coarse sand fraction in sandy soil responded positively to residue retention, implying that maintaining carbon inputs is essential for improving SOC content in such soils. In contrast, the fine sand fraction in clayey soil responded well to reduced tillage, indicating that minimizing tillage disturbance is crucial for reducing SOC decomposition in these soils. Gattinger et al., (2012) found notable increases in SOC concentrations, stocks, and the rate of sequestration in soils treated with external C inputs (farmyard manure). These findings highlight the potential of organic inputs to contribute to soil carbon accumulation. However, it's noted that the data primarily covered top soil and temperate zones, with limited representation from tropical regions and subsoil horizons. Page et al., (2020) reviewed the substantial role of conservation farming practices in increasing SOC leading to enhanced soil properties and yields, in semi-arid environments. The study underscored the importance of locally tailored systems and resources to overcome challenges and facilitate effective soil carbon buildup. The study aligns with the adoption of locally accessible organic inputs to boost soil fertility and increase organic matter content. Organic inputs-based farming is typically much richer in soil nutrients and more diverse in organisms than conventional systems (Gomiero et al., 2011). By adopting conservation farming practices and integrating organic inputs, such as crop residues and locally sourced organic matter, soil organic carbon levels can be further augmented (Krauss et al., 2022). Therefore, organic inputs contribute to the build-up of SOM and its associated benefits (Fairhurst, 2012). The amount of SOM is influenced by soil moisture availability. High soil moisture content promotes faster soil organic decomposition.

Improving SOM content and raising soil nutrients' bioavailability for improved soil quality requires good management of applied organic inputs (Kiboi et al., 2019). Maintaining a high SOM status is desirable in the long term due to its multiple beneficial effects attributable to its structure, such as its physical and water-holding capacity and good biological properties (von Lützow et al., 2002; Laudicina et al., 2012). Besides its dependence on edaphic factors, the SOM quality and quantity in agricultural soils can vary due to agriculture-related management techniques like applying organic inputs (Martyniuk et al., 2019). Soils can thus function as both C sources and sinks, contingent upon the chemical composition of SOM (Li et al., 2015), changes in the micro- and bioclimate, amount of biomass input (Zomer et al., 2017), and management.

Maximizing soil fertility inputs is vital for efficient nutrient turnover of organic and inorganic sources. Berti et al. (2016) observed farmyard manure as the most influential input, followed by crop residues in increasing soil C stocks. Green manure contributes to the amount of lignin, polyphenols, and available N in the soil, all of which aid in the formation of SOM, enhancing microbial activity, and C sequestration. Furthermore, the combining organic inputs with inorganic fertilizers increases SOM due to the supplementary effects of inorganic fertilizers and their interactive effects with organic inputs (Nayak et al., 2012). Inorganic fertilizers indirectly increase SOM by promoting higher plant biomass and crop residue inputs and, as well as influencing microbial activity.

1.2 Statement of the problem

Smallholder farmers experience food shortages due to declining agricultural productivity and land degradation associated with nutrient and soil carbon depletion. Conventionally, inorganic fertilizers are added to replace the lost nutrients with little regard for soil carbon status. However, most smallholder farmers face cost-related challenges of commercial inorganic fertilizers and lack the knowledge on how to incorporate organic inputs into their cropping systems (Shisanya et al., 2009). This exacerbates soil carbon and fertility decrease, becoming a significant constraint to improving food security. Soil fertility research over the years has established ISFM as a basic plan to promote crop productivity in small-scale farming systems sustainably. Combining organic and inorganic fertilizers can restore fertility, increase organic matter content and achieve better crop yields. However, there is limited knowledge of the quantities, composition, and stability dynamics of soil organic matter impacted by organic and inorganic inputs. This is knowledge that can assist farmers in making informed decisions on how to apply organic fertilizers to supplement inorganic fertilizers. The management strategies for building soil carbon have been the subject of numerous studies, but, 13C cross-polarization magic angle spinning (CPMAS) nuclear magnetic resonance (NMR) spectroscopy may be employed to structurally characterize SOM as well as analyze changes caused by various management methods (Berns et al., 2008; Knicker, 2011; Panettieri et al., 2013).

1.3 Justification of the study

Addressing the factors that control soil organic matter (SOM) stability, including its physicochemical environment and organic carbon chemical structure, is expected to yield significant socioeconomic and environmental benefits. This could result in improved nutrient availability for plants, enhanced carbon sequestration, and better soil health. The development of stable SOM fractions through reduced chemical recalcitrance could lead to increased agricultural productivity and resource efficiency. Measuring soil organic carbon (SOC) and understanding its dynamics can aid in achieving a balance between carbon input and output, influencing crop yields. Furthermore, by characterizing SOM, we can validate organic matter input, estimate carbon sequestration potential, and better manage carbon stocks, contributing to sustainable agricultural systems and addressing climate change concerns.

1.4 Objectives

1.4.1 Overall objective

The study's main objective was to determine the influences of organic and inorganic inputs on the chemical properties of the soil, the organic fractions, and the yield of maize in the Mbeere South sub-county.

1.4.2 Specific objective

i. To evaluate the effects of organic and inorganic inputs on chemical properties of soil.
ii. To determine the impact of organic and inorganic inputs on the soil carbon fractions.
iii. To assess the impact of organic and inorganic inputs on maize yield.

1.5 Hypotheses

The hypotheses tested in the study were as follows:

i. Organic and inorganic inputs do not have significant effects on soil chemical properties.
ii. Organic and inorganic inputs do not have significant effects on soil organic fractions.
iii. Organic and inorganic inputs do not have significant effects on maize yield.

1.6 Conceptual framework

Soil fertility and SOM declines are caused mainly by depleted nutrient levels, soil erosion, and inadequate farming practices. This results in low SOM hence affecting soil carbon content. Precipitation intensity, frequency, and spatial and temporal distribution are all impacted by climatic changes, exacerbating soil degradation and lowering crop yields. Incorporating organic, inorganic, or combination improves soil structure and fertility. This can ensure food security is achieved through increased agricultural productivity (Figure 1.1).

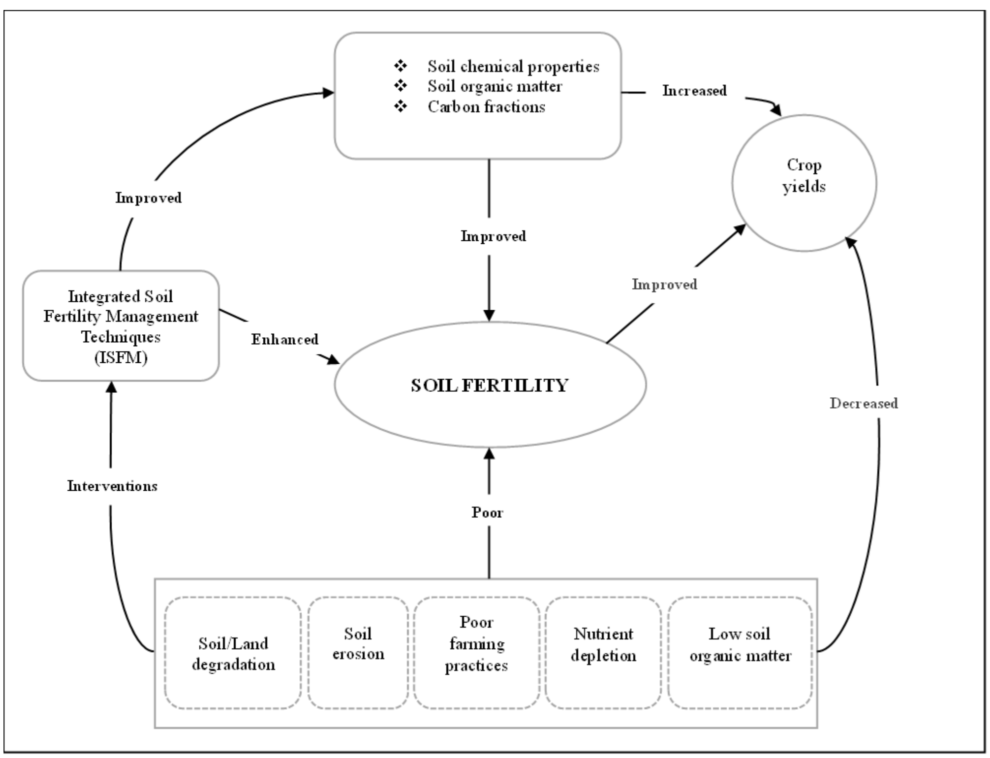

Figure 1.1. Conceptual framework.

CHAPTER 2
LITERATURE REVIEW

2.1 Overview

Maintaining soil fertility is critical to sustaining food security under the prevailing climate variability and increasing population. Deteriorating soil fertility reduces crop yields and increases the threat of food insecurity. Continuous cultivation and soil nutrient mining due to low levels of soil replenishment are the leading causes of declining soil fertility (Shisanya et al., 2009). Consequently, ISFM technologies that employ a judicious application of organic and inorganic soil amendments are used to mitigate nutrient mining, enhance soil, and increase or sustain crop productivity. Hence, within the majority of small-scale farming systems of Sub-Saharan Africa (SSA), locally available organic inputs are employed to counteract deteriorating soil fertility and boost SOM (Kiboi et al., 2018).

2.2 Organic inputs

Crop residues, green manures and animal manure are some of the important organic sources. Organic amendments are regularly used to improve the SOM levels and increase atmospheric CO_2 sequestration potential in soils (Yu et al., 2015). Thelen et al. (2010) described SOC storage in agricultural systems as a balance among organic amendments, carbon input from crop residues, and carbon losses. Crop residues are added to soil to increase soil quality and yields due to the beneficial influence on soil characteristics (Jordán et al., 2010). Crop residue mulching improves the organic matter content of cultivated soils. Increasing mulch application increases soil porosity, aggregates' stability, organic matter content, and decreased bulk density. This enhances the chemical properties of the soil. On the other hand, green manures, also called cover crops, are cultivated with the purpose of enhancing organic matter, nutrient content, and soil structure. They are typically incorporated into the soil before any crop is grown and frequently before the plants bloom. They boost and recycle organic matter and plant nutrients while also enhancing the soil's capacity to retain moisture.

Lantana camara is a good source of organic matter (Chattaerjee, 2015) in balanced proportions when introduced to soil despite being described as a noxious weed (Sharma et al., 1988). This, often classified as an invasive toxic plant species (Batianoff & Butler, 2003), has been incorporated as mulch to enrich the soil with organic matter (Rameshwar & Argaw, 2016). It is copiously available; therefore, farmers integrate Lantana to supplement chemical fertilizers. Lantana exhibits greater chemical recalcitrance due to its higher lignin content. The green biomass of Lantana is a high source of N and P content, accelerates the decomposition rate and nutrient release, and improves SOM and crop yield (Kumar et al., 2017; Wang et al., 2015).

Tithonia diversifolia is also identified as the Mexican flower. It is a perennial plant that decomposes quickly in soil and effectively provides crops with N, P, and K (Jama et al., 2000). Tithonia has high nutrient concentrations as it is categorized in class I high-quality residues, which contain lignin content of less than 15%, less than 4% polyphenol content, and exceeding 2.5% nitrogen (Gentile et al., 2011). It has been introduced to farms as green manure and revealed that the addition of fresh leaves and stems of Tithonia significantly supplies organic matter to the soil (WB et al., 2012; Habte, 2013) and increases crop yields (Ganunga et al., 2005; WB et al., 2012; Kolawole et al., 2014).

Mucuna Pruriens, also commonly known as velvet bean, is a leguminous plant that improves soil fertility when incorporated as green manure or a cover crop. Mucuna contributes to N-fixation in the soil, regulating the C: N ratio and increasing soil organic matter (Bayer et al., 2006). This SOM creates a carbon sink (Barthès et al., 2004), promoting SOC accumulation. Mucuna decomposes relatively slowly due to its high lignin content and high C: N ratios, exhibiting greater chemical recalcitrance. This recalcitrance contributes to stable SOC buildup. The combination of benefits of Mucuna on the chemical properties of soil eventually leads to increased crop yield. Kaizzi et al. (2004) study reported increased maize yields (25 to 68% increase) from Mucuna as a biological nitrogen-fixing plant.

Animal (farmyard) manure is a valuable organic input that provides essential nutrients for plant growth and enhances soil fertility. It preserves more nitrogen, enhancing its fertilizing capacity. Its application results in a higher organic matter content derived from angiosperms. Animal manures supplementing fertilizer significantly increase SOC. This study explored the benefits of animal manure as an organic fertilizer, with a particular emphasis on goat manure. While various animal manures, such as cattle and poultry manure, offer benefits as organic fertilizers, goat manure also has balanced nutrient composition, high micronutrient content, low C: N ratio, and reduced environmental impact (Ewulo, 2005; Abou El- Magd et al., 2006; Uwah et al., 2014; Des et al., 2015; Mbatha et al., 2021); Dhaliwal et al., 2021). The nutrient richness in goat manure contributes to its effectiveness as a fertilizer, promoting robust crop productivity. The increased micronutrient content in goat manure can help address soil nutrient deficiencies, supporting soil fertility. Goat manure contains low lignin content, making it more readily decomposable by soil microorganisms and less chemically recalcitrant. Goat manure offers environmental advantages compared to other animal manures. Due to its lower volume (pelleted) and reduced water content, goat manure generates less waste and occupies less space during storage and transportation.

2.3 Soil organic matter

A critical factor in the soil quality of semi-arid soils is soil organic matter (Jordan, Zavala, & Gil, 2010). Degradation of soil quality due to intensive soil use has resulted in subsequent loss of organic matter and lower yields (Reicosky et al., 1995). Soil organic matter has essential effects on soil structure, water relationships, and soil pH buffering. The best management of implemented organic inputs that increase the SOM content and soil nutrient bioavailability is necessary to ameliorate soil quality (Kiboi et al., 2019). Maintenance of a high SOM status is desirable in the long-term due to its multiple beneficial effects attributable to its structure, the influence on soil physical properties, and water holding capacity (Leifeld & Kainz, 2002). Besides its dependence on edaphic and environmental factors, the quality and quantity of SOM in agricultural soil change in response to agriculture-related management practices such as organic amendments (Martyniuk et al., 2019). Soils can therefore function as both sinks and sources of carbon contingent on management, biomass supply, microclimate conditions, changes in bioclimate (Zomer et al., 2017), and the chemical composition of SOM (Li et al., 2015).

2.4 Soil organic carbon fractions

Soil organic C, a measurable component of SOM, affects soil's biological, physical, and chemical characteristics (Were et al., 2015). It comprises inorganic and organic components (Wang et al., 2012). Its dynamics can denote the balance of C input and C output (Breulmann et al., 2010) and influence crop productivity. SOC accumulation is controlled by organic C input and SOC degradation rates. Given projected climate change, little is known about the capacity of soils to store C and thus act as sinks or sources to increase anthropogenic CO_2 concentrations (Trumbore, 2009; Solomon et al., 2012). Therefore, SOM characterization can serve as a soil input C sequestration potential indicator or a verification tool for SOM changes in accounting for C stocks (Leifeld and Ko, 2005) for different agricultural production systems.

O-alkyl C fraction is a component of SOM that represents the labile or easily decomposable fraction of organic compounds (Erhagen et al., 2013). It is associated with carbohydrates and is often used as an indicator of the readily available carbon pool in soils (Chen et al., 2004). These fractions can stabilize over time due to microbial processes and bonding to minerals. Inorganic inputs like mineral fertilizers indirectly affect O-alkyl by promoting root exudation and microbial activity, impacting organic matter decomposition (Ni et al., 2021). O-alkyl fraction varies depending on factors such as the type and composition of the inputs, soil properties, climate, management practices, and the overall balance of carbon inputs and outputs in the system (Sun et al., 2019). Additionally, long-term soil management practices, such as cover cropping, crop rotations, and conservation practices, can have cumulative effects on the O-alkyl fraction and overall soil organic matter dynamics.

Alkyl C fraction signifies the portion of organic carbon linked to alkyl groups (-CH3, -CH2-) in organic compounds, comprising hydrocarbon chains devoid of functional groups (Carrington et al., 2012). It is characterized as labile and easily decomposable, readily utilized by soil microorganisms for energy and nutrients, resulting in the release of carbon dioxide (CO_2) during decomposition (Kögel-Knabner 2002). Alkyl C serves as a vital energy source for soil microorganisms, supporting microbial activity, nutrient cycling, and soil fertility due to its rapid turnover. It commonly originates from plant and microbial residues in the soil ecosystem.

Aromatic C fraction constitutes the organic carbon fraction linked to aromatic rings, cyclic structures featuring alternating single and double bonds (Lützow et al., 2006). These compounds often stem from lignin, a complex plant tissue polymer. Aromatic C exhibits higher recalcitrance (Ahmed, 2018) and resistance to decomposition in comparison to other carbon fractions due to its intricate structures and chemical stability, requiring more time for microbial breakdown. It contributes to soil aggregation and stability, facilitating the formation of enduring organic matter. Moreover, it impacts nutrient cycling, soil structure, and the long-term preservation of organic carbon in the soil ecosystem.

Methoxyl C fraction comprises the fraction of organic carbon associated with methoxy (-OCH3) functional groups in complex organic compounds, typically found in substances like lignin (Li et al., 2015) . It is notably resistant to microbial decomposition, contributing to the stability of organic compounds containing methoxyl groups (Yao et al., 2022). Its role involves both chemical and physical protection of SOM, forming stable complexes with minerals and enhancing soil aggregation. Its persistence in the soil influences soil properties such as structure, nutrient cycling, and water retention, playing a pivotal role in soil health and carbon cycling dynamics.

Carboxyl C fraction denotes the organic carbon fraction connected to carboxyl (-COOH) functional groups, commonly present in organic acids like humic and fulvic acids (Klučáková & Kolajová, 2014). Its stability varies based on complexation and specific compounds, influencing both labile and recalcitrant carbon fractions through chemical interactions. Carboxyl C contributes to soil acidity and cation exchange capacity, affecting pH, and nutrient availability. Moreover, carboxyl groups participate in the creation of humic substances, promoting soil fertility and the stability of organic matter (DiDonato & Hatcher, 2017).

Phenolic C fraction represents the organic carbon fraction associated with phenolic compounds characterized by a phenol (-OH) group attached to an aromatic ring, commonly found in plant residues (Kokaly & Skidmore, 2015). It is highly recalcitrant and stable due to the complex molecular structures and chemical properties of phenolic compounds that hinder microbial breakdown(Min et al., 2015). Despite their resistance to decomposition, phenolic compounds play essential roles in the soil, exhibiting antioxidant and allelopathic properties that impact plant-microbe interactions, nutrient availability, and soil chemistry. Additionally, they contribute to the formation of stable humic substances (Klučáková & Kolajová, 2014), preserving organic matter over extended periods in the soil ecosystem.

Verchot et al. (2011) and Gillespie et al. (2014) noted that differences in SOC functional groups stabilize C fractions under different input treatments. Also, compared to mineral fertilizer application, organic manure has the potential to decrease the alkyl C/O-alkyl C ratio and aromatic C of SOC following years of ongoing fertilization (Li et al., 2015). Identifying SOC fractions can help reveal shifts and trajectories in the soil carbon pools at the initial stages of changes in soil fertility and land-use management.

2.5 NMR spectroscopy

To structurally characterize SOM as well as to analyze changes caused by the various management methods ^{13}C cross-polarization magic angle spinning (CPMAS) nuclear magnetic resonance (NMR) spectroscopy could be implemented (Berns et al., 2008; Knicker, 2011; Panettieri et al., 2013). Since most SOM-constituting compounds have poor solubility, solid-state NMR spectroscopy is appropriate for in-depth characterization. NMR spectroscopy involves subjecting nuclei to a magnetic field and determining the energy level required to bring different nuclei into resonance (Freitas et al., 2012). The NMR spectrum provides peaks/signals that help determine the structure of carbon fractions in soil samples (Martínez-Richa and Silvestri, 2017). The number of peaks in the spectrum equals the number/type of hydrogen or other atoms in a molecule (Freitas et al., 2016). The major

C forms in ^{13}C NMR spectra of soil samples often identified include carboxyl, methoxyl, aromatic, O-alkyl, alkyl C, and phenolic C. Solid-state CPMAS ^{13}C NMR can provide an extensive understanding of C composition (Normand et al. 2017). Based on chemical peak changes, it determines the organic functional groups present in organic matter whose molecular make-up and microbial use vary (Knicker, 2011). Hence, NMR spectroscopy can be applied to evaluate changes and trajectories in the soil C pools at various stages of changes in soil fertility and land-use management (Ndung'u et al., 2021).

CHAPTER 3

MATERIALS AND METHODS

3.1 Study area

The study was conducted in Machang'a (-0.790791, 37.6625) Secondary school situated in the sub-county of Mbeere South, Embu County, Kenya (Figure 3.1). It is accessible to the local farmers who are interested in learning about the research on soil fertility management methods.

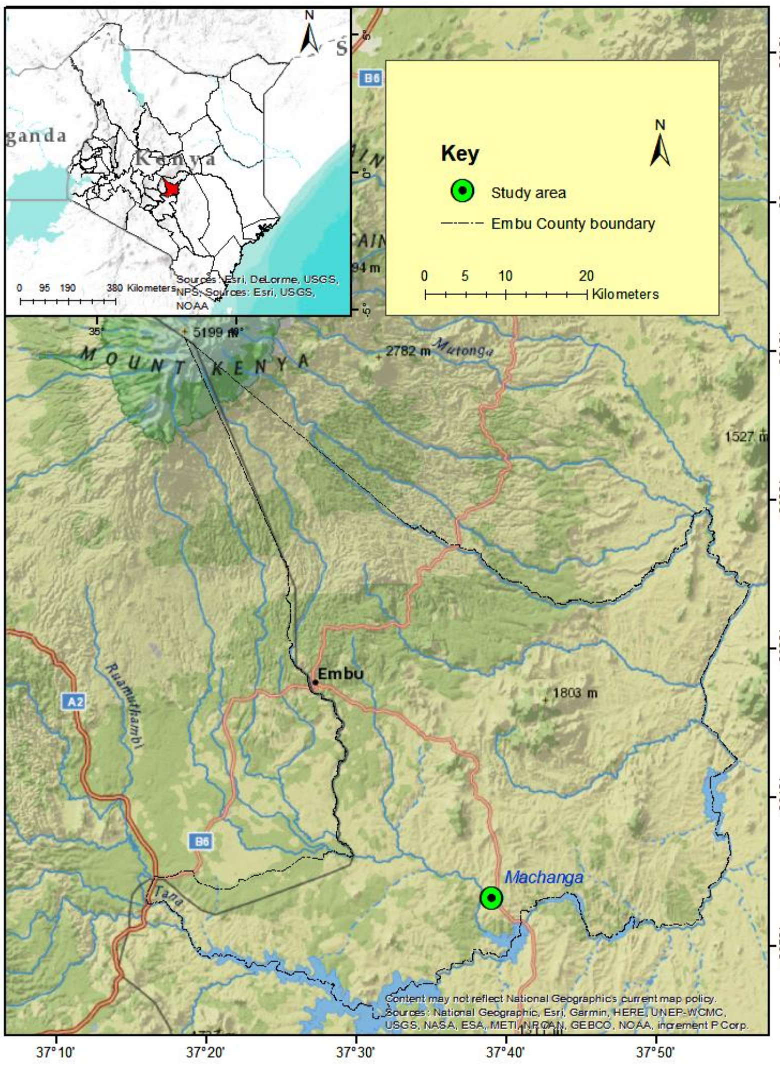

Figure 3.1. Map indicating the location of the research site.

Most of the soils are sandy-clay-loam, in the classification of Nitro-rhodic Ferralsols (FAO 1991), and are either blackish-grey or reddish-brown. They are typically low in fertility and require intensive manuring and continuous fertilization throughout the year (Micheni et al., 2004; Jaetzold et al., 2006). Insufficient additional organic material inputs and inadequate water erosion control cause soils to rapidly deplete organic matter, including aggregates rich in nutrients, within the first three to four years of cultivation. Soils are shallow (approximately 1 m in depth) (Micheni et al., 2004; Jaetzold et al., 2006). The site's predominant soil type is sandy clay loam, which contains about 60% sand, 10% silt, and 30% clay (Ngetich et al., 2014). On average, typical 0-15 cm topsoil of Machang'a has a pH of 6.4, about 0.1% total N, 1% total organic C (TOC), 12 mg kg^{-1} bicarbonate extractable P, 1.49 $Cmol_c$ kg^{-1} exchangeable cation exchange capacity (ECEC), 0.35, 1.0, and 1.49 $Cmol_c$ kg^{-1} of exchangeable K, Ca, Mg, respectively (Mucheru-muna et al., 2010).

The study area is located in the agro-ecological zone of marginal cotton (lower midland 4 - LM 4) (Jaetzold et al., 2006). The area experiences a bimodal precipitation pattern, with a long rainfall (LR) spanning from March to June and a short rainfall (SR) occurring between October and December.. The mean annual rainfall ranges from 800 to 900 mm, and the total amount of precipitation is unreliable.

The site is typical of the low-potential agriculturally marginal region found in Lower Midland Agro-ecological Zones 4 (LM4). A short cropping season is a characteristic of the Lower Midland 4 cotton (*Gossypium hirsutum*)/livestock-millet (*Pennisetum glaucum* and *Eleusine coracana*) zone. Cowpeas (*Vigna unguiculata*), common beans (*Phaseolus vulgaris*), green grams (*Vigna radiata*), chickpeas (*Cicer arietinum*), dryland composite and hybrid maize - sorghum (*Sorghum bicolour*), including other crops, are also suitable for this zone (Jaetzold et al., 2006). This depicts the agro-climatic conditions that are almost semi-arid and have a low potential for agricultural output. Because the area is better suited for livestock and drought-tolerant crops (Jaetzold et al., 2006), the most prevalent domestic crops are maize, pigeon peas (*Cajanus cajan*), cowpeas, as well as common beans (*Phaseolus vulgaris*) (Ngetich et al., 2014).

3.2 Experimental layout and management

Experiment plots were 6 m by 4.5 m and set up in a randomized complete block design replicated three times. The trial crop was maize (*Zea mays* L, var. DH04) was sown at 0.9m and 0.6m inter- and intra-row distances, respectively. DH04 variety was developed for Kenya's semi-arid and lowland areas because it matures early and requires little water. The variety is adapted to marginal areas of Kenya at elevations ranging from 100 to 1200 meters above sea level. Each hole received three seeds, which were thinned into two plants after four weeks. *Tithonia diversifolia* (TD), *Lantana camara* (LC), *Mucuna pruriens* (MP), as well as goat manure (GM) were the organic sources. A total of 60 kg N ha^{-1} was obtained using external nutrient replenishment inputs (Table 3.1).

Table 3.1. Experimental treatments and amounts of N supplied by the different treatments

Treatments	**Abbreviation**	**N from biomass (kg N ha^{-1})**	**N from inorganic fertilizer (kg N ha^{-1})**
Control	Ctrl	0	0
Goat Manure	GM60	60	0
Inorganic fertilizer (30 kg ha^{-1} N)	IF30	0	30
Inorganic fertilizer (60 kg ha^{-1} N)	IF60	0	60
Goat Manure + Fertilizer (30 kg ha^{-1} N)	GM+IF30	30	30
Inorganic fertilizer (90 kg ha^{-1} N)	IF90	0	90
Lantana camara	LC60	60	0
Lantana camara + Inorganic Fertilizer (30 ha^{-1} N)	LC30+IF30	30	30
Mucuna pruriens	MP60	60	0
Mucuna pruriens + Inorganic Fertilizer (30 kg ha^{-1} N)	MP30+IF30	30	30
Tithonia diversifolia	TD60	60	0
Tithonia diversifolia + Inorganic Fertilizer (30 kg ha^{-1} N)	TD30+IF30	30	30

The recommended N rate above indicates nutrient requirements for maize to ensure optimal crop production (FURP, 1987), apart from the herbaceous legume treatment, which bases its N content on the amount of harvested biomass added to the specific treatments. *Lantana camara* and *Tithonia diversifolia* were harvested from adjacent plots set up for the research (biomass transfer). Table 3.2 data shows the N content of all organic inputs, and the amounts required to provide 30 or 60 kg N were calculated.

Table 3.2. Nutrient composition of organic inputs used throughout the experiment

Treatment	**N** (%)	**P** (ppm)	**Ca** (me%)	**Mg** (me%)	**K** (me%)
GM	2.0	0.7	4.3	1.2	4.2
TD	3.0	0.2	2.2	0.6	2.9
LC	1.5	0.1	1.1	0.4	0.8
MP	2.4	0.1	1.2	0.2	0.7

*me% - milliequivalence percent

Where: LC60 - *Lantana camara*, GM60 - Goat Manure, MP60 - *Mucuna pruriens*, and TD60 - *Tithonia diversifolia*.

At the onset of each season, the organic inputs were collected (from the hedgerows and those planted on the soil conservation structures/terraces). Subsequently, these inputs were then dried under a shade, chopped, and weighed the required amounts per plot. Organic inputs were integrated to a 15 cm depth into the soil during land preparation. Mineral N, in the form of calcium ammonium nitrate (CAN), was introduced in two stages: 1/3 was applied as a top dressing after four weeks, and the remaining 2/3 after six weeks of planting. Phosphorus (P), on the other hand, was uniformly applied across all plots at the prescribed rate of 60 kg P ha^{-1} as triple super phosphate (TSP). This approach was adopted to minimize any unexpected influence of P particularly because organic inputs were used in the experiment, and these inputs often have limited P availability due to their low P content (Palm et al., 1997). Thus, it implied that nitrogen was the primary limiting macronutrient for maize yields. Following planting, all other necessary agronomic practices for maize production were properly carried out.

When the maize reached maturity, harvest was conducted within a 21 m^2 out of the total 27 m^2 plot. To mitigate any potential edge effects, one row of maize on each side of the plot, as well as the first and last maize plants, were intentionally left unharvested. The dry matter content of maize grains was measured after drying. All of the maize stovers in the experimental plots were harvested to prevent any nutrients from the stovers from returning to the plots and interfering with the impacts of adding material with distinct qualities.

Stover samples underwent a 72-hour drying process in an oven at 70°C to evaluate their moisture levels, which were used to convert field-measured stover yields to dry matter produced. Once dry hand-shelling, weighing, and grain moisture content determination (Dickey-john MiniGAC® moisture meter equipped with a moisture range spanning from 5% to 45% with a 0.02% precision) (http://www.dickey-john.com/product/mini-gac/) were done. To standardize the yields, grain weight correction was done by comparing the determined weight with the measured moisture content in order to achieve a standard moisture level of 12.5%. The grain weight was then presented on Mg per hectare basis.

Soil samples were collected at the end of the 2017 short rains growing season (February 2018). Before sampling, the surface was cleared of obvious plant debris and other obvious organic material. Each experimental plot had seven disturbed soil sub-samples taken at 0 to 15 cm depth using a stainless Edelman auger, composited, and resampled. The composite samples were then air-dried and split into two portions per sample. For NMR analysis, one portion of about 50 g was put into 60 ml plastic vials, labeled, and dispatched for analysis to the National High Magnetic Field Laboratory, USA. The second portion of about 60 g was put into plastic bags, labeled, and shipped to the National Agriculture Laboratories, Kenya, for carbon analysis.

3.3 Parameters

The following parameters were: (i) pH, (ii) Total nitrogen, (iii) Potassium, (iv) Phosphorous, (v) Soil organic carbon, and (vi) Maize yield.

3.4 Laboratory analysis

Soil samples and organic amendments were air-dried to constant weight, ground using an automatic grinding machine, and sieved through a 100-mesh sieve prior to analysis.

Soil pH: pH was determined following the Soil-Potassium chloride solution (KCl) system method as described in FAO, (2022).

Nutrients: The organic C was determined using the modified Walkley and Black method, and total N using the Kjeldahl method (Ryan et al., 2001). The Olsen method, as described by Olsen and Sommers (1982) was used to determine total P. Potassium (K) was measured with a flame photometer following extraction with 20 ml of Mehlich 3 solution, as outlined in Mehlich (1984).

Carbon fractions: The characterization of soil organic matter (SOM) was conducted using ^{13}C solid-state nuclear magnetic resonance (ssNMR) (Ndung'u et al., 2021).

3.4.1 Soil pH

The procedure involved weighing 10.0 g of soil sample and adding 50 mL of 1.0 M potassium chloride solution in a polyethylene bottle. The soil-KCl mixture was shaken for 60 minutes using glass rods for homogenization. After allowing it to stand for 60 minutes, the pH was measured in the unstirred supernatant at a stable 25 °C temperature using a pH electrode. The obtained pH values were recorded.

3.4.2 Total nitrogen

The Kjeldahl procedure was used to obtain nitrogen (Ryan et al., 2001). The portion of nitrogen nitrate (NO_3-N) in the soil was reduced and distilled. A 15 mm ground soil sample was mixed thoroughly, and then ten small parts were taken to obtain a representative sample of 3 g of nitrogen. 250 ml graduated digestion tubes containing 0.01 g of the sample were then filled with 10 ml of distilled water, and the soil was vigorously spun to moisten it. The tubes were then left for 30 minutes.

Each batch containing 0.1 g of EDTA standard digest and a blank digest was prepared. After adding 10 ml potassium permanganate solution, the digestion tube was kept at a 45° angle as 20 ml 50% sulfuric acid was cautiously added. After letting it sit for 15 minutes, the mixture was swirled. The blank, EDTA, and sample digest tubes were each filled with a small quantity of boiling pumice granules. 2.5g of reduced iron was added, swirled, and 5ml distilled water also added to reduce excess frothing, then left overnight.

The samples were heated at 100°C on a cold block for an hour to pre-digest them. The samples were taken out of the block digester and stirred for 45 minutes before cooling. Then, each tube received 5 g of the catalyst mixture and 25 ml of concentrated sulfuric acid, which were thoroughly mixed. The tubes were returned to the preheated block digester, heated to 240°C, boiled for one hour, and further heated to 380°C for 4 hours. After digestion, 50 ml of deionized water was added, the solid residue was separated, and additional DI water was added to reach a final volume of 250 ml.

Prior to distillation, the contents within the digestion tube were thoroughly mixed, and then promptly, 50 ml of this mixture was transferred into a 250 ml distillation flask. Distilling the acid digests was done using extra NaOH. The condenser tip was positioned to touch the surface of a saturated solution of boric acid and distilled water in a 100 ml Pyrex evaporating dish. The distillation flask containing the digest was then held at a 50° tilt, a sufficient amount of 10N NaOH cautiously discharged, and the distillation process began.

The steam source was switched off once approximately 35 ml of distillate was obtained. DI water was used to wash the condenser tip into an evaporating dish. The Auto-Titrator was used to titrate the distillate to a pH of 5.0 using standardized 0.01 N H_2SO_4. Different samples were steam-extracted. In the distillation apparatus, the flasks containing the digested sample and NaOH were then replaced with empty 100-ml distillation flasks. An empty 100-ml beaker was put under the condenser's top; the cooling water source was disconnected and then steamed. Each distillation contained a minimum of two standards and two blanks. Equations 1 and 2 were then used to determine the percentage N.

$$\% \, Recovery = \frac{(V-B)\times N\times R\times 186.1\times 100}{Wt_1\times 1000} \qquad \textbf{Equation 1}$$

$$\% \, N = \frac{(V-B)\times N\times R\times 14.01\times 100}{Wt_2\times 1000} \qquad \textbf{Equation 2}$$

Where: V is the volume of 0.01 N H_2SO_4 titrated for the sample (ml),

B is the digested blank titration volume (ml),

N is the normality of H_2SO_4 solution,

14.01 is the atomic weight of N,

R is the ratio between the total volume of the digest and the digest volume used for distillation,

Wt_1 is the Weight of EDTA (g),

Wt_2 is the weight of air-dry soil (g), and

186.1 is the equivalent weight of the EDTA.

3.4.3 Total phosphorus

The Olsen and Sommers' (1982) method was employed to assess total phosphorus content in soil by dissolving all insoluble inorganic minerals and organic phosphorus forms. This procedure involved placing 2 g of air-dried soil, along with 30 ml of 60% perchloric acid and boiling pumice granules, into a 250 ml digestion tube within a digestion chamber. Using a block digester, the temperature was incrementally raised from 100°C to 180°C until thick white acid fumes were observed, which took approximately 40 minutes. Additional perchloric acid was used to wash the sides of the digestion tube as needed, and heating was maintained at a boiling temperature for an extra 15 minutes, resulting in the formation of an insoluble substance akin to white sand.

A Whatman No. 1 filter paper was used to filter the mixture following the addition of 250 ml of distilled water and cooling. A 50 ml volumetric flask was filled with a little more than 5 ml of sample digest, along with 10 ml of the ammonium-vanadomolybdate reagent, and then diluted to volume using DI water. A standard curve was created by dispensing 5 ml and preparing a blank containing 10 ml of ammonium-vanadomolybdate reagent. Absorbance of the blank, standards, and samples was then measured. The absorbance was plotted against each P concentration to create a calibration curve. The P concentration in the unknown samples was measured using the calibration curve and calculated using Equation 3.

$$TotalP(ppm) = ppmP(fromcalibrationcurve) \times \frac{A}{W_t} \times \frac{50}{V} \qquad \textbf{Equation 3}$$

Where: A is the total volume of the digest (ml),

W_t is the weight of air-dry soil (g), and

V is the volume of digest used for measurement (ml).

3.4.4 Extractable potassium

Using the flame photometric method, the soil exchange complex's cations are substituted by a neutral salt solution (Ryan et al., 2001). 5 g of air-dried soil and 33 ml of ammonium acetate solution were mixed thoroughly for 5 minutes in a 50 ml centrifuge tube. The tubes were centrifuged until the supernatant became transparent. A 100 ml volumetric flask was used to accumulate the extract after passing it through filter paper to remove any soil particles. Extracts were taken each time as this procedure was conducted two times. The combined extracts were diluted to 100 ml with a 1 N ammonium acetate solution. A calibration curve was created using a number of suitable potassium standards. Equation 4 was used to obtain emission readings from a Flame Photometer at a wavelength of 767 nm from the extracted samples. The standard curve was used to determine the potassium (K) level.

$$Extractable\ K\ (ppm) = ppm\ K\ (from\ calibration\ curve) \times \frac{A}{W_t} \qquad \textbf{Equation 4}$$

Where: A is Total volume of the extract (ml)

W_t is the weight of air-dry soil (g)

3.4.5 Organic carbon

The Ryan et al. (2001) method was used to measure the amount of organic carbon. 10 ml of 1 N potassium dichromate was added after weighing 0.5 g of sieved air-dried soil into a 500 ml wide-mouth conical flask. 15 ml of concentrated sulfuric acid was quickly added into a fume cupboard, with the flow aimed into the suspension. The flasks were initially slowly swirled to ensure that the soil and chemicals were combined, then vigorously swirled for a minute and left to stand for 30 minutes. It was then combined with 150 ml of distilled water, cooled, and then mixed with 10 ml of 85% orthophosphoric acid and ten drops of diphenylamine indicator. 0.5 N ammonium ferrous sulfate was used to titrate the solutions. Equations 5 and 6 were used to determine the organic carbon content.

$$\%OrganicCarbon = \frac{V_{Blank-V_{Sample}} \times M \times B \times 10^{-5} \times 100}{W_t}$$ **Equation 5**

Where: V_{Blank} is the volume (ml) of ferrous ammonium sulfate solution to titrate the blank,

V_{Sample} is the volume (ml) of ferrous ammonium sulfate solution required to titrate the sample,

W_t is the weight (g) of air-dry soil, 3 x 10^{-3}=Equivalent weight of carbon, 100 is the percentage,

M is the molarity of ferrous ammonium sulfate solution (approximately 0.5M, i.e., $10/V_{Blank}$).

Equation 6 was used to calculate the amount of organic matter and the organic carbon factor.

$$\%OrganicMatter(w/w) = 1.724 \times \%TotalOrganicCarbon$$ **Equation 6**

3.4.6 Soil carbon fractions

Ground soil and organic amendments samples were analyzed using magic angle spinning (MAS) ^{13}C ssNMR, on a Bruker 4.0 mm double resonance MAS NMR probe equipped 300 MHz NMR spectrometer (Bruker DRX300 - https://einstei nmed.org/research/shared-facilities/nmr/bruker-drx300/). Before spinning to 9.5 kHz ± 3 Hz at RT using a Bruker pneumatic MAS control unit, samples were packed into 4.0 mm zirconia rotors with Kel-F drive caps. Through cross-polarization, i.e., A 4.0 μs 1H π/2 pulse followed by a ^{1}H spin-lock field of 45 kHz for 1.0 ms contact time, and the ^{13}C RF field ramped from 35 to 50 kHz, all ^{13}C signals were enhanced. Under the irradiation of the SPINAL64 decoupling sequence, and with a ^{1}H RF amplitude of 62.5 kHz, ^{13}C signals were recorded (Fung et al., 2000). The signals were accumulated using 10,000 and 50,000 scans, with recycle delays of

2s depending on the samples. Based on assignments from Knicker (2011), the spectral regions were integrated to determine the contribution of each C functional group in the sample: alkyl (0–45 ppm), methoxyl (45–60 ppm), O-alkyl (60–110 ppm), aromatic (110–140 ppm), phenolic (140–160 ppm), and carboxyl (160–220 ppm). The functional group's %C was converted to g functional group per kg sample using soil C values of the soil samples, after which the ^{13}C chemical shifts were referenced to the carbonyl C of glycine at 176.4 ppm.

3.5 Data analysis

SAS 9.4 (SAS Institute, 2004) was used to analyze the data. Soil carbon, nitrogen, and grain yields were subjected to analysis of variance to establish the effects across the treatments. The least significant difference (LSD), at $p = 0.05$, was used in mean separation. The relationship of grain yields against soil N or soil C was evaluated by subjecting the data to bivariate Pearson Correlation to produce a correlation coefficient.

CHAPTER 4

RESULTS

4.1 Effects of organic and inorganic inputs on soil chemical properties

4.1.1 Carbon fractions of the organic inputs

The total C of MP60, GM60, LC60, and TD60 were 40.53 g kg^{-1}, 40.13 g kg^{-1}, 39.8 g kg^{-1}, 36.52 g kg^{-1}, respectively (Figure 4.1). The O- alkyl C fraction was comparatively the highest across the organic inputs, ranging from 19.14 g kg^{-1} in TD to 25.83 g kg^{-1} in LC60. It was evident that alkyl was the second-highest fraction. The Alkyl C fraction was highest in GM60 (10.35 g kg^{-1}) and lowest in MP60 (5.03 g kg^{-1}). Aromatic C and methoxyl C fractions did not vary much across the organic inputs. Compared to the other soil organic inputs, GM60 had the lowest carboxyl C and phenolic C content (0.71 g kg^{-1} and 0.46 g kg^{-1}, respectively) compared to the other inputs.

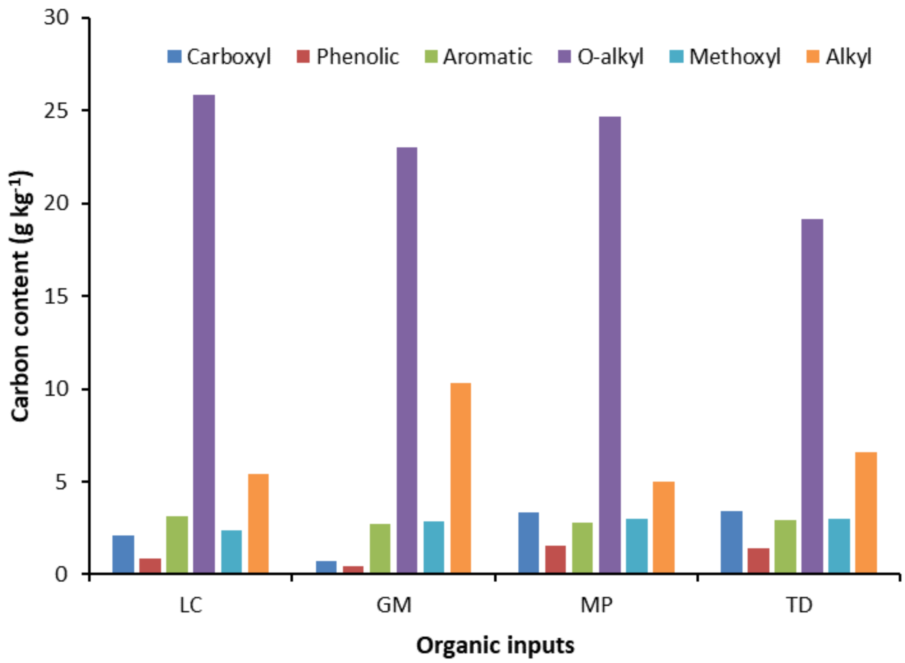

Figure 4.1. Carbon fractions composition of the organic inputs used in the experiment. Where: LC60 - *Lantana camara*, GM60 - Goat Manure, MP60 - *Mucuna pruriens*, and TD60 - *Tithonia diversifolia*.

4.1.2 Soil organic carbon fractions

For the relative abundance of C functional groups, based on ^{13}C NMR spectra of the different soil input treatments, a declining trend was observed from soils treated with only organic amendments, followed by soils with organic + inorganic amendments, and then soils with only inorganic amendments (Figure 4.2). The reported high C content under organic amendments was consistent with Goyal et al. (1999). The carbon functional groups of the soil treated with sole organic inputs was in the order of O-alkyl C > alkyl C >methoxyl > carboxyl > aromatic C content, with GM60 treatment having the highest fractions. The C fractions in the inorganic fertilizer-based treatments were closely identical to the control (Figure 4.2).

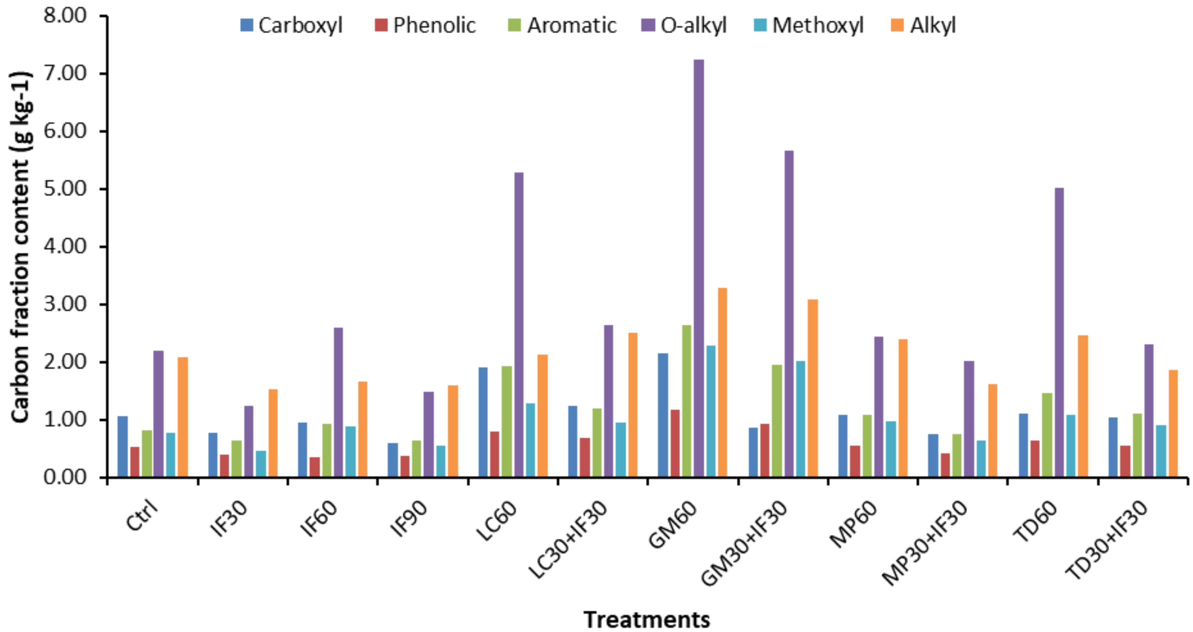

Figure 4.2. The total amount of each soil C fraction (Carboxyl, Phenolic, Aromatic, O-alkyl, Methoxyl, and Alkyl) in each treatment.
Where: Ctrl - the Control; IF30 - Inorganic fertilizer (30 kg ha^{-1} N); IF60 - Inorganic fertilizer (60 kg ha^{-1} N); IF90 - Inorganic fertilizer (90 kg ha^{-1} N); LC60 - *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 - *Lantana camara* +Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); GM60 - Goat Manure (60 kg ha^{-1} N); GM30+IF30 - the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 - *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 - *Tithonia diversifolia* (60 kg ha^{-1} N); and TD30+IF30 - *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

4.1.3 Macronutrients (Total nitrogen, phosphorus, and potassium)

The Chemical analysis was done for total nitrogen, phosphorus, and potassium. Total nitrogen (%) in soil: Table 4.1 shows the amount of total nitrogen from each treatment. Both the plots with the goat manure and GM30+IF30 treatments recorded maximum available nitrogen in the soil of 0.14%, while the minimum available nitrogen in the soil was recorded in the plot treated with IF90. The available nitrogen in the control treatment was found to be 0.09%, which is not significantly different from the MP, LC30+IF30, TD30+IF30, MP30+IF30, and IF60 treatments.

Table 4.1. Nutrient concentration

Treatment	**Total N (%)**	**P (ppm)**	**K Cmol/kg**
GM60	0.14^{a}	154.7^{a}	1.9^{a}
M60	0.09^{c}	112.5^{ab}	0.6^{cd}
LC30+IF30	0.08^{c}	90.0^{ab}	0.7^{bcd}
TD30+IF30	0.09^{c}	106.7^{ab}	0.6^{cd}
IF30	0.07^{cd}	76.7^{b}	0.3^{d}
MP30+IF30	0.09^{c}	106.7^{ab}	0.3^{d}
TD60	0.12^{b}	103.3^{ab}	1.1^{bc}
IF90	0.06^{d}	135.0^{ab}	0.2^{d}
IF60	0.09^{c}	126.7^{ab}	0.4^{d}
GM30+IF30	0.14^{a}	117.3^{ab}	2.2^{a}
LC60	0.12^{ab}	112.0^{ab}	1.2^{b}
Ctrl	0.09^{c}	153.3^{a}	0.4^{d}
LSD	0.0207	64.967	0.5896
P value	<.0001	0.4727	<.0001

* Mean with same superscript letters indicate no significant difference between treatments.

Where: Ctrl - the Control; IF30 - Inorganic fertilizer (30 kg ha^{-1} N); IF60 - Inorganic fertilizer (60 kg ha^{-1} N); IF90 - Inorganic fertilizer (90 kg ha^{-1} N); LC60 - *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 - *Lantana camara* +Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); GM60 - Goat Manure (60 kg ha^{-1} N); GM30+IF30 - the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 - *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 - *Tithonia diversifolia* (60 kg ha^{-1} N); and TD30+IF30 - *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

The treatments did not significantly influence total phosphorous, while Table 4.1 shows that the available potassium (cmol kg^{-1}) among the treatments was significantly different. The plot treated with GM30+IF30 recorded maximum available potassium in the soil of 2.2 cmol kg^{-1}. Minimum available potassium in soil was observed in IF90 treatment with 0.2 cmol kg^{-1}.

Table 4.2, based on the experiment, illustrates how the soil pH varies between the various treatments. Soil pH in the different treatment plots ranged from 4.8 to 8.0, revealing acidic to slightly alkaline soils. The maximum pH of 8.0 was recorded in treatment GM60. Soil analysis reveals significantly different soil pH among the treatments when subjected to statistical analysis. The experimental soil has a pH range of 7.36 to 7.85, indicating it is slightly alkaline in reaction. The pH of soil shows an increasing trend.

Table 4.2. Soil pH

Treatment	**Soil pH**
GM60	7.97^{a}
M60	5.42^{ef}
LC30+IF30	6.14^{cd}
TD30+IF30	5.70^{de}
IF30	5.02^{fg}
MP30+IF30	5.09^{fg}
TD60	6.51^{bc}
IF90	4.80g
IF60	6.03^{ed}
GM30+IF30	7.87^{a}
LC60	6.86^{b}
Ctrl	5.89^{de}
LSD	*0.5248*
P value	*<.0001*

* Mean with same superscript letters indicate no significant difference between treatments.

Where: Ctrl - the Control; IF30 - Inorganic fertilizer (30 kg ha^{-1} N); IF60 - Inorganic fertilizer (60 kg ha^{-1} N); IF90 - Inorganic fertilizer (90 kg ha^{-1} N); LC60 - *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 - *Lantana camara* +Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); GM60 - Goat Manure (60 kg ha^{-1} N); GM30+IF30 - the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 - *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 - *Tithonia diversifolia* (60 kg ha^{-1} N); and TD30+IF30 - *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

4.2 Effects of organic and inorganic inputs on soil organic fraction

4.2.1 O-alkyl C

O-alkyl C was the dominant C fraction among the different functional groups under different treatments (Figure 4.3). Compared to the control, GM60 treatment had significantly ($p<0.001$) the highest content (231%) followed by GM30+IF30 (159%), then sole LC60 (142%) followed by TD60 (129%) (Figure 4.3). Compared to the control, slight differences were observed in the remaining treatments ranging from -44% in IF30 to 21% in LC30+IF30. The O-alkyl C content in the sole inorganic fertilizer treatments was generally low, with IF30 and IF90 having significantly ($p<0.001$) lower O-alkyl C (about -44% and -33%, respectively) than that of the control. IF60, LC30+IF30, MP30+IF30, TD30+IF30 and MP60 treatments were not significantly different from the control.

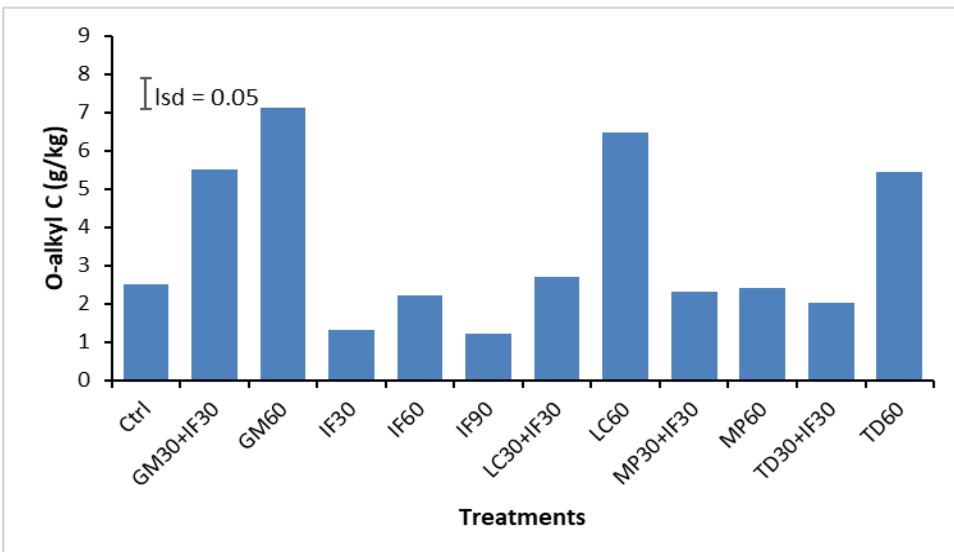

Figure 4.3. The total amount of O-alkyl C fraction in each treatment.
Where: Ctrl - the Control; IF30 - Inorganic fertilizer (30 kg ha^{-1} N); IF60 - Inorganic fertilizer (60 kg ha^{-1} N); IF90 - Inorganic fertilizer (90 kg ha^{-1} N); LC60 - *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 - *Lantana camara* +Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); GM60 - Goat Manure (60 kg ha^{-1} N); GM30+IF30 - the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 - *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 - *Tithonia diversifolia* (60 kg ha^{-1} N); and TD30+IF30 - *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

4.2.2 Alkyl C

The GM60 treatment had significantly ($p<0.001$) the highest Alkyl C content (58%) followed by GM+IF30 (48%) treatment, then LC30+IF30 (20%) and TD60 (19%), compared to the control (Figure 6). Except for MP60, all the other treatments (LC60, IF60, IF90, MP30+IF30, TD30+IF30, IF30) had significantly lower Alkyl C content than the control (Figure 4.4).

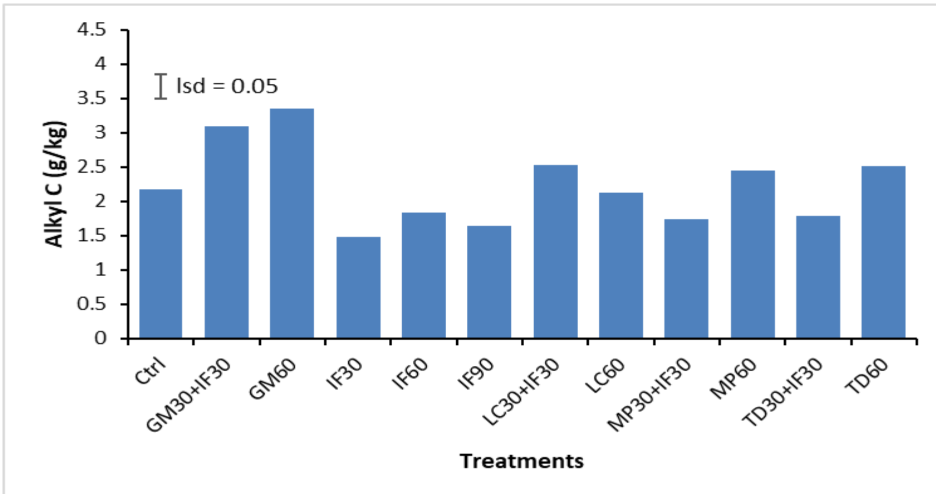

Figure 4.4. Total amount of Alkyl C fraction in each treatment.

Where: Ctrl - the Control; IF30 - Inorganic fertilizer (30 kg ha^{-1} N); IF60 - Inorganic fertilizer (60 kg ha^{-1} N); IF90 - Inorganic fertilizer (90 kg ha^{-1} N); LC60 - *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 - *Lantana camara* +Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); GM60 - Goat Manure (60 kg ha^{-1} N); GM30+IF30 - the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 - *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 - *Tithonia diversifolia* (60 kg ha^{-1} N); and TD30+IF30 - *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

4.2.3 Aromatic C

Compared with control, GM60, LC60, GM30+IF30, LC30+IF30, TD60, and TD30+IF30 treatments had significantly ($p<0.001$) higher aromatic C contents (Figure 4.5). The aromatic C content in soils treated with MP60, IF60, and MP30+IF30 treatments was not significantly ($p<0.001$) different from the control, while those of IF30 (by -22%) and IF90 (by -23%) treatments were significantly lower.

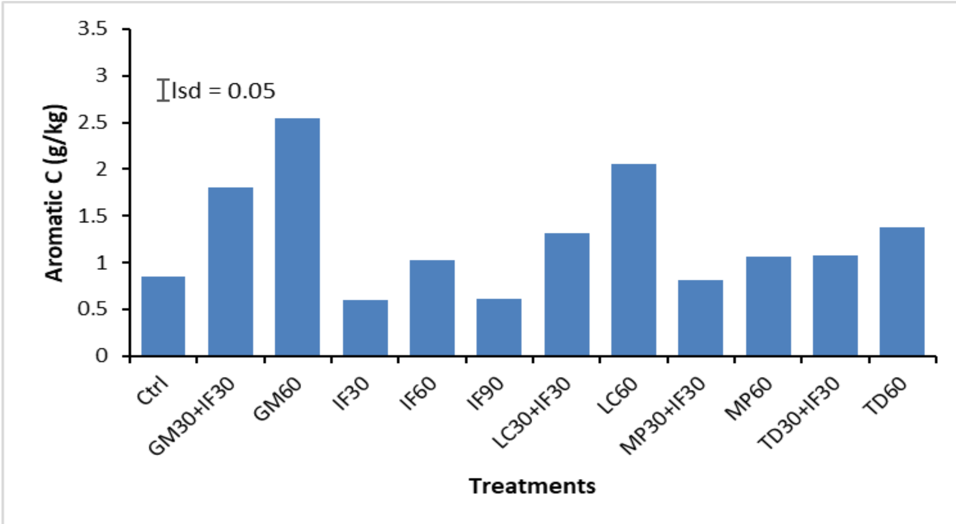

Figure 4.5. The total amount of Aromatic C fraction in each treatment.
Where: Ctrl - the Control; IF30 - Inorganic fertilizer (30 kg ha^{-1} N); IF60 - Inorganic fertilizer (60 kg ha^{-1} N); IF90 - Inorganic fertilizer (90 kg ha^{-1} N); LC60 - *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 - *Lantana camara* +Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); GM60 - Goat Manure (60 kg ha^{-1} N); GM30+IF30 - the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 - *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 - *Tithonia diversifolia* (60 kg ha^{-1} N); and TD30+IF30 - *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

4.2.4 Methoxyl C

Methoxyl C content was significantly ($p<0.001$) the highest in GM30+IF30, GM60, LC60, LC30+IF30, MP60 and TD60 compared to the control (Figure 4.6). IF30 had the lowest ($p<0.001$) amounts compared to the control (Figure 8). There was no significant difference ($p<0.001$) between the control and IF60, TD30+IF30, MP30+IF30, and IF90.

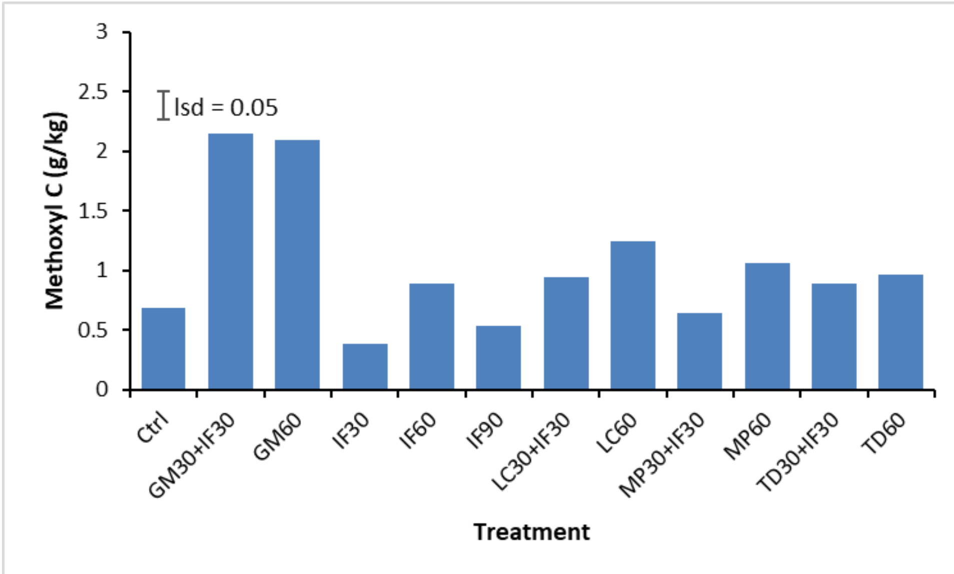

Figure 4.6. Total amount of Methoxyl C fraction in each treatment.

Where: Ctrl - the Control; IF30 - Inorganic fertilizer (30 kg ha^{-1} N); IF60 - Inorganic fertilizer (60 kg ha^{-1} N); IF90 - Inorganic fertilizer (90 kg ha^{-1} N); LC60 - *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 - *Lantana camara* +Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); GM60 - Goat Manure (60 kg ha^{-1} N); GM30+IF30 - the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 - *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 - *Tithonia diversifolia* (60 kg ha^{-1} N); and TD30+IF30 - *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

4.2.5 Carboxyl C

Carboxyl C content was significantly ($p<0.001$) highest in GM60 and LC60 treatments by 106% and 74%, respectively, compared to control (Figure 4.7). Carboxyl C content in LC30+IF30, MP60, TD60, IF60, and TD30+IF30 treatments were not significantly ($p<0.001$) different from the control. On the other hand, carboxyl C content in GM30+IF30, IF30, MP30+IF30 and IF90 treatments was significantly lower than the control.

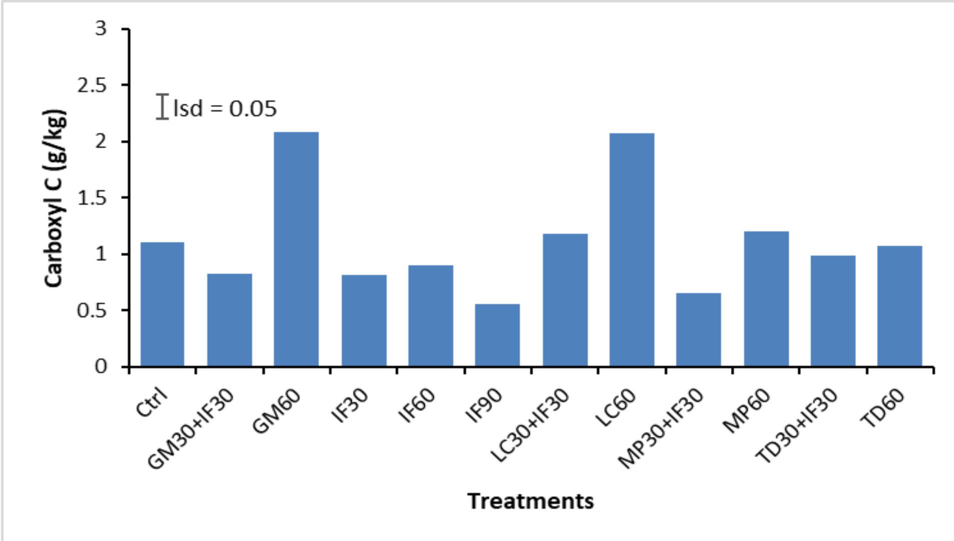

Figure 4.7. The total amount of Carboxyl C fraction in each treatment.
Where: Ctrl - the Control; IF30 - Inorganic fertilizer (30 kg ha^{-1} N); IF60 - Inorganic fertilizer (60 kg ha^{-1} N); IF90 - Inorganic fertilizer (90 kg ha^{-1} N); LC60 - *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 - *Lantana camara* +Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); GM60 - Goat Manure (60 kg ha^{-1} N); GM30+IF30 - the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 - *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 - *Tithonia diversifolia* (60 kg ha^{-1} N); and TD30+IF30 - *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

4.2.6 Phenolic C

The GM60 treatment had significantly the highest Phenolic C contents, followed GM30+IF30, LC30+IF30, LC60, TD60, and MP60 treatments compared to the control (Figure 4.8). Phenolic C contents in the TD30+IF30 MP30+IF30 IF30 and IF90 treatments were not any different ($p<0.001$) relative to the control. However, phenolic C contents, IF60, were significantly ($p<0.001$) lower than the control.

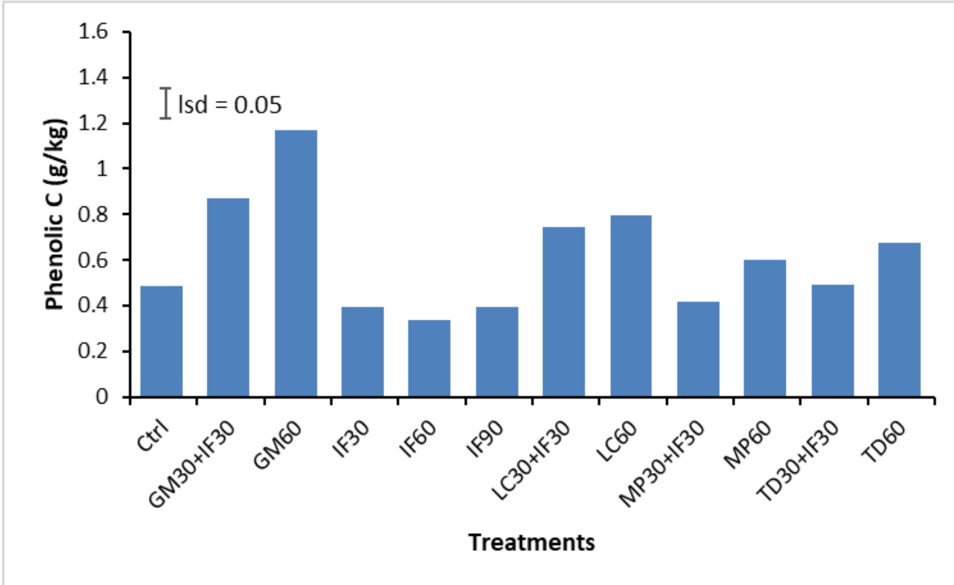

Figure 4.8. Total amount of Phenolic C fraction in each treatment.
Where: Ctrl - the Control; IF30 - Inorganic fertilizer (30 kg ha^{-1} N); IF60 - Inorganic fertilizer (60 kg ha^{-1} N); IF90 - Inorganic fertilizer (90 kg ha^{-1} N); LC60 - *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 - *Lantana camara* +Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); GM60 - Goat Manure (60 kg ha^{-1} N); GM30+IF30 - the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 - *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 - *Tithonia diversifolia* (60 kg ha^{-1} N); and TD30+IF30 - *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

4.3 Effects of organic and inorganic inputs on yields

The average grain yield ranged from 0.56 Mg ha^{-1} in the control to 4.60 Mg ha^{-1} in the MP30+IF30 treatment (Table 4.3). The IF30, IF60, IF90, and LC60 treatments had low grain yields within the range of the control. Concurrently, the combination of organic and inorganic amendments. The LC30+IF30 and LC60 treatments had an average effect on grain yields. At the same time, the combination of organic and inorganic amendments, i.e., fertilizer LC30+IF30, TD30+IF30, GM30+IF30, and MP30+IF30 (2.98 Mg ha^{-1}, 3.30 Mg ha^{-1}, 3.36 Mg ha^{-1}, and 4.6 Mg ha^{-1}, respectively) and sole application of MP60 and GM60 (4.03 Mg ha^{-1} and 4.16 Mg ha^{-1}) produced higher grain yield compared with control.

Table 4.3. Treatment effect on soil Nitrogen (g kg^{-1}), carbon (g kg^{-1}), and maize grain yields (Mg ha^{-1}).

Treatment	***Nitrogen (g kg^{-1})***	***Carbon (g kg^{-1})***	***Grain Yield* (Mg ha^{-1})**
Control	0.73 ± 0.03^{ef}*	7.47 ± 0.50^{de}	0.56 ± 0.045^{f}
IF30	0.53 ± 0.12^{ef}	5.03 ± 1.14^{e}	1.89 ± 0.338^{def}
IF60	0.80 ± 0.06^{def}	7.37 ± 0.61^{de}	1.51 ± 0.171^{ef}
IF90	0.50 ± 0.06^{f}	5.27 ± 0.63^{e}	1.99 ± 0.457^{cdef}
LC60	1.37 ± 0.07^{bc}	13.37 ± 0.71^{bc}	1.94 ± 0.091^{cdef}
LC30+IF30	0.97 ± 0.03^{cde}	9.23 ± 0.38^{cde}	2.98 ± 0.366^{bcd}
GM60	1.83 ± 0.12^{a}	18.77 ± 1.11^{a}	4.16 ± 0.208^{ab}
GM30+IF30	1.47 ± 0.12^{ab}	14.50 ± 1.50^{a}	3.36 ± 0.191^{abc}
MP60	0.97 ± 0.03^{cde}	9.57 ± 0.41^{bcde}	4.03 ± 0.516^{ab}
*MP*30+*IF30*	0.70 ± 0.15^{ef}	7.03 ± 1.78^{de}	4.60 ± 0.151^{a}
TD60	1.23 ± 0.09^{bcd}	11.77 ± 1.52^{bcd}	2.23 ± 0.103^{cde}
TD30+IF30	0.80 ± 0.06^{def}	7.77 ± 0.57^{de}	3.30 ± 0.345^{abcd}
P value	*<0.0001*	*<0.0001*	*<0.0001*

* Mean with same superscript letters indicate no significant difference between treatments.

Ctrl is the Control; GM60 is Goat Manure (60 kg ha-1 N), IF30 is Inorganic fertilizer (30 kg ha^{-1} N), IF60 is Inorganic fertilizer (60 kg ha^{-1} N); GM30+IF30 is the Goat Manure + Fertilizer (at a rate of 30 kg ha^{-1} N each); IF90 is Inorganic fertilizer (90 kg ha^{-1} N); LC60 is *Lantana camara* (60 kg ha^{-1} N); LC30+IF30 is *Lantana camara* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); MP60 - *Mucuna pruriens* (60 kg ha^{-1} N); MP30+IF30 is the *Mucuna pruriens* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each); TD60 is *Tithonia diversifolia*; and TD30+IF30 is *Tithonia diversifolia* + Inorganic Fertilizer (at a rate of 30 kg ha^{-1} N each).

4.3.1 Correlation of maize grain yield to soil carbon and soil nitrogen content

The effects of the treatments on the soil C content followed almost the same trend as the soil N, with GM60 and GM30+IF30 treatments having the highest soil C levels (Figure 4.10). Except for the sole MP60 treatment, the soil C content increased in organic-based treatments, i.e., TD60, LC60, and GM60, compared to the control. Besides GM30+IF30 treatment, combined organic and inorganic inputs slightly changed soil C contents. The amount of C was much lower for these treatments than the organic inputs when applied solely. Sole inorganic fertilizer-based treatments had the lowest soil C content, close to that of the control.

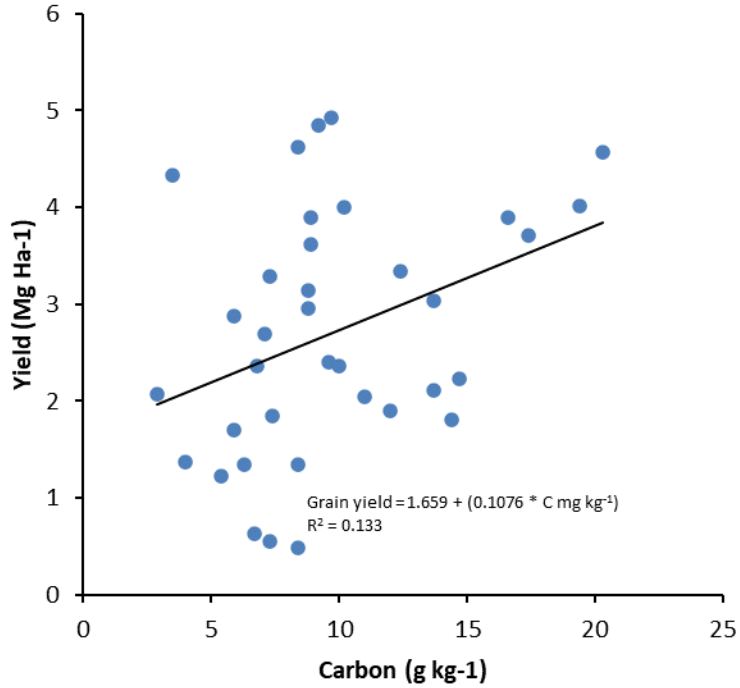

Figure 4.9. Correlation of grain yields to soil organic carbon.

The GM60 and GM30+IF30 treatments had the highest soil N, while IF30, IF60, IF90, MP30+IF30, and TD30+IF30 treatments had the lowest. The LC60, LC30+IF30, MP60, and TD60 treatments had moderate amounts of soil N (Table 4.9). There was a positive correlation between grain yields and soil N content. Concerning grain yields, MP60 and MP30+IF30 treatments had the highest grain yields. The high soil N in the GM60 and GM30+IF30 treatments are indicative of the potential of these treatments to build up soil N over time.

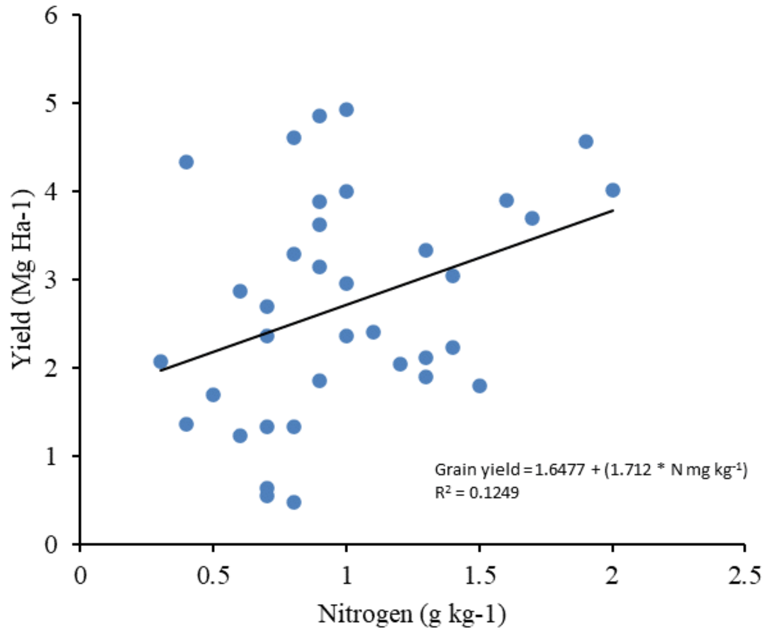

Figure 4.10. Correlation of grain yields to soil nitrogen content.

CHAPTER 5
DISCUSSION

5.1 Effects of organic and inorganic inputs on soil chemical properties

The results demonstrated the role, as well as the interaction of nitrogen, phosphorus, and potassium, in boosting SOC. Similarly, Samimi et al. (2016) discussed the importance of these nutrients in the soil. It revealed that nitrogen in nitrate and water form is very mobile, and crops require it in high amounts. Phosphorus is the least mobile, and potassium is comparatively immobile, essential plant nutrients. This could be attributed to the combination of inorganic fertilizers and organic inputs that help improve soil nutrient concentration.

The GM60 increased soil nutrients. Awodun, Omonijo, and Ojeniyi (2007) recorded similar results, which found that goat manure increased soil nutrient availability and yield. GM60 decomposition released organic matter, N, P, K, and other micronutrients in the soil. The plots treated with IF90 showed significantly different nutrient concentrations and recorded the lowest amounts. Studies that evaluate Fertilizer N management show that varying amounts could result in high levels of soil mineral N that cause soil degradation (Poudel et al., 2001). Most of the nitrogen added is removed during harvest, stored as soil organic matter, or lost during leaching, denitrification, and ammonia volatilization (Sainju, 2017). Therefore, the results of the IF90 treatment indicate that C inputs are beneficial in balancing soil N. The decrease in C inputs from inorganic inputs may have affected the soil's capacity to store N.

Soil pH also plays an important role in maintaining SOC. Applying alkaline fertilizers was attributed to the highest pH recorded in the GM60 treatment. Organic inputs can influence the soil pH positively, making it more favourable for plant growth and microbial activity. The nutrients required for optimal growth are present in goat manure in sufficient quantities. SOC, N, P, and K, were all relatively high in goat manure.

Soil testing laboratories are given access to relevant technical literature on a variety of soil testing-related topics, such as testing procedures and fertilizer recommendation formulations. Farmers can use it to determine how much farmyard manure and fertilizer to implement at different stages of the crop's growth cycle. Bulk density is one of the physical characteristics of soil that significantly influences the stock of organic and inorganic carbon forms.

5.2 Effects of organic and inorganic inputs on soil organic fraction

The carbon functional groups in the soil treatments demonstrated the following sequence in abundance: O-alkyl C > alkyl C > methoxyl > carboxyl > aromatic C content.

O-alkyl C is composed of methoxyl C (lignin) and carbohydrate C (cellulose and hemicellulose) components (Wang et al., 2013; Yu et al., 2015; Li et al., 2017; He et al., 2018; Guan et al., 2018). Based on the C fraction composition of the organic inputs (Table 1), it is evident that the amounts of O-alkyl C across the four organic inputs were almost equal. Contrariwise, the soil residual O-alkyl C at the end of the season showed significant variation across the sole organic inputs and their combinations with the inorganic inputs. GM60 treatment showed strikingly high amounts of O-alkyl C, depicting a potential for high contribution to SOM. The high decrease of the O-alkyl in the three plant-based residues suggests that a larger portion of the constituent is cellulose and hemicellulose, which are easily biodegraded by microorganisms (Schöning et al., 2005; Solomon et al., 2010). Organic + inorganic inputs applied to the soil that showed no difference in O-alkyl C content relative to the untreated control could be due to the positive effect on the organic input mineralization rated of the N from the inorganic fertilizers. It can indicate that integrating inorganic and organic inputs facilitates a faster decomposition of the original inputs throughout the season (Gram et al., 2020).

Alkyl C is a recalcitrant C; that is, it is more stable, hydrophobic (Carrington et al., 2012; Chen et al., 2013; Habte, 2013; Yu et al., 2015), and an aliphatic hydrocarbon with strong chemical structure bonds which are less susceptible to degradation (Zhang et al., 2019). Singh and Rengel (2007) associate high recalcitrant organic C content in the soil with alkyl C. The accumulation of alkyl C content, derived from lignin and polyphenol components of the plant residues, occurs at the onset of decomposition of the plants. In this study, the organic amendments provided lower proportions of alkyl C compared to O-alkyl C, indicating that the stable alkyl C is preserved during the decomposition of plant residues while the carbohydrate C (O-alkyl C) is decomposed. Furthermore, the degradation of labile O-alkyl results in the accumulation of alkyl C and aromatic C (Quideau et al., 2001). However, the presence of oxygen enhances degradation of aromatic C (Fuchs et al., 2011). The findings of Kögel-Knabner (2002) corroborates this and further underscores that the lignin component minimizes the decomposition of the plant residues and increases the likelihood of the organic inputs to contribute to soil C stocks.

The presence of Aromatic C is indicative of the dominance of the stable and recalcitrant C fraction in the organic inputs (Fuchs et al., 2011). The results indicated an increase in aromatic C under the treatments composed of organic inputs and showed a positive relationship with the high O-alkyl C trends. Panettieri et al. (2014) reported similar results, attributing the high aromatic C content to the incorporation of high amounts of crop residues due to minimum tillage effects. Aromatic C is derived from lignin and tannin (Nogueirol et al., 2014), which undergoes microbial degradation. On degradation, the lignin-derived aromatic C contributes to a humic fraction of SOM (humification), which is core to soil fertility (Fuchs et al., 2011). Abakumov et al. (2018) suggest that humification processes supplemented by organic inputs application boosts SOM. Conversely, applying the application of sole inorganic inputs decreases aromatic C, underscoring the potentially adverse effects of inorganic fertilizers on SOM content in agricultural lands. Furthermore, the observed results accentuate the importance of the applied organic inputs in increasing aromatic C, and, by extension, enhancing SOM content. The relatively high resistance of aromatic C to microbial decomposition (Eldridge et al., 2017) shows that GM60, GM30+IF30, LC60, TD60, and MP60 treatments have a high potential to promote soil C sequestration.

Methoxyl C is mostly associated with O-alkyl C's lignin and phenolic part (Wang et al., 2013; Yu et al., 2015). It is considered relatively resistant to microbial degradation, thus suggesting a significant contribution to the soil's SOM content. The high contents of methoxyl C in the GM60 and GM30+IF30 indicate high lignin and polyphenols in the constituent dietary composition of the GM60. GM60 is, being goat manure from drier areas of the Central Highlands of Kenya, their diets are mostly acacia and herbaceous plants common in marginal lands. The high methoxyl C in GM60 treatment can also be attributed to the process the goat manure undergoes, from production to application as soil input. Part of the process is the decomposition, meaning which might have some impact on its stability. This opinion is based on the organic input C fractions analysis shown in Table 1, which indicated almost equal amounts of methoxyl C across LC60, MP60, GM60, and TD60. Hence, GM60 has a high potential for sequestering C than other organic inputs.

Carboxyl C, an aliphatic acid of plant and microbial origins (Yu et al., 2015), was relatively abundant under the GM60, although they were very low in the input characterization (Figure 1). Carboxyl C is an organic input constituent, and it is also microbially generated. Carboxylic compounds occur through oxidizing biomolecules produced from plants, including lignin and related phenolic substances (Xue et al., 2020). Although highly oxidized lignin polyphenols, tannins, and other recalcitrant plant-derived compounds are partly solubilized and mobilized by peroxidase and ligninase enzymes in the soil, the resulting carboxyl-rich ring structures are more resistant to microbial biodegradation (Kalbitz et al., 2006). Carboxyl C is regarded as an effective pathway for SOM production and has the potential to accumulate the same (Kramer et al., 2012). The high amounts of carboxyl C under the GM60 treatment indicate the high potential of the GM60 treatment to contribute significantly towards SOM enrichment over time, hence soil C sequestration. Besides the SOM enrichment, Carboxyl C is responsible for the negative charge of soil organic matter (Anda et al., 2013), which relates to in cation exchange capacity (CEC) of soil (Schnitzer & Desjardins, 1965); hence soil fertility potential. Although the carboxyl C for the other three treatments was also high, it is worth noting that, compared to the amounts of carboxyl C in the organic characterization, the observed results show a general decline in the amounts, unlike in the GM60 treatment. In contrast, treatments with organic + inorganic inputs and sole inorganic inputs led to decreased carboxyl C content, which might be detrimental to soil C stocks.

Phenolic C is a less humified organic material in SOM, as it contains an abundance of diester P and amide N (Wissing et al., 2013). Generally, phenolic C was significantly the lowest C fraction in the soil, indicating, but then, based on Table 1, the difference between the phenolic C in the inputs and the residual at the end of the season was small. Phenols originate from recalcitrant plant litter compounds (Rumpel et al., 2004); hence, its degradation is slower than the degradation of other C fractions (Min et al., 2015). Therefore, the observed high phenolic contents in the GM60 treatment indicate its high potential to contribute to SOM. This observation is supported by Yu et al. (2015), who observed that due to the lignin recalcitrance of organic inputs, there was an accumulation of phenolic C in the soil. Pane et al. (2013) also reported that high phenolic C content reflects the lack of microbial degradation due to the recalcitrant characteristic of the organic inputs. Further, according to Ng et al. (2014), phenolic compounds correlate with the antioxidant capacity of soils that neutralize free radicals and protect organic matter from oxidation.

5.3 Effects of organic and inorganic inputs on yields

Based on the observed results, GM60 and GM30+IF30 treatments emerged superior in terms of enhancing grain yields, soil N and C. Coincidentally, the two treatments had high O-alkyl and alkyl C fractions, most likely attributable to the nature of goat manure. This indicates not only the potential dual benefits the treatments have both in terms of soil C sequestration and enhancing crop productivity but also the synergetic influence of N and C on crop yields. Additionally, based on the chemical composition, goat manure had superior levels of P, Ca, Mg, and K levels, excluding N content. According to the law of the minimum as applied to soil fertility and plant nutrition, GM-related treatments provide more nutrient-balanced soil fertility inputs than other inputs. This is consistent with the finding made by Awodun et al. (2007) that manure increases crop growth and yields while also improving soil nutrient availability and nutrient status. Thelen et al. (2010) observes that SOC storage in agricultural systems is a balance between carbon losses and additions (from crop residues and organic inputs) which leads to increased soil fertility and high yield associated with improved physical soil properties (Stroosnijder, 2009; Nayak et al., 2012). Amendments are regularly used to improve the SOM levels and increase atmospheric CO_2 sequestration potential in soils (Yu et al., 2015).

Besides the goat manure-related treatments, the MP30+IF30 treatment registered the highest grain yields. The high grain yield was probably due to a lower C: N ratio than other treatments. The additional inorganic N created an N (mineralization) surplus in this treatment, allowing decomposition, N uptake, and significantly increased yield (Shang et al., 2014). It points to the novelty of combining the inorganic and organic amendment, which is commonly called integrated nutrient management (Schuman et al., 2002). Contrariwise, the treatment effect on soil C content was detrimental, probably due to the observed low Alkyl and O-alkyl fraction present in MP60, making it less recalcitrant and prone to exhaustion within a season of application. The low recalcitrance directly affects the SOC status in that, to sustain SOM, there will be a need for the continuous addition of Mucuna. Integration of chemical fertilizers into farming systems through a combination of inorganic fertilizers and organics such as farmyard manure or crop residue, or green manure improves the SOC (Kirkby et al., 2011; Nayak et al., 2012; Kirkby et al., 2013).

The observed negative effects of the sole inorganic-related treatments on yields and soil N and C were attributed to the lack of organic inputs. Nitrogen is highly mobile, and with limited SOM, it is prone to losses through leaching, runoff, and volatilization (Wissing et al., 2013). Previous studies evaluating Fertilizer N management have shown similar results: varying amounts of N fertilizer can produce significantly high levels of soil mineral N, leading to soil degradation (Owens et al., 1994). A significant portion of the applied N is removed during harvest. The remaining N may be stored in soils as organic matter, while some might be lost through different pathways, such as N denitrification, volatilization, and leaching. The lower C content under inorganic inputs compromised the N storage ability of soil. Given the prevailing rainfed conditions, leaching is inevitable. As a result, this creates N deficiency and makes these treatments unsustainable in the long term.

CHAPTER 6
CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

High SOM under the GM60, GM30+IF30, LC60, and TD60 treatments were linked to the high Alkyl and O-alkyl C fractions. This points towards a high C sequestration potential of these treatments, besides having an immediate beneficial impact on crop productivity. Besides the sole organic inputs, the results imply that using organic inputs coupled with inorganic fertilizers can have a dual effect, i.e., improved soil physicochemical properties and crop productivity. This was demonstrated by the GM+IF30, a treatment where significant soil N and C built-up was observed, besides enhanced grain yields.

GM60, with its high Alkyl and O-alkyl fractions, can significantly influence SOM and crop productivity; the dominance of alkyl and O-alkyl C fractions in an organic input directly affected its SOC recalcitrance; hence SOM content and built-up potential; goat manure contained adequate amounts of nutrients to meet plant requirements for optimal growth. As a result, the manure retained more N, thus increasing its fertilizing potency; a combination of organic and inorganic inputs can simultaneously improve crop productivity (economic and social benefits) and soil C sequestration (environmental benefit).

The knowledge of the C fraction content of organic soil inputs is critical for soil input characterization and the development of soil fertility ameliorating technologies to help farmers make informed decisions on integrated fertilizer use.

6.2 Recommendations

1. The organic manures with or without inorganic fertilizers improved soil conditions and maize yield. It also provided insight into how organic inputs are diverse, inexpensive, and readily accessible. The study recommends that smallholder farmers widen their options and utilize integrated soil fertility inputs, which are also cost-effective.
2. The decomposition rates determine which inputs are influential in short-term and long-term soil improvement. GM is recommended in the long term since it decomposes slowly and releases its nutrients. It retains more nitrogen hence increasing its fertilizing

potency. Tithonia has a high decomposition rate and is, therefore, suitable for use in the short term. Therefore, this study recommends farmers practice efficient fertilizer application that ensures soil nutrient cycling and prevents losses.

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APPENDICES

Appendix 1: ANOVA for soil organic carbon.

Source	**DF**	**Sum of Squares**	**Mean Square**	**F Value**	**Pr>F**
Model	13	3.75904	0.289157	15.15	<0.001
Error	28	0.5344	0.019086		
Corrected Total	41	4.29344			