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RESOURCE MANAGEMENT THESIS**

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**RESILIENCE OF *NITISOLS* AND *FERRALSOLS* TO EROSION
AS INFLUENCED BY LEVELS OF SOIL ORGANIC CARBON IN
THARAKA-NITHI COUNTY, KENYA**

MERCY KANGAI RUGENDO

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REQUIREMENTS FOR THE AWARD OF THE DEGREE OF
MASTER OF SCIENCE IN AGRICULTURAL RESOURCE
MANAGEMENT OF THE UNIVERSITY OF EMBU**

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DECLARATION

This thesis is my original work and has not been presented elsewhere for a degree or any other award.



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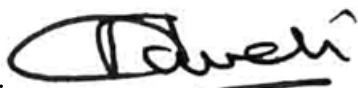
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DEDICATION

This work is dedicated to God for giving me wisdom and to my parents Mr and Mrs Rugendo, siblings and friends for their unwavering support towards my study.

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TABLE OF CONTENTS

DECLARATION	ii
DEDICATION	iii
ACKNOWLEDGEMENTS	iv
TABLE OF CONTENTS	v
LIST OF PLATES	xi
LIST OF APPENDICES	xii
ABBREVIATIONS AND ACRONYMS	xiii
LIST OF SYMBOLS	xiv
ABSTRACT	xv
CHAPTER ONE	1
INTRODUCTION	1
1.1 Background of the study	1
1.2 Statement of the problem	4
1.3 Justification of the study	5
1.4 Hypotheses	6
1.5 Research objectives	6
1.5.1 General objective	6
1.5.2 Specific objectives	6
1.6 Conceptual framework	7
CHAPTER TWO	8
LITERATURE REVIEW	8
2.1 Overview	8
2.2 Introduction to soil erosion and land degradation	9
2.3. Soil organic carbon and its role in soil resilience	12
2.4 Effect of soil organic carbon on runoff and sediment concentration	15
2.4.1 Soil organic carbon influence on surface runoff	16
2.4.2 Soil organic carbon influence on sediment concentration	18
2.5 Influence of soil organic carbon on soil physical properties	20
2.5.1 Soil organic carbon influence on bulk density	21
2.5.2 Soil organic carbon influence on hydraulic conductivity	23
2.5.3 Soil organic carbon influence on water retention	26
2.6 Soil organic carbon influence on soil nutrient losses	28
2.8 Critical synthesis	31

2.9 Research gap	31
CHAPTER THREE	33
MATERIALS AND METHODS	33
3.1 Description of the study area.....	33
3.2 Sampling, experimental design, and layout	35
3.2.1 Selection of farms.....	35
3.2.2 Determination of soil organic carbon levels.....	36
3.2.3 Field experimental design and layout.....	36
3.2.4 Calibration of the rainfall simulator	37
3.3 Data collection	38
3.3.1 Determination of surface runoff and sediment loss.....	38
3.3.2 Determination of soil bulk density	38
3.3.3 Determination of soil hydraulic conductivity.....	38
3.3.4 Determination of soil water retention.....	39
3.3.5 Determination of nutrient losses via erosion.....	39
3.4 Statistical data analysis	41
CHAPTER FOUR.....	42
RESULTS	42
4.1 Effects of soil organic carbon and rainfall intensity on soil erosion.....	42
4.1.1 Effects of soil organic carbon on runoff and sediment losses.....	42
4.1.2 Effects of rainfall intensity on runoff and sediment losses	43
4.1.3 Interactive effects of soil organic carbon and rainfall intensity on runoff and sediment losses	44
4.1.4 Overall influence of soil type, soil organic carbon levels and rainfall intensities on runoff and sediment losses	45
4.1.5 Relationship between run-off and sediment loss.....	47
4.2 Effects of soil organic carbon and rainfall intensity on physical properties ...	49
4.2.1 Effects of soil organic carbon and rainfall intensity on bulk density	49
4.2.2 Effects of soil organic carbon and rainfall intensity on hydraulic conductivity	51
4.2.3 Effects of soil organic carbon and rainfall intensity on water retention .	54
4.3 Nutrient erosion as influenced by SOC levels and rainfall intensity	58
4.3.1 Effects of SOC and rainfall intensity on nutrient loss via sediment loss	58
4.3.2 Effects of SOC levels and rainfall intensity on nutrient loss via runoff..	64

CHAPTER FIVE	71
DISCUSSION, CONCLUSION AND RECOMMENDATIONS.....	71
5.1 Discussion	71
5.1.1 Effect of soil organic carbon levels on soil erosion	71
5.1.2 Effect of organic carbon and rainfall intensity on soil physical properties	73
5.1.3 Effects of soil organic carbon and rainfall intensity on nutrient loss	76
REFERENCES	82
LIST OF APPENDICES	102

LIST OF TABLES

Table 3.1: General soil properties in the study areas	35
Table 4.1: The Influence of different Soil organic carbon levels on runoff and sediment losses in Nitisols and Ferralsols.	42
Table 4.2: Influence of different rainfall intensities on runoff and sediment loss in Nitisols and Ferralsols.....	43
Table 4.3: Interactive treatment effects (SOC × rainfall intensity) on runoff and sediment loss in Nitisols and Ferralsols.....	45
Table 4.4: Relationship between runoff and sediment loss in both soil types	48
Table 4.5: Effect of different organic carbon levels and rainfall intensities on soil bulk density in Nitisols and Ferralsols.....	50
Table 4.6: Interactive effects of different organic carbon levels and rainfall intensities on soil bulk density in Ferralsols and Nitisols	50
Table 4.7: Influence of different organic carbon levels and rainfall intensities on hydraulic conductivity in Ferralsols and Nitisols.	52
Table 4.8: Interactive effects of different organic carbon levels and rainfall intensities on hydraulic conductivity in Ferralsols and Nitisols	53
Table 4.9: Influence of different organic carbon levels on water retention at six matric potentials in Ferralsols and Nitisols.....	54
Table 4.10: Influence of different rainfall intensities on water retention at six matric potentials in Ferralsols and Nitisols	55
Table 4.11: Interactive effects of different organic carbon levels and rainfall intensities on water retention at six matric potentials in Ferralsols and Nitisols	56
Table 4.12: Soil water retention as affected by soil type, organic carbon and rainfall intensity. main effects and interactions.....	57
Table 4.13: Pearson correlations among quantitative variables (bulk density, hydraulic conductivity, and water retention in Ferralsols and Nitisols.....	58
Table 4.14: Effect of different organic carbon levels on nutrient loss through sediment loss in Ferralsols and Nitisols.....	60
Table 4.15: Effect of different rainfall intensities on nutrients loss through sediment loss in Ferralsols and Nitisols	60
Table 4.16: Interactive effects of different organic carbon levels and rainfall intensity on sediment nutrient loads in Ferralsols and Nitisols	62

Table 4.17: Sediment nutrient load as affected by soil type, rainfall intensity and organic carbon levels	63
Table 4.18: Runoff nutrient concentrations as influenced by different organic carbon levels in Ferralsols and Nitisols	64
Table 4.19: Runoff nutrient loads as influenced by different rainfall intensities in Ferralsols and Nitisols.....	65
Table 4.20: Interactive effects of soil organic carbon and rainfall intensity on nutrient loss in Ferralsols and Nitisols	66
Table 4.21: Runoff nutrient loads as affected by soil type, combined levels of organic carbon and rainfall intensities	67
Table 4.22: Pearson correlation between sediment nutrient loads.....	68
Table 4.23: Pearson correlation between runoff nutrient concentrations	70

LIST OF FIGURES

Figure 1.1: Conceptual framework showing the interrelation of the study variables ..	7
Figure 3.1: Map of the Study area.....	34
Figure 4.2: Relationship between runoff and sediment loss against varying levels of soil organic carbon and rainfall intensity in Ferralsols and Nitisols.....	49
Figure 4.3: Soil bulk density as affected by soil type, soil organic carbon and rainfall intensities..	51
Figure 4.4: Soil hydraulic conductivity as affected by soil type, soil organic carbon and rainfall intensities.	53

LIST OF PLATES

Plate 3.1: Experimental layout with a display of the rainfall simulation.....	37
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LIST OF APPENDICES

Appendix 1: Protocol for determination of organic carbon	102
Appendix 2: Protocol for determination of Bulk density.....	103
Appendix 3: Protocol for determination of Hydraulic conductivity	104
Appendix 4: Protocol for determination of Water retention	105
Appendix 5: Protocol for determination of Nitrate (NO ₃)	106
Appendix 6: Protocol for Total Phosphorous content.....	107
Appendix 7: Protocol for determination of Potassium, Sodium, Calcium and Magnesium.....	108
Appendix 9: Protocol for Total Nitrogen content	110
Appendix 10: Protocol for determination of Copper, Iron and Zinc	111

ABBREVIATIONS AND ACRONYMS

AEZ	Agro-Ecological Zone
ANOVA	Analysis of Variance
AWC	Available Water Content
BD	Bulk Density
EC	Electrical Conductivity
FAO	Food and Agriculture Organization of United Nations
FC	Field Capacity
GDP	Gross Domestic Product
HC	Hydraulic Conductivity
IPBES	Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IPCC	Intergovernmental Panel on Climate Change
ITPS	Intergovernmental Technical Panel on Soils
LM	Lower Midland
RCBD	Randomized Complete Block Design
RI	Rainfall Intensity
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SSA	Sub-Saharan Africa
TOC	Total Organic Carbon
UM	Upper Midland
UNCCD	United Nations Convention to Combat Desertification
WHO	World Health Organization
WP	Wilting Point

LIST OF SYMBOLS

C	-	Carbon
Cm/hr	-	Centimeter per hour
cm	-	Centimeters
°C	-	Degree Celsius
E	-	East
gcm ⁻³	-	Grams per cubic centimeter
ha	-	Hectares
Kg	-	Kilogram
L/m ²	-	Litre to square meter
m	-	Meters
mg/l	-	Milligrams per liter
mm	-	Millimeters
NO ₃	-	Nitrate
%	-	Percentage
pF	-	Piezometric head of free energy
ppm	-	Parts per million
PgC	-	Petagrams of carbon
S	-	South
SO ₄	-	Sulphate

ABSTRACT

Declining soil fertility resulting from nutrient losses due to erosion is a major constraint to agricultural productivity and food security among smallholder farmers in Sub-Saharan Africa (SSA). Managing soil organic carbon (SOC) levels is a promising strategy to mitigate erosion since SOC directly influences soil structure, water retention, infiltration, and nutrient cycling. This study aimed to evaluate the effect of different SOC levels under varying simulated rainfall intensities on water retention, infiltration rates, runoff volume, sediment yield, and nutrient losses in *Nitisols* and *Ferralsols* soils found in Tharaka-Nithi County, Kenya. The research was conducted in farmers' fields located in Chuka and Tharaka-South sub-counties, representing the *Nitisols* and *Ferralsols*, respectively. Soil samples were analyzed and categorized into low (1.0 to 1.5), moderate (1.6 to 2.5) and adequate SOC (above 2.5%) content. The experiment was laid out in a split plot design arranged in randomized complete block design, where SOC levels were main plots and rainfall intensities were the sub-plots. Rainfall intensities of 80, 100, and 120 mm/hr were simulated on 1 m² experimental plots fenced with corrugated iron sheets to accurately collect runoff and sediments. Key parameters measured included runoff volume, sediment yield, soil bulk density, hydraulic conductivity, and water retention. Runoff and sediment samples were analyzed for primary and secondary macronutrient concentrations using standardized laboratory methods. The collected data were subjected to analysis of variance (ANOVA) followed by Tukey's Honest Significant Difference (HSD) test. Pearson correlation analysis was performed to examine the relationship between the different variables of interest. The findings revealed that higher SOC levels significantly reduced runoff volumes and sediment losses across both soil types and all rainfall intensities. Specifically, soils with high SOC exhibited a 40–55% decrease in runoff and a 35–50% reduction in sediment yield compared to low SOC soils. Runoff and sediment volumes were also significantly higher in *Ferralsols* than in *Nitisols*. Water retention and infiltration rates improved markedly with increased SOC, indicating enhanced soil physical properties. Nutrient losses, particularly nitrogen and phosphorus, were lower in plots with higher SOC, demonstrating improved nutrient retention capacity. Pearson correlation analysis confirmed a strong positive ($r = 0.85$) relationship between runoff volume and sediment loss, underscoring the importance of reducing runoff by improving infiltration. The study concluded that enhancing SOC levels is essential in improving soil resilience against erosion, enhancing water availability, and conserving nutrients in *Nitisols* and *Ferralsols*. Sustainable agricultural practices such as organic amendments, that build SOC should be promoted to improve soil health and agricultural productivity. These results make a clear practical case: prioritize SOC-building practices (residue retention, organic amendments, cover crops, reduced tillage) to reduce runoff, sediment, and nutrient losses from *Nitisols* and *Ferralsols*.

CHAPTER ONE

INTRODUCTION

1.1 Background of the study

Soil erosion constitutes a critical global environmental issue that represents a significant challenge to sustainable land management practices, threatening agricultural productivity, food security, ecosystem services, and livelihoods (Filchev & Kolev, 2023; Smith et al., 2025; Borrelli et al., 2025). The removal and transport of the topsoil horizon result in the exposure of subsoil strata characterized by diminished fertility, depleted nutrient reserves, suboptimal soil structure, and reduced chemical properties (Kodaparthy et al., 2024; Mir et al., 2025). This global challenge is intensified in highly weathered and inherently fragile soils that experience rapid degradation (Lal, 2015a). *Nitisols* and *Ferralsols*, two predominant tropical and subtropical soil types, exhibit varying degrees of susceptibility to soil erosion under different land use and management practices (FAO, 2015; Rugendo et al., 2023). The consequences of eroded soils vary widely depending on intensity, frequency, and environmental context.

Soil erosion significantly influences surface runoff and sediment concentrations. Surface runoff, the portion of precipitation flowing overland when soil infiltration capacity is exceeded, may disrupt soil physical properties by degrading structure, causing compaction, and reducing pore continuity (Zhang et al., al 2024). The degradation of soil aggregates reduces aggregate stability, compromising permeability and water retention, and promoting surface saturation, which further intensifies runoff during rainfall (Smith & Johnson, 2023; Lee et al., 2024). Sediment concentration in runoff increases as detached particles ranging from coarse sand to fine clay are transported by water flow (Garcia et al., 2025). Selective particle detachment alters soil texture and nutrient availability, depleting topsoil quality and organic matter (Zhang et al., 2025c; Patel & Kumar, 2024). Elevated sediment loads export soil nutrients and removes fertile layers, reducing soil productivity and ecosystem resilience (Ahmed et al., 2023; Mwangi & Kimani, 2025). In agricultural lands, sediments from runoff may cause compaction and crusting upon deposition, inhibiting seedling emergence and root growth (Nguyen et al., 2024).

Soil erosion may also alter key soil physical properties such as bulk density, hydraulic conductivity, and water retention capacity, thereby reducing soil functionality. The removal of topsoil diminishes organic matter and fine particles, leading to compaction and increased bulk density, which restricts root penetration and gas exchange (Borrelli et al., 2023). Concurrently, the loss of structure reduces pore connectivity resulting in decreased hydraulic conductivity and impaired water infiltration (Zhang et al., 2025a). Moreover, the depletion of organic matter adversely affects water retention capacity, leaving eroded soils more prone to drought and less resilient to climate variability (Mekuria et al., 2021). These interrelated changes exacerbate land degradation and compromise sustainable land management efforts.

Soil erosion is a major driver of nutrient depletion, particularly in agricultural landscapes, as it selectively removes the nutrient-rich topsoil layer, thereby impairing fertility and crop productivity (Wang et al., 2024). Essential macronutrients such as nitrogen (N), phosphorus (P), and potassium (K) are often bound to fine particles and organic matter the most vulnerable fractions to erosion (Lal, 2020a). The loss of these nutrients reduces the soil's capacity to support plant growth and increases dependence on external inputs, raising both production costs and environmental risks (Zhao et al., 2024). In erosion-prone areas like the highlands of Sub-Saharan Africa, nutrient loss via water erosion leads to long-term degradation and threatens food security (Amare et al., 2023). The eroded topsoil typically contains up to three times the nutrient concentration and up to five times more organic matter than the underlying subsoil (Bagarello & Ferro, 2017). This necessitates soil resilience to erosion for long-term sustainability.

Soil resilience the capacity to withstand, recover from, or adapt to erosive impacts is critical to maintaining ecosystem functionality (McBratney et al., 2022). Resilient soils exhibit improved structural integrity, higher fertility, and better aggregation, which reduce susceptibility to erosion (Smith & Jones, 2022). *Nitisols* and *Ferralsols* differ in resilience due to their inherent properties. *Nitisols* are deep, well-structured, and rich in clay and iron oxides, giving them moderate erosion resistance and strong recovery potential under sound management (FAO, 2015; Rugendo et al., 2023). *Ferralsols*, though nutrient-depleted and highly weathered, possess well-developed

microaggregates and deep profiles that confer SOC erosion resilience (Huntley, 2023). However, understanding how SOC and factors such as climatic conditions and soil physical and chemical traits influence resilience remains crucial.

Rainfall intensity is a key erosive driver in tropical environments. When rainfall exceeds infiltration capacity, it generates runoff that detaches and transports soil particles (Wolka et al., 2022). In *Nitisol*- and *Ferralsol*-dominated regions, high rainfall intensity threatens soil stability, especially on sloped lands. Though these soils are well-drained, they become susceptible to erosion when organic matter is depleted, reducing aggregation and water retention (Kibet et al., 2025b). Rainfall also increases kinetic energy at the surface, disrupting aggregates and enhancing fine particle loss (Mutua et al., 2023). Rainfall simulation experiments are widely used to quantify erosion under controlled conditions (Ndung'u et al., 2023).

Soil organic carbon (SOC) is the carbon fraction of soil organic matter (SOM) and is the variable measured and analysed in this thesis. SOM is used only when referring to materials or management (e.g., residues, compost) (Lal, 2015a). Soil organic carbon (SOC) is a key determinant of soil resilience, affecting structure, SOM, porosity, and hydrological response (Minasny et al., 2023). SOC promotes aggregation, improves porosity, and prevents surface sealing (Cesarz et al., 2023). Soils with higher SOC retain favorable physical properties under stress, including lower bulk density and better infiltration (Kamau et al., 2025a). However, SOC depletion due to tillage and climate-induced mineralization remains a global concern (Paustian et al., 2019). Climate change projections, especially those showing increased storm frequency and intensity, are expected to exacerbate erosion (IPCC, 2023). Vulnerability is heightened by intense rains, unsustainable land practices, and weak soil conservation (Lal, 2015b). Rainfall increases erosion risk by enhancing runoff and sediment transport, especially where SOC is low (Mwangi et al., 2025a; Adebayo & Chisale, 2025).

In Kenya, soil erosion is widespread in highland agricultural areas. Practices such as steep slope cultivation, deforestation and poor soil conservation practices have degraded *Nitisols* and *Ferralsols* (Kithiia & Lyth, 2011). Declining SOC from tillage and poor residue management further weakens these soils (Muthoni & Oduor, 2023b).

Rainfall variability worsens erosion by triggering runoff and nutrient losses (Githongo et al., 2023). However, practices such as organic amendments and mulching can improve SOC and enhance resilience (Taddese, 2017). Kenya thus presents a relevant context for exploring soil type-specific erosion dynamics and the protective role of SOC in sustainable agriculture.

The Central Highlands of Kenya, characterized by steep slopes and fertile volcanic soils, including *Nitisols* and *Ferralsols*, are among the most productive agricultural zones in the country. However, the region experiences severe soil erosion driven by rainfall intensity and poor land management practices, threatening long-term sustainability (Gachene & Kimaru, 2003). Tharaka-Nithi County, located in Kenya's Central Highlands, faces significant erosion challenges due to its steep topography, variable rainfall, and intensive cultivation (Macharia et al., 2014). The region is dominated by *Nitisols* and *Ferralsols*, which support smallholder farming yet vary in erosion resistance. Conventional tillage reduces SOC, increases bulk density, and impairs hydraulic properties (Mulenga et al., 2023; Mwangi et al., 2025b; Kinyua & Mugambi, 2025). Understanding the role of SOC in soil erosion resilience in this region is therefore vital.

Despite their prevalence in tropical highlands, little is known about their erosion behavior under controlled rainfall simulations. Tharaka-Nithi County provides a strategic case due to its rainfall patterns, slope gradients, and dominance of these soil types (Okello et al.;2021; Gitari et al., 2025). This study will quantify the effects of SOC levels on erosion indicators such as runoff, sediment concentration, and soil physical and chemical properties using simulated rainfall techniques (Musyoka & Ouma, 2025; Kones et al., 2022), with findings expected to inform sustainable land policies (Mwangi et al, 2025b).

1.2 Statement of the problem

Many farming households in the Central Kenya highlands have increasingly experienced food insecurity due to low agricultural productivity coupled with growing human population. The declining productivity has been attributed to soil nutrient deficiency caused by nutrient loss through soil erosion, which continuously depletes

the available cropland every year. Overall, the soil is being lost from land areas upto forty times faster than the rate of soil renewal imperilling future human food security and environmental quality. Consequently, a significant proportion of the topsoil has been lost due to soil erosion in the past decade. This is attributed to poor farm management practices and lack of adaptive capacity. This is further compounded by a lack of knowledge on the impact of soil organic carbon levels and the resilience of different soil types to erosion. This limits the formulation of soil-specific conservation practices, particularly in highland ecosystems that face increasing anthropogenic pressure and rainfall variability. This has led to land degradation, poor soil water retention, poor infiltration rate, and declining fertility. Despite the many studies conducted to determine the causes and effects of soil erosion, it is still evident in different soils, resulting in significant decline in productivity of crops. Although soil organic carbon is known to strengthen soil structure and reduce erosion, there is limited local research quantifying its effect on runoff and sediment loss under varying rainfall intensity. Consequently, the potential of SOC in reducing erosion has not been fully exploited and the optimal level of SOC that would reduce soil erosion is yet to be well established. This study sought to investigate the resilience of different types of soils to erosion as influenced by soil organic carbon levels.

1.3 Justification of the study

A healthy and stable soil is a valuable economic resource as it supports environmental sustainability, ecosystem balance, sustainable food supply, biodiversity, water security, and human health (Karuma et al., 2016). Therefore, any initiative aimed at reducing soil erosion is usually very impactful. According to Wekesa et al. (2025), soil organic carbon has the potential to improve the soil structure, which increases water infiltration in the soil, thus reducing runoff and subsequently preventing soil erosion. Soil organic carbon is reported to strengthen soil structure and reduce erosion (Karimi et al., 2024), but there is a need to validate its effect on runoff and sediment loss under varying rainfall intensity. It is therefore important to examine how varying SOC levels influence surface runoff, sediment concentration, and key soil properties such as bulk density and water retention (Munyao et al., 2025). By filling these knowledge gaps through simulated rainfall experiments, this study will generate practical data needed to design targeted soil conservation measures for erosion-prone highlands facing

growing climate variability (IPCC, 2023). Therefore, the study will support climate-smart soil and water management practices tailored to improve soil conditions. The findings will help policymakers, extension officers, and farmers to adopt effective strategies to boost soil health, conserve nutrients, and sustain food security especially in fragile highland landscapes under increasing environmental pressure.

1.4 Hypotheses

This study was guided by the following hypotheses:

- i) Soil organic carbon levels have no significant effect on surface runoff and sediment concentration in *Nitisols* and *Ferralsols* under varying rainfall intensities.
- ii) Different soil organic carbon levels have no significant effect on soil's bulk density, hydraulic conductivity and water retention in *Nitisols* and *Ferralsols*.
- iii) Different soil organic carbon levels have no significant effect on nutrient loss through soil erosion in *Nitisols* and *Ferralsols* under varying rainfall intensities.

1.5 Research objectives

1.5.1 General objective

The general objective of this study was to evaluate the resilience of *Nitisols* and *Ferralsols* to soil erosion as influenced by varying soil organic carbon levels in Tharaka-Nithi County, Kenya.

1.5.2 Specific objectives

The specific objectives were:

- i) To determine the effect of soil organic carbon levels on surface runoff and sediment concentration in *Nitisols* and *Ferralsols* in Tharaka-Nithi County under simulated rainfall conditions.
- ii) To evaluate the effect of soil organic carbon levels on soil's bulk density, hydraulic conductivity and water retention in *Nitisols* and *Ferralsols* in Tharaka-Nithi County.
- iii) To assess the effect of soil organic carbon levels on soil nutrient losses in *Nitisols* and *Ferralsols* in Tharaka-Nithi County under simulated rainfall conditions.

1.6 Conceptual framework

Soil erosion, poor physical and chemical soil properties, and soil moisture stress are key factors contributing to the low agricultural productivity observed in Tharaka-Nithi County, Kenya (Mucheru-Muna et al., 2014). Variability in rainfall patterns exacerbates moisture stress for crops while simultaneously increasing the risk of soil erosion through intensified surface runoff (Wang et al., 2018). A critical driver of these challenges is the reduction of soil organic carbon (SOC), which diminishes soil aggregate stability and leaves soils more vulnerable to erosion and nutrient loss (Smith, 2008). Therefore, understanding the SOC levels required to mitigate soil erosion forms the foundation for recommending targeted management practices. These practices aim to optimize SOC content to reduce surface runoff, improve soil moisture retention, and ultimately enhance agricultural productivity in the region. The conceptual framework guiding this study is illustrated in Figure 1.1.

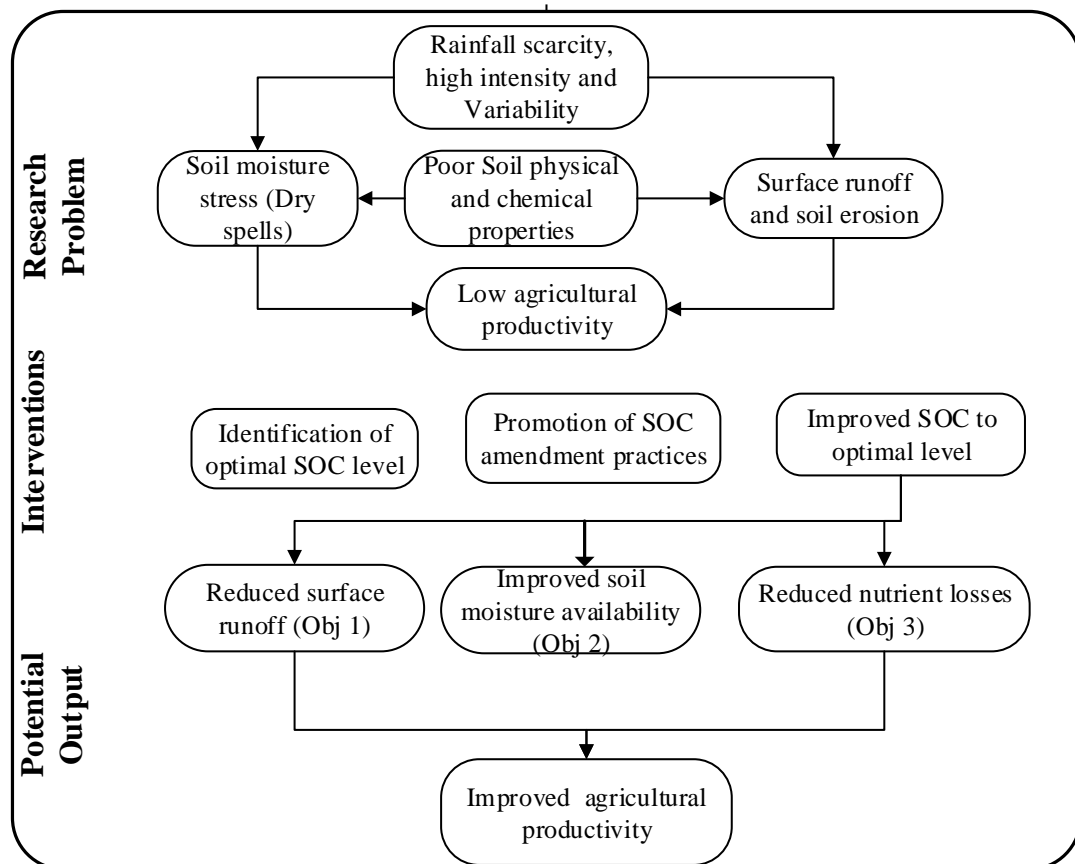


Figure 1.1: Conceptual framework showing the interrelation of the study variables

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview

Soil degradation, particularly through erosion, continues to pose a significant global threat to agricultural productivity and environmental sustainability. This degradation stems from complex interactions among physical, chemical, and biological processes that weaken soil structure, reduce nutrient availability, and diminish the soil's ability to support crops (Ebabu et al., 2019; Smith et al., 2024). In Sub-Saharan Africa (SSA), these challenges are exacerbated by climate variability and poor land management practices, disproportionately affecting smallholder farmers who rely heavily on rain-fed agriculture (Belemsobgo et al., 2020; Kamau & Wanjiru, 2025). Soil erosion is a primary driver of nutrient loss in the region, especially where soil resilience is low, vegetation cover is sparse, and rainfall is often intense but erratic (Rockström et al., 2009). The intensity and erratic nature of rainfall events, coupled with sparse vegetation and fragile soils, amplify the rate of nutrient loss and erosion in this region (Ochieng et al., 2023).

In Kenya's highland regions, such as Tharaka-Nithi County, these problems are magnified due to the dominance of inherently fragile soils such as *Nitisols* and *Ferralsols*. These soil types are highly susceptible to degradation under unsustainable land use and shifting rainfall regimes (Muthoni & Oduor, 2023a; Njiru et al., 2024). A central determinant of soil resilience in such contexts is Soil organic carbon (SOC), used as an indicator of soil health because it affects fertility, water retention, and erosion resistance (Cowie et al., 2018). SOC, particularly a key component of Soil Organic Matter (SOM), enhances soil structure, boosts water infiltration, and serves as a critical reservoir for nutrients through mineralization processes (Karlen & Rice, 2015; Nyang'au et al., 2025).

Recent studies confirm that depletion of SOC mainly through intensive cultivation, biomass removal, and inadequate organic matter inputs exacerbates soil compaction and decreases hydraulic conductivity (Karuma et al., 2016). This, in turn, accelerates surface runoff and erosion (Wekesa et al., 2024). The cyclical degradation resulting from low SOC not only reduces crop productivity but also entrenches food insecurity

among vulnerable communities (Nyawade et al., 2018; Musyoka & Ouma, 2025). Despite global recognition of SOC's importance, a significant gap remains in understanding how SOC modulates erosion processes, particularly under simulated rainfall scenarios tailored to Kenyan soil types and climatic conditions (Kamau & Wanjiru, 2025).

Moreover, the critical role of SOC in nutrient cycling deserves emphasis. Most soil nitrogen, sulfur, and phosphorus are housed in the organic fraction, released slowly through microbial activity (Cowie et al., 2018; Wanjala et al., 2023). Unfortunately, unsustainable land use accelerates erosion-induced nutrient depletion, undermining long-term soil fertility (Okeyo et al., 2016; Limo & Mutua, 2024). This underscores the need to investigate how varying SOC levels influence both physical erosion parameters such as runoff and sediment concentration and associated nutrient loss, especially in the highland agroecologies of Kenya.

2.2 Introduction to soil erosion and land degradation

Soil Organic Carbon (SOC) plays a pivotal role in regulating sediment concentration through its influence on soil structure, aggregate stability, and resistance to detachment. Sediment concentration, defined as the amount of soil particles transported by surface runoff, serves as a reliable proxy for gauging erosion severity and is a major pathway for nutrient and carbon loss from agricultural landscapes (Lal, 2015b; Zhang et al., 2025d). High sediment loads in runoff not only reduce on-site soil fertility but also contribute to off-site water pollution, reservoir siltation, and ecological degradation (Muriithi et al., 2024). Globally, research has consistently shown that declining SOC levels are closely linked to increased sediment yields, especially in areas characterized by high rainfall intensity and suboptimal land management (Cerdà et al., 2016; Chandra & Singh, 2023).

Soils enriched with organic carbon typically exhibit improved porosity, water retention, and aggregate stability, which reduce surface sealing and promote infiltration. These conditions mitigate overland flow and lessen the energy available to dislodge and transport soil particles (Bronick & Lal, 2005). Despite such positive correlations, the global literature tends to generalize these processes across soil types

and climatic zones, often neglecting how local edaphic and topographic variables modify SOC–erosion interactions. For example, studies conducted in temperate regions may not adequately reflect conditions in tropical or semi-arid areas where rainfall characteristics, soil mineralogy, and vegetation cover differ significantly. Consequently, extrapolating global findings to diverse agroecological zones like those found in Kenya can lead to inaccurate or suboptimal conservation recommendations (Njiru et al., 2024).

In Sub-Saharan Africa (SSA), sediment transport is one of the leading causes of land degradation, particularly in smallholder farming systems. SOC depletion is prevalent in this region due to continuous cropping, residue removal, overgrazing, and the use of inorganic fertilizers with little organic matter input (Ebabu et al., 2019; Belemsobgo et al., 2020; Wekesa et al., 2024). Empirical studies across SSA agroecosystems including the Ethiopian highlands, the Sahel, and parts of Southern Africa have shown that soils with low SOC levels tend to yield 2–3 times more sediment during rainfall events compared to soils with higher organic matter (Bayabil et al., 2015a; Kamau & Wanjiru, 2025). Erratic and intense rainfall patterns in the region further exacerbate erosion by generating high-energy runoff that accelerates particle detachment and slope degradation (Chandra & Singh, 2023). However, these studies are observational or correlational in nature, offering limited causal inference about the specific role of SOC. Few have incorporated controlled rainfall simulations to isolate the impact of SOC from other confounding variables such as slope, crop type, and land cover, which limits their utility in designing precision soil management strategies. Notable exceptions that employed controlled rainfall simulation include Rugendo et al. (2023), Fufa et al. (2002), and Nyamadzawo et al. (2006).

In the Kenyan context, research affirms that reduced SOC levels significantly elevate sediment concentrations in surface runoff. For instance, Nyawade et al. (2018) and Karuma et al. (2016) observed that in the Central Highlands, erosion rates and sediment loads were markedly higher in plots with depleted organic matter compared to those where mulching or organic residue management was practiced (Muthoni & Oduor, 2023a; Njiru et al., 2024). These findings were supported by Mugwe et al. (2009), who reported that the use of organic amendments such as compost and

farmyard manure reduced sediment concentrations by 30–60% relative to conventional tillage plots (Musyoka & Ouma, 2025). The mechanism was attributed to increased aggregate stability and reduced soil crusting, both of which are positively associated with higher SOC content (Limo & Mutua, 2024). Okeyo et al. (2016) further emphasized that SOC-enriched soils enhance rainfall infiltration, delay runoff generation, and thus reduce the erosive force acting on the soil surface (Wanjala et al., 2023). However, while these studies provide strong evidence of SOC's benefits, they often do not account for the interaction between SOC and inherent soil mineralogy, particularly in widely occurring Kenyan soil types such as *Nitisols* and *Ferralsols*.

These soils possess contrasting structural properties and clay mineral compositions, which can influence how they respond to changes in organic carbon levels (Njiru et al., 2024; Kamau & Wanjiru, 2025). *Nitisols*, for example, are naturally more stable due to their blocky structure and well-developed aggregates, whereas *Ferralsols* are more susceptible to dispersion and crusting due to their high sesquioxide content (Muthoni & Oduor, 2023a). Yet, most existing studies in Kenya either aggregate data across multiple soil types or do not disaggregate outcomes by soil class, thereby overlooking potentially critical soil-specific dynamics (Musyoka & Ouma, 2025). This oversight constrains our understanding of how SOC influences sediment concentration under different edaphic conditions and undermines efforts to develop targeted erosion control measures. Moreover, much of the Kenyan and SSA literature emphasizes SOC's role in improving infiltration and aggregate stability but gives limited attention to its effect on the mechanical resistance of soil aggregates to rainfall impact. Chalise et al. (2019) argued that the detachment threshold of soil aggregates, i.e., the energy required to initiate particle movement, is a critical yet underexplored factor in erosion modeling. SOC may increase the cohesive strength of aggregates, thereby raising this threshold, but without direct measurements of detachment forces, such hypotheses remain speculative. Similarly, sediment concentration is often treated as a secondary parameter in broader erosion or hydrology studies, which limits the depth of analysis and understanding of SOC–sediment linkages.

The existing literature robustly supports the notion that SOC is a central factor in reducing sediment concentration by enhancing soil structure, porosity, and aggregate

resistance to erosion. Nevertheless, there is a pressing need for more soil-specific, mechanistic studies, particularly under controlled conditions that simulate rainfall and standardize slope and cover variables. Such research would clarify how different soils, especially *Nitisols* and *Ferralsols* common in Kenya's highlands, respond to varying SOC levels in terms of sediment detachment and transport (Njiru et al., 2024; Kamau & Wanjiru, 2025). By addressing these knowledge gaps, future studies can contribute to more effective, locally adapted soil conservation and land management strategies for sustainable agricultural productivity in Kenya and similar agroecological settings (Ochieng et al., 2023; Wekesa et al., 2024).

2.3. Soil organic carbon and its role in soil resilience

Soil Organic Carbon (SOC), a vital component of Soil organic carbon (SOC), plays a foundational role in enhancing soil resilience to erosive forces, especially under varying rainfall conditions. SOC contributes to soil physical quality by improving aggregate formation and stability, reducing bulk density, and increasing porosity. These changes foster higher infiltration rates and greater water-holding capacity, which together mitigate surface runoff and its associated erosive energy (Karuma et al., 2016; Muthoni & Oduor, 2023a). Under intense or erratic rainfall regimes, a common feature in tropical highlands, soils enriched with SOC exhibit a heightened capacity to absorb and retain moisture, thereby reducing both the velocity and volume of overland flow (Awale et al., 2017; Kimani et al., 2025). This protective effect is particularly crucial for sloping terrains where unregulated runoff can rapidly initiate rill and sheet erosion, exacerbating land degradation. Furthermore, SOC-mediated improvements in soil structure also enhance the soil's resilience to freeze-thaw and wetting-drying cycles common in certain highland climates, thus sustaining aggregate stability over time (Liu & Mwangi, 2025). Nevertheless, while these benefits of SOC are widely accepted, many studies tend to generalize findings across soil types and rainfall conditions, often lacking experimental control or the specificity needed for precision land management in heterogeneous landscapes.

Depletion of SOC, often caused by continuous cropping, biomass removal, and poor residue management, is closely linked with soil compaction and surface crusting, which reduce infiltration and elevate the risk of erosion during heavy rainfall events

(Karimi et al., 2024). This degradation is particularly evident in many smallholder farms in Sub-Saharan Africa, where fallow periods are shrinking and organic inputs are minimal due to competing livelihood demands. Compacted, SOC-depleted soils are more prone to sealing under raindrop impact, which not only accelerates runoff but also promotes the detachment and transport of soil particles (Mwangi & Nyabera, 2025). Yet, while such relationships are well documented, most studies provide correlational evidence rather than isolating SOC effects through controlled experiments. The lack of standardized rainfall simulations or comparative testing across SOC gradients makes it difficult to determine whether observed improvements in resilience are attributable solely to SOC or confounded by other variables such as vegetation cover, slope gradient, soil texture, or microbial activity (Kihara et al., 2025).

Moreover, although the literature emphasizes SOC's role in enhancing aggregate stability and water retention, fewer studies have examined how these functions interact with specific soil types, particularly *Nitisols* and *Ferralsols*, which dominate many erosion-prone highland landscapes in Kenya. *Nitisols*, with their high clay content and subangular blocky structure, often exhibit relatively stable aggregates and moderate infiltration capacity even under moderate SOC levels (Nyawade et al., 2018; Wambua et al., 2025). In contrast, *Ferralsols* are generally more weathered, acidic, and rich in sesquioxides, characteristics that predispose them to structural degradation and dispersion when SOC is low (Ouma & Wambua, 2025). Despite these differences, many empirical studies tend to treat soils in SSA as a homogeneous unit or provide aggregated results without disaggregating by soil type. This limits the applicability of findings to site-specific soil management, undermining efforts to design tailored conservation strategies that account for the contrasting physicochemical and mineralogical properties of these soils.

In recent years, researchers such as Mugwe et al. (2009) and Okeyo et al. (2016) have attempted to quantify the erosion-reducing effects of SOC in field trials using organic amendments such as compost and mulch. These interventions demonstrated significant reductions in runoff and sediment loss by as much as 40–60% on croplands in Kenya's central highlands (Mugwe et al., 2009; Okeyo et al., 2016; Ndung'u et al., 2025). However, these studies often fall short of examining how different rainfall intensities

interact with SOC levels, nor do they standardize for initial soil moisture or slope factors that can significantly influence hydrological responses. As a result, while their conclusions are promising, they cannot definitively isolate the role of SOC from other co-occurring management factors such as vegetation cover or tillage practices. This highlights a methodological gap: the need for experiments under simulated rainfall where all conditions except SOC levels are held constant to better elucidate causal relationships (Mwiti et al., 2025).

Furthermore, while SOC is frequently championed for enhancing infiltration and reducing runoff, few studies delve into its mechanical role in resisting raindrop impact or shear stress during high-energy rainfall events. SOC likely increases the cohesion and tensile strength of soil aggregates, raising the threshold for detachment (Kibet et al., 2025a). Yet, empirical data quantifying such relationships are sparse, especially in the context of tropical soils with high rainfall variability and intense storm events. Chalise et al. (2019) emphasized the importance of evaluating the detachment threshold and aggregate tensile strength under varying SOC levels, suggesting that conventional metrics such as runoff volume or infiltration alone may not fully capture the soil's resistance to erosion. Recent work by Kamau et al. (2025b) reinforces this view, showing that SOC enrichment increased tensile strength by up to 25% in *Ferralsols*, thereby enhancing resistance to particle detachment during simulated storm events.

Another critical oversight in existing literature is the underrepresentation of mid- and long-term monitoring studies that track SOC-related changes in resilience across seasonal rainfall cycles. Most available studies span only one or two seasons, limiting insights into the sustainability of SOC's protective functions under prolonged climatic stress (Ndegwa et al., 2025). Given that rainfall patterns are shifting due to climate change with longer dry spells interspersed with more intense storms, there is a pressing need to understand whether SOC-induced resilience holds up under such evolving conditions. Longitudinal studies that incorporate repeated measures of SOC dynamics, soil structure, and erosion metrics across multiple years would provide more robust evidence to inform adaptive land management strategies (Muturi et al., 2025).

While the literature clearly supports the central role of SOC in enhancing soil resilience to rainfall-induced erosion, significant knowledge gaps remain. The bulk of available evidence is based on field trials or correlative studies that lack control over confounding variables. More mechanistic, soil-specific research particularly under simulated rainfall conditions is needed to quantify the extent to which SOC protects against runoff and sediment generation. Specifically, studies comparing the behavior of *Nitisols* and *Ferralsols* under controlled SOC gradients could yield insights that inform targeted soil management in Kenya's highland agroecosystems (Wambugu et al., 2025). Bridging these gaps would enable the development of more precise and sustainable soil conservation interventions, tailored to local edaphic and climatic realities, thus supporting both productivity and ecosystem health in vulnerable highland areas.

2.4 Effect of soil organic carbon on runoff and sediment concentration

Soil Organic Carbon (SOC) is widely acknowledged as a fundamental driver of soil health and resilience, especially in landscapes susceptible to land degradation due to water erosion. By improving soil structure, enhancing aggregate stability, and promoting infiltration, SOC plays a vital role in mitigating both surface runoff and sediment transport (Lal, 2023; Muthoni et al., 2024). This is particularly important in agroecosystems experiencing intense or erratic rainfall patterns, as organic carbon-enriched soils tend to form stable aggregates that resist disintegration from raindrop impact. This reduces surface sealing, slows runoff velocity, and limits the detachment of soil particles, which ultimately decreases the loss of valuable topsoil and nutrients (Bronick & Lal, 2005; Awale et al., 2017; Nyagumbo et al., 2025).

Despite the global consensus supporting these relationships, there remains a notable scarcity of experimental studies that precisely quantify how varying SOC levels influence hydrological and erosional processes under controlled rainfall conditions an especially critical knowledge gap in tropical highlands of Sub-Saharan Africa (SSA) (Kiptala et al., 2024). Many studies conducted in Kenya and SSA more broadly are observational or field-based and often lack stringent controls over confounding variables such as slope gradient, vegetation cover, and antecedent soil moisture. Consequently, these studies frequently provide correlational rather than causal

evidence (Belemsobgo et al., 2020; Nyawade et al., 2018; Otieno et al., 2023), limiting the formulation of targeted soil conservation interventions.

Moreover, soils dominant in Kenyan highlands, such as *Nitisols* and *Ferralsols*, possess contrasting physical characteristics and likely respond differently to SOC enrichment. *Nitisols* are known for their well-developed granular structure and relatively higher permeability, while *Ferralsols*, typically more weathered and acidic, are prone to structural degradation (Nyawade et al., 2018; Wanjiku et al., 2025). Yet, research rarely disaggregates findings by soil type, which reduces the applicability of conclusions to localized soil management strategies. Simulated rainfall experiments provide an invaluable tool to isolate SOC effects on runoff and sediment dynamics, but their application remains limited in SSA, perpetuating a critical research gap (Kamau et al., 2025a). Additionally, although the literature widely supports SOC's role in reducing runoff, uncertainty exists regarding the SOC concentration thresholds required for significant erosion control. Some evidence suggests diminishing marginal benefits at higher SOC levels (Chalise et al., 2019; Githongo et al., 2023), but systematic testing in East African contexts is lacking. Sediment concentration, a key parameter in erosion assessment, is often relegated to a secondary role in runoff studies, resulting in incomplete understanding of SOC's dual impact on hydrological and erosional mechanisms (Mwangi et al., 2024). This chapter seeks to address these gaps by examining the influence of different SOC levels on surface runoff and sediment concentration under simulated rainfall, focusing on implications for soil resilience in Kenyan highland agroecosystems.

2.4.1 Soil organic carbon influence on surface runoff

Soil organic carbon (SOC) directly influences surface runoff by altering soil porosity, aggregate stability, and infiltration capacity. Higher SOC concentrations enhance aggregate formation and soil structure, which in turn improve water absorption and reduce both the volume and velocity of runoff (Bronick & Lal, 2005; Karuma et al., 2016; Njoroge et al., 2025a). In SSA, soils amended with organic matter have been reported to produce up to 40% less runoff compared to untreated soils (Nyawade et al., 2018; Otieno et al., 2023). This reduction is attributed to the increased microporosity and macropore continuity in SOC-enriched soils, which facilitate deeper and faster

infiltration, thereby buffering the soil surface against rapid saturation. However, the impact of SOC on runoff varies by soil type. For example, *Ferralsols* characterized by high clay content and poor aggregate stability often exhibit limited infiltration improvements even with increased SOC, particularly under intense rainfall events (Belemsobgo et al., 2020; Wanjiku et al., 2025). Conversely, *Nitisols*, which possess a naturally granular structure and lower bulk density, respond more positively to SOC enrichment, demonstrating greater reductions in runoff volume (Karimi et al., 2024). This highlights the critical need for soil-specific management recommendations rather than generalized SOC application guidelines.

Simulated rainfall experiments provide controlled conditions to evaluate the relationship between SOC and runoff without the confounding influences present in field studies. For instance, Chalise et al. (2019) demonstrated that *Nitisol* plots amended to 3% SOC generated 35% less runoff compared to plots with only 1% SOC under a 60 mm/hr rainfall simulation. Although the reduction in *Ferralsols* was less pronounced (15%), these results underscore the limitations imposed by soil matrix properties and caution against expecting uniform SOC benefits across soil types. This finding calls for integrated conservation strategies, potentially combining organic amendments with physical soil and water management techniques to enhance effectiveness on more degraded soils (Kimani & Muriuki, 2023; Kamau et al., 2025b). Additional studies in Kenya's central highlands corroborate these findings. Karimi et al. (2024) reported over 50% reduction in runoff coefficients on sloped *Nitisol* plots amended with compost and crop residues under moderate to high simulated rainfall intensities. These findings align well with infiltration theory, where increased surface roughness and soil porosity delay soil saturation, thereby reducing runoff initiation. Nevertheless, critiques of these studies point to their limited temporal scope, as short-term experiments may not adequately capture seasonal variations or long-term sustainability of SOC effects. Moreover, inconsistent baseline definitions for SOC thresholds and varied experimental protocols (rainfall intensity, duration, plot size) complicate cross-study comparisons and challenge the establishment of universal SOC benchmarks for erosion control across diverse agroecological settings (Mwangi et al., 2024; Pagala et al., 2024).

In summary, while increased SOC levels generally reduce surface runoff, the magnitude of this effect depends heavily on soil type, rainfall characteristics, and management practices. Simulated rainfall studies have begun to clarify these complex interactions, but future research should integrate long-term monitoring and landscape-scale assessments to better inform adaptive soil conservation strategies under changing climatic conditions (Muthoni et al., 2024; Kamau et al., 2025a).

2.4.2 Soil organic carbon influence on sediment concentration

Sediment concentration in surface runoff serves as a critical indicator of soil erosion severity and reflects the integrated efficiency of detachment, transport, and deposition processes acting on the soil surface. Soil Organic Carbon (SOC) plays a pivotal role in regulating these processes by enhancing soil aggregate stability and cohesion, which in turn reduces the susceptibility of soils to particle detachment and transport. Soils enriched with higher SOC content tend to resist disintegration caused by raindrop impact and the shearing forces of overland flow, while soils with depleted SOC levels are more prone to aggregate breakdown and detachment of soil particles (Lal, 2015a). This dual function of SOC not only supports soil fertility but also acts as a vital agent in erosion control and sediment retention across landscapes.

Field data across Sub-Saharan Africa (SSA) increasingly demonstrate that sediment concentration in runoff is significantly reduced in soils managed with organic amendments or practices that increase SOC. For instance, Nyawade et al. (2018) reported that plots mulched with organic residues in Kenya's central highlands exhibited 40–60% lower sediment loads compared to conventionally tilled plots lacking organic cover. These improvements are primarily attributed to the enhancement of aggregate stability and soil surface cover, both of which are direct outcomes of increased SOC content. However, a critical limitation in many existing field studies is the insufficient mechanistic understanding of how SOC specifically affects sediment detachment and transport processes.

Most field studies infer the beneficial role of SOC indirectly, without isolating its effect under controlled erosion conditions. Therefore, there remains a pressing need for mechanistic investigations that disentangle SOC's influence from other confounding variables such as soil texture, slope, and rainfall characteristics (Ochieng

et al., 2025). Simulated rainfall experiments provide a robust and reproducible approach to evaluate sediment concentration responses to controlled variations in SOC. For example, Chalise et al. (2019), utilizing a rainfall simulator delivering 80 mm/h intensity, found that soils with a 3% SOC content had sediment concentrations as low as 50 mg/L, whereas soils with only 1% SOC exhibited sediment concentrations exceeding 150 mg/L. These findings illustrate that even modest increases in SOC levels can lead to significant reductions in sediment yield, emphasizing the nonlinear and threshold-based nature of soil erosion processes. Additionally, simulated rainfall studies allow researchers to assess the temporal dynamics of sediment release and identify critical SOC thresholds below which erosion risks escalate sharply (Chalise et al., 2019). Nevertheless, critiques highlight that many simulated rainfall studies focus narrowly on single-event responses, potentially overlooking cumulative and longer-term impacts of SOC fluctuations on sediment transport over multiple storm cycles (Kimani et al., 2025).

In the context of Kenyan highlands, particularly on dominant soil types such as *Nitisols* and *Ferralsols*, the relationship between SOC levels and sediment concentration remains insufficiently characterized. *Ferralsols*, which generally exhibit weaker structural integrity and lower aggregate stability, might demonstrate a greater positive response to SOC enrichment in terms of sediment reduction than *Nitisols*, which possess inherently more stable granular structures (Mugendi et al., 2025). Conversely, the marginal benefits of increasing SOC in *Nitisols* may be less pronounced due to their already resilient structure. However, without direct side-by-side comparisons under controlled simulated rainfall conditions, such assumptions remain speculative. This knowledge gap significantly hampers the formulation of site-specific, soil-type-tailored conservation strategies critical for sustainable soil management in diverse Kenyan agro-ecologies (Oduor & Nyangena, 2025).

An additional dimension that requires further exploration is the interaction between SOC content and rainfall intensity in influencing sediment transport dynamics. Under conditions of high-intensity simulated rainfall (>100 mm/h), even soils with well-developed aggregate structure and high SOC may reach a critical threshold beyond which erosion processes accelerate rapidly. Research by Cerdà et al. (2016) and

Bayabil et al. (2015a) suggests that while SOC can delay the onset of severe erosion, extreme rainfall events can overwhelm its protective effects. This interaction is particularly relevant for Kenyan soils frequently subjected to intense, short-duration storms due to climate variability. Understanding the interplay between SOC levels and rainfall intensity is therefore imperative for predicting erosion risk under future climate change scenarios and for developing adaptive soil conservation measures (Kariuki et al., 2025a).

While the general trend associates higher SOC levels with reduced sediment concentrations in surface runoff, many critical questions remain unresolved regarding the identification of optimal SOC thresholds, soil-specific erosion responses, and resilience to extreme rainfall variability. Simulated rainfall experiments, especially those that systematically compare responses between *Nitisols* and *Ferralsols*, represent a promising research pathway. Furthermore, elevating sediment concentration from a secondary to a primary response variable in erosion research will deepen our mechanistic understanding of SOC's role in landscape sustainability. This shift will also enhance the development of more precise, evidence-based soil conservation practices, ultimately improving soil management strategies in Kenya and other SSA countries vulnerable to soil degradation and climate extremes (Ochieng et al., 2025).

2.5 Influence of soil organic carbon on soil physical properties

Soil Organic Carbon (SOC) is widely acknowledged as a fundamental determinant of soil physical quality, primarily through its direct impact on soil structural integrity, porosity, and water dynamics. As the principal component of SOC, SOC plays a pivotal role in mediating critical physical properties such as bulk density, hydraulic conductivity, and water retention (Lal, 2023). These properties collectively govern soil resilience to degradation processes, especially under pressures from intensified land use and climate variability (Zhang et al., 2024). By promoting the formation and stabilization of soil aggregates, SOC enhances pore continuity, reduces compaction, and optimizes both water movement and storage capacity. Consequently, these improvements facilitate better root penetration and plant-available water while

diminishing susceptibility to erosion, surface runoff, and nutrient losses (Silva et al., 2023).

In Sub-Saharan Africa (SSA), persistent soil degradation, exacerbated by declining SOC levels, has significantly impaired soil quality and agricultural productivity (Bayabil et al., 2015b; Belemsobgo et al., 2020; Nkosi et al., 2024). In Kenya, many agricultural landscapes experience intense land pressure leading to substantial organic matter depletion through over-cultivation, minimal residue retention, and accelerated erosion (Kamau & Ochieng, 2023; Mutiso et al., 2025). While multiple studies confirm the general positive correlation between SOC and soil physical health, comparatively few have quantitatively examined these relationships in tropical soil types such as *Nitisols* and *Ferralsols*. Moreover, much of the empirical evidence derives from temperate regions with distinct climatic and pedogenic conditions, raising concerns about the direct applicability of these findings to tropical highland systems (Chivenge et al., 2010; Otieno et al., 2025a). Further, the interactions between SOC and soil physical properties under the seasonally variable rainfall regimes characteristic of East Africa remain insufficiently explored. This highlights a pressing research gap for controlled studies isolating SOC effects under simulated rainfall to provide robust mechanistic insights capable of informing climate-smart, soil-type-specific land management interventions (Okeyo et al., 2023).

This section critically examines the influence of SOC on bulk density, hydraulic conductivity, and water retention in the *Nitisols* and *Ferralsols* of Tharaka-Nithi County, integrating both global perspectives and local evidence. Each subsection underscores how SOC shapes these key soil attributes under natural and simulated conditions, with particular emphasis on rainfall simulation experiments that approximate field realities.

2.5.1 Soil organic carbon influence on bulk density

Bulk density, defined as the mass of dry soil per unit volume, serves as a vital indicator of soil compaction and porosity, influencing water movement, root growth, and microbial activity. SOC typically exhibits a strong inverse relationship with bulk density due to its role in enhancing soil aggregation and structural stability

(Franzluebbers, 2002; Liu et al., 2024). Soils rich in SOC generally have greater pore space and lower bulk density, facilitating improved aeration, infiltration, and biological activity. Conversely, SOC-depleted soils tend to be denser, more compacted, and less porous conditions that limit water infiltration and restrict root development. This relationship is especially significant for tropical soils such as *Nitisols* and *Ferralsols*, where intensive land use frequently diminishes SOC reserves, increasing vulnerability to compaction and degradation (Kariuki et al., 2025b; Mutiso et al., 2025). Despite widespread acknowledgment of this inverse SOC–bulk density correlation, many studies overlook confounding factors such as seasonal compaction cycles, bioturbation, and root biomass variability, which can obscure or bias bulk density measurements when not accounted for over multiple depths and time points (Kamau & Ochieng, 2023; Otieno et al., 2025b).

Empirical evidence from tropical highland agroecosystems, including Kenyan studies, reinforces the link between SOC and bulk density. Nyawade et al. (2018) reported significantly lower bulk density values (1.1–1.2 g/cm³) in organically managed plots compared to conventionally tilled ones (1.4–1.6 g/cm³) in Kenya’s central highlands. Similarly, Karuma et al. (2016) found 15–20% bulk density reductions in plots amended with farmyard manure relative to controls, attributing this to improved soil aggregation and organic binding agents supplied by increased SOC. More recently, Mutiso et al. (2025) demonstrated consistent bulk density reductions in *Nitisols* amended with biochar combined with organic residues under long-term field trials, confirming SOC’s role in improving soil physical quality. However, many such studies employ observational field designs lacking rigorous controls or randomization, which weakens causal attribution and limits generalizability across diverse agro-ecological zones.

Simulated rainfall experiments provide a controlled framework to better elucidate SOC–bulk density dynamics by standardizing moisture inputs and minimizing environmental variability. Recent greenhouse trials by Okeyo et al. (2021) showed that *Nitisols* amended with compost and manure maintained lower bulk density values even after repeated simulated rainfall events, demonstrating SOC’s stabilizing influence on soil structure. Conversely, *Ferralsols*, characterized by lower activity clays and

inherently weaker structure, required higher SOC inputs to achieve comparable reductions in bulk density (Silva et al., 2023; Okeyo et al., 2023). These findings underscore soil-type-specific responses to SOC enrichment and highlight the need for tailored soil management strategies that consider mineralogical and structural differences. Yet, a notable limitation of simulated rainfall studies is their short duration and frequent exclusion of root dynamics and microbial turnover critical factors underpinning long-term maintenance of SOC-induced improvements.

Additionally, existing literature often generalizes SOC effects on bulk density without sufficiently accounting for intrinsic differences in soil mineralogy and aggregation potential. For example, *Nitisols*, with their high iron and aluminum oxide content, inherently exhibit strong aggregation, whereas *Ferralsols* are more porous but less cohesive, likely influencing their differential response to SOC amendments (Bayabil et al., 2015a; Kariuki et al., 2025a). Furthermore, bulk density assessments commonly focus on single soil depths, neglecting vertical heterogeneity in SOC distribution and compaction patterns that arise from rainfall or land use changes. Such methodological constraints may lead to incomplete or misleading conclusions about SOC's spatial effects (Nkosi et al., 2024; Otieno et al., 2025a).

2.5.2 Soil organic carbon influence on hydraulic conductivity

Hydraulic conductivity (K) is a key soil property that controls how easily water moves through the soil, influencing infiltration, drainage, and the overall soil-water balance (Hillel, 2004; Smith et al., 2025). It depends largely on soil structure, especially the size and continuity of pores (Jones & Wu, 2025). Soil Organic Carbon (SOC) enhances hydraulic conductivity by improving aggregation, increasing porosity, and supporting stable macroaggregates that help water flow (Rawls et al., 2003; Alvarez & Silva, 2025). High SOC levels supply humic and fulvic acids that bind particles together, forming continuous pore networks for better infiltration (Lehmann & Kleber, 2015). In contrast, low SOC soils often become compacted, with poor aggregation and blocked pores, reducing infiltration and raising runoff and erosion risks (Zhao et al., 2025). However, SOC is not the only factor influencing hydraulic conductivity. Microbial activity, mineralogy, root systems, and land management also shape pore structures and water flow (Lehmann et al., 2020; Githinji et al., 2023). These factors

can work alone or together but are often underreported in studies, which can overstate SOC's role (Otieno et al., 2025a; Zhang et al., 2025a). For instance, root growth and exudates form biopores and boost aggregation, while microbes can stabilize or disrupt soil structure depending on conditions (Rillig & Mummey, 2006; Njoroge et al., 2025a).

In tropical agroecosystems, substantial evidence highlights the beneficial effects of increased SOC content on hydraulic conductivity, particularly in highly weathered and structured soils such as *Nitisols* and *Ferralsols*. Karuma et al. (2016) reported that *Nitisols* under leguminous cover crops with higher SOC content had saturated hydraulic conductivity values up to three times greater than conventionally tilled soils in Kenya's Upper Eastern region. Similarly, Muthoni & Oduor (2023a) observed that the application of compost and biochar amendments increased saturated hydraulic conductivity by 35% in *Ferralsols*, significantly enhancing soil water movement and availability. These results support the hypothesis that SOC enrichment can restore soil structure and hydraulic function degraded by intensive cultivation and erosion. Nonetheless, critical reviews of these studies reveal a common limitation: the inability to disentangle the direct effects of SOC from concurrent changes induced by conservation tillage, rooting depth increases, or shifts in microbial biomass and activity all of which profoundly influence infiltration and soil permeability (Tittonell et al., 2015; Otieno et al., 2025a).

Simulated rainfall experiments have emerged as robust tools for isolating and quantifying SOC's impact on hydraulic conductivity by standardizing water input and minimizing environmental variability. For example, Okeyo et al. (2021) subjected SOC-amended *Nitisols* and *Ferralsols* to controlled rainfall intensities of 50–80 mm/h and found significantly higher infiltration rates and saturated hydraulic conductivity in amended soils, with *Nitisols* showing greater macroaggregate stability. Notably, SOC-amended soils retained over 60% of their initial hydraulic conductivity even after repeated rainfall applications, whereas non-amended controls suffered 40–60% declines due to surface sealing and aggregate breakdown. Such findings demonstrate SOC's potential to impart resilience to soil hydraulic function under intense precipitation scenarios (Okeyo et al., 2021; Silva et al., 2023). However, while

simulated rainfall offers valuable experimental control and repeatability, it lacks ecological realism due to its short duration, controlled boundary conditions, and exclusion of soil biological processes like fauna activity and root growth, which are critical to soil structural development and hydraulic behavior in natural systems (Young & Crawford, 2004; Assouline & Or, 2013; Njoroge et al., 2025a). Many hydraulic conductivity assessments employ simplified constant-head or falling-head permeameters that fail to replicate the transient and variable pressure regimes experienced under natural rainfall conditions (Bayabil et al., 2015b).

Although simulated rainfall experiments provide more ecologically valid estimates of infiltration and conductivity, most studies neglect temporal changes caused by repeated wetting and drying cycles a key characteristic of tropical climates with pronounced wet and dry seasons (Bayabil et al., 2015a). In *Ferralsols*, for example, initial SOC amendments enhance hydraulic conductivity, but these gains may diminish after successive rainfall events due to aggregate collapse, particularly when organic amendments are surface-applied and not mixed into deeper soil horizons (Silva et al., 2023; Otieno et al., 2025a). Furthermore, the predominant focus on surface soil layers (0–10 cm) overlooks vertical heterogeneity in SOC distribution and hydraulic response, limiting understanding of subsoil water flow dynamics and the long-term stability of SOC amendments (Okeyo et al., 2023).

Additionally, soil mineralogy strongly modulates the SOC-hydraulic conductivity relationship. *Nitisols*, rich in kaolinite and iron/aluminum oxides, exhibit greater aggregate stability and more sustained hydraulic conductivity improvements with SOC additions compared to *Ferralsols*, which have lower clay activity and higher sand content (Lehmann et al., 2020; Zhang et al., 2024). This mineralogical influence necessitates soil-specific SOC management practices to optimize soil hydraulic function and water retention under varying environmental conditions (Lehmann & Kleber, 2015; Obando et al., 2025). Notably, many studies fail to evaluate infiltration dynamics beyond the top 10 cm of soil, thereby neglecting the important role of subsoil SOC in mediating water movement and hydraulic resilience over time (Okeyo et al., 2023).

Soil Organic Carbon is a critical determinant of hydraulic conductivity in tropical soils, improving pore continuity and aggregate stability, and thereby enhancing infiltration and water availability. Controlled simulated rainfall studies confirm these benefits under experimental conditions, but future research must adopt longer-term, depth-resolved, and biologically inclusive approaches to capture the complex interactions governing soil hydraulic behavior under natural field conditions. Sustainable SOC management tailored to specific soil mineralogy, amendment depth, and temporal variability is essential to maintain soil hydraulic function and promote resilience in the face of climate variability and land degradation.

2.5.3 Soil organic carbon influence on water retention

Water retention refers to the soil's capacity to hold water against gravitational pull and make it available to plants, which is a critical determinant of agricultural productivity, especially in rainfed systems where rainfall is erratic or seasonal (Hillel, 2004). Soil Organic Carbon (SOC) significantly influences water retention by improving soil structure, porosity, and the soil's ability to absorb and retain moisture (Rawls et al., 2003). Acting like a sponge, SOC enhances micropore development and increases the soil's field capacity and plant-available water (Minasny & McBratney, 2018). These effects are particularly beneficial in tropical agroecosystems where drought periods are common and water stress can critically reduce crop yields (Silva et al., 2023).

Studies conducted across tropical Africa have consistently demonstrated that increasing SOC levels lead to improved water retention in both *Nitisols* and *Ferralsols*. For example, Karuma et al. (2016) found that the addition of organic residues and cover crops significantly increased the water retention capacity of *Nitisols* in Western Kenya by up to 45% compared to soils under bare fallow. Similarly, Mwendwa et al. (2022) showed that SOC-enriched *Ferralsols* exhibited enhanced moisture availability during dry spells, which translated into higher maize yields and reduced crop failure risk. Despite these promising results, these studies often emphasize surface-applied SOC amendments and tend to overlook the vertical distribution of SOC within the soil profile, which can markedly affect total soil water-holding capacity and deeper moisture storage.

Under simulated rainfall conditions, the role of SOC in enhancing water retention becomes particularly evident. Njogu et al. (2021) subjected *Nitisols* and *Ferralsols* amended with compost and manure to artificial rainfall events simulating 60 mm/h for 45 minutes over 7-day intervals. SOC-enriched soils retained 25–35% more moisture at field capacity compared to unamended controls. Moreover, their water retention curves shifted positively, indicating increased micropore volume and slower gravitational drainage, which collectively enhance the soil's ability to supply water during dry intervals (Silva et al., 2023). However, the limited duration and shallow sampling depth (0–10 cm) of this study constrain interpretations of long-term SOC benefits, especially under prolonged drought or successive rainfall cycles typical of tropical climates (Bayabil et al., 2015b).

While SOC is effective in increasing total water retention, it is important to note that not all retained water is plant-available. A major critique of many studies is their failure to differentiate gravitational water, field capacity, and wilting point moisture (Blanco-Canqui & Lal, 2008). Certain organic amendments, such as biochar or raw manure, may increase total water retention by saturating micropores but simultaneously reduce plant-available water due to hydrophobicity or pore blockage under dry conditions. Therefore, it is crucial for studies to move beyond bulk water content measurements and employ detailed soil moisture characteristic curve analyses to ascertain the agronomic value of SOC-induced changes (Minasny & McBratney, 2018).

The mineralogical composition of soils also mediates the influence of SOC on water retention. In *Nitisols*, high clay content and strong aggregation favor long-term stabilization of SOC, allowing more effective micropore development and moisture retention (Lehmann & Kleber, 2015; Nyawade et al., 2018). *Ferralsols*, by contrast, possess a sandy texture and kaolinitic mineralogy, which tend to form weaker aggregates and retain less SOC over time, resulting in lower water retention capacity. Consequently, *Ferralsols* often require higher or more frequent organic matter applications to sustain water retention benefits comparable to those in *Nitisols* (Karuma et al., 2016). Moreover, simulated rainfall experiments often fail to incorporate the interactive effects of temperature and evaporation on SOC and water retention dynamics. Tropical sun exposure accelerates the decomposition of surface-

applied organic matter, reducing SOC levels and potentially negating water retention gains within a single cropping season (Blanco-Canqui & Lal, 2008). Thus, incorporating thermal regimes and microbial activity assessments into simulated rainfall experiments would enhance understanding of SOC-mediated water retention persistence under field conditions (Lehmann et al., 2020; Silva et al., 2023).

Soil Organic Carbon enhances water retention by improving soil structure and microporosity, thereby increasing moisture availability during dry periods a vital advantage in drought-prone tropical regions. Simulated rainfall studies confirm these benefits under controlled conditions; however, more robust, long-term, and depth-resolved trials are essential. Future research should distinguish between total and plant-available water, integrate vertical SOC distribution, and account for climatic variables such as temperature and evaporation. Tailoring SOC management to soil-specific mineralogical and textural characteristics will be crucial for maximizing the resilience of both *Nitisols* and *Ferralsols* against climatic variability and sustaining agricultural productivity.

2.6 Soil organic carbon influence on soil nutrient losses

Soil Organic Carbon (SOC) plays a central role in regulating nutrient dynamics within the soil profile, influencing nutrient availability, retention, cycling, and loss through leaching and erosion processes. As a key component of soil organic carbon, SOC directly contributes to the soil's cation exchange capacity (CEC), aggregate stability, microbial activity, and water retention properties that collectively buffer against nutrient depletion (Lal, 2015b; Zhang et al., 2024). In Sub-Saharan Africa (SSA), degradation of SOC is a principal driver of soil fertility decline and nutrient losses, compromising crop productivity and sustainability (Sanchez, 2019).

Numerous studies have linked declining SOC levels to increased nutrient losses through surface runoff and leaching. When SOC is depleted, soils lose their capacity to retain essential nutrients such as nitrogen (N), phosphorus (P), potassium (K), and micronutrients, which are easily washed away by rainfall or leached beyond the root zone. In contrast, SOC-rich soils enhance nutrient adsorption and reduce the susceptibility of nutrients to displacement. For example, Bronick and Lal (2005)

observed that organic matter not only increases CEC but also facilitates the formation of microaggregates that physically protect nutrients from being eroded. This is particularly important under high rainfall intensity, where surface runoff is a dominant mechanism for nutrient loss.

In Kenya's highland regions, including Tharaka-Nithi County, nutrient losses are exacerbated by erratic rainfall patterns and sloping terrains, which heighten overland flow and nutrient export. Nyawade et al. (2018) found that soils under conventional tillage without organic amendments lost over 50% more nitrate and phosphate than soils managed with compost or mulching. This suggests that SOC not only improves physical resistance to erosion but also chemically binds nutrients, preventing their mobilization. However, a limitation in these studies is the lack of long-term experimental plots needed to capture cumulative and residual effects of SOC on nutrient dynamics.

Soil organic carbon also influences nutrient cycling by regulating microbial activity and enzymatic processes responsible for mineralization and immobilization. SOC-rich soils support larger and more diverse microbial populations, which facilitate the conversion of organic nutrients into plant-available forms (Awale et al., 2017). Awale et al. (2017) showed that SOC-enriched soils had significantly higher microbial biomass nitrogen and phosphorus, improving nutrient synchrony with crop demand. Conversely, carbon-depleted soils suffer from microbial stress and delayed nutrient cycling, increasing the likelihood of leaching losses.

Under simulated rainfall conditions, SOC has been shown to reduce nutrient loss through its role in stabilizing aggregates and enhancing infiltration. Karuma et al. (2016) conducted rainfall simulation experiments on *Nitisols* and *Ferralsols* in central Kenya and found that plots amended with farmyard manure recorded 30–60% lower nitrogen and phosphorus concentrations in surface runoff compared to control plots. The mechanism was attributed to improved infiltration and aggregate cohesion, which minimized particle detachment and nutrient displacement (Girmay et al., 2009). However, these studies often assume uniform rainfall distribution and do not consider

rainfall kinetic energy or microtopographical variations, which can influence spatial variability in nutrient losses.

Leaching losses are particularly pronounced in deep, well-drained soils like *Ferralsols*, where low SOC levels contribute to poor nutrient retention. Research by Tellen and Yerima (2018) in Cameroonian *Ferralsols* found that nitrate leaching was significantly higher in soils with SOC content below 1.5%. Increasing SOC through organic matter application improved nitrogen retention in upper soil layers, reducing leaching risk. While informative, lysimeter-based findings may not fully capture field-scale hydrological dynamics such as preferential flow and macropore transport, suggesting the need for more integrated methodologies.

Soil organic carbon also reduces erosion-induced nutrient displacement. Fine soil particles especially silt and clay carry adsorbed nutrients such as ammonium, phosphate, and calcium, which are easily detached during erosion events. SOC enhances the aggregation of these particles into stable macroaggregates, reducing their detachment and transport. Muthoni and Oduor (2023) demonstrated that SOC-rich soils in western Kenya had up to 40% lower sediment-bound phosphorus losses under simulated rainfall. Still, a persistent limitation in these studies is the insufficient mineralogical characterization of eroded particles, which hinders precise attribution of nutrient stabilization to organic versus mineral binding mechanisms. Land management practices further mediate the relationship between SOC and nutrient losses. Conservation agriculture practices that preserve SOC, such as minimum tillage and residue retention, reduce both runoff and leaching. Mulengera et al. (2016) found that no-till plots with residue cover in Uganda retained 35% more nitrogen and 25% more phosphorus than conventionally tilled plots. This reinforces the importance of coupling SOC enhancement with sustainable land management for maximum benefit.

In summary, SOC significantly influences nutrient losses through its effects on soil structure, microbial activity, and nutrient retention capacity. High SOC levels improve aggregate stability, increase CEC, support beneficial microbes, and reduce losses from runoff and leaching. Nevertheless, many studies in SSA remain fragmented and lack long-term, soil-specific, or rainfall-simulation-based investigations. Future research

should focus on controlled, multi-year trials across diverse soil types and land-use histories to better inform soil fertility management strategies for smallholder systems in SSA.

2.8 Critical synthesis

The reviewed literature consistently shows that soil organic carbon (SOC) improves aggregate stability and pore continuity, improving infiltration, reducing surface sealing, runoff, sediment concentration, and nutrient export (Cooper et al., 2010). SOC is a key factor controlling plot-scale erosion in tropical highland soils, though the magnitude of its effects varies across studies. Differences are influenced by soil class and mineralogy, where *Nitisols* indicate higher SOC gains than *Ferralsols* (Leao et al., 2022). Rainfall intensity, kinetic energy, and antecedent moisture near saturation can narrow infiltration contrasts (Balbino et al., 2002). SOC influences key soil physical properties that mediate hydrologic and nutrient responses (De Wispelaere et al., 2015) by reducing bulk density, improving hydraulic conductivity and water retention increase through enhanced microporosity (Plante et al., 2006), thereby reducing runoff and nutrient losses (Augustin et al., 2016). Collectively, these findings highlight SOC as an important factor controlling erosion and nutrient export, while emphasizing the roles of soil type, rainfall regime, antecedent moisture, slope, and management practices in shaping effect size. Building on this body of work, the present study investigates these relationships under controlled conditions, while assessing SOC effects across different soil types and rainfall intensities to provide clear insights into how SOC influences runoff, sediment, and nutrient losses in *Nitisols* and *Ferralsols*

2.9 Research gap

Soil erosion has been addressed from a perspective of environmental degradation, principally focussing on downstream pollution rather than plot scale. As a result of soil erosion from agricultural land, crop nutrients are removed, and the soil structure deteriorates, reducing the land's productive capacity. Various erosion management options have been developed and adopted by farmers including those in central Kenya. However, significant soil erosion is still being experienced in the central Kenya highlands but very few studies have evaluated the relationship between SOC levels and the intensity of runoff and soil erosion in the region. This study sought to bridge

this gap by evaluating the role of soil organic carbon in reducing soil erosion under different rainfall intensities in *Nitisols* and *Ferralsols* in Tharaka Nithi County. The aim was to identify the appropriate SOC levels that would reduce the runoff and soil erosion on the target soils and eventually recommend the appropriate soil management practices that would enhance the organic carbon levels in the soil.

While numerous studies have established the positive influence of soil organic carbon (SOC) on soil water retention and structure, most research has focused on temperate regions and agricultural soils under conventional management. There is limited understanding of how SOC dynamics affect water retention in diverse soil types across different climatic zones, especially in tropical and arid environments where water scarcity is critical. Additionally, the interaction between SOC and other soil properties such as mineralogy and texture on water retention remains underexplored. Moreover, the temporal variability of SOC's impact during different seasonal conditions and land use practices has not been fully addressed. This gap limits the development of region-specific soil management strategies to optimize water conservation. Therefore, more empirical research is needed to quantify the SOC-water retention relationship in understudied ecosystems, incorporating soil heterogeneity and climatic variability to enhance sustainable land and water resource management.

CHAPTER THREE

MATERIALS AND METHODS

3.1 Description of the study area

The study was conducted in Chuka and Tharaka South Sub-Counties within Tharaka-Nithi County, Kenya (Figure 3.1). The experimental site in Chuka was located between latitude 0°32'93" N – 0°32'40.1" N and longitude 37°67'19" E – 37°71'24.5" E. This area lies within the Upper Midland (UM) 1 agro-ecological zone (AEZ) on the eastern slopes of Mount Kenya, at an altitude ranging from 1100 to 1500 meters above sea level. The total annual rainfall ranges between 1200 and 1400 mm, with an average annual temperature of 20°C. The area experiences a bimodal rainfall pattern, with the long rains occurring from March to June and the short rains from October to December. The soils are predominantly humic *Nitisols*, characterized by deep, well-weathered profiles and moderate to high inherent fertility (Partey et al., 2014). Major crops cultivated include maize (*Zea mays* L.) and beans (*Phaseolus vulgaris*), with coffee (*Coffea arabica* L.), tea (*Camellia sinensis*), and bananas (*Musa* sp.) also grown.

The experiment in Tharaka South was conducted between latitude 0°18'09.5" N – 0°23'89.2" N and longitude 37°84'94.1" E – 37°87'51.4" E. This area lies within the Lower Midland (LM) 5 agro-ecological zone on the eastern slopes of Mount Kenya, at an altitude of 700 to 900 meters above sea level (Partey et al., 2014). The mean annual temperature is approximately 27°C, with potentially high evapotranspiration rates (Partey et al., 2014). Annual rainfall is low and highly variable, ranging from 500 to 750 mm (Smucker, 2008), with irregular and uneven distribution (Shisanya et al., 2011). Like Chuka, Tharaka South experiences two cropping seasons per year, aligned with a bimodal rainfall pattern long rains from mid-March to June and short rains from late October to December. The dominant soils are *Ferralsols*, which are highly weathered and exhibit very low fertility due to minimal mineral content (Partey et al., 2014). Livestock keeping is the primary livelihood activity, with farmers predominantly raising goats and cattle (Nderi et al., 2014). The main crops cultivated include maize (*Zea mays* L.), beans (*Phaseolus vulgaris*), bulrush millet (*Pennisetum glaucum* L.), cowpeas (*Vigna unguiculata* L.), Dolichos lablab (*Lablab purpureus*), finger millet (*Eleusine coracana*), groundnut (*Arachis hypogaea*), pigeon peas

(*Cajanus cajan*), sorghum (*Sorghum bicolor* L.), and sweet potatoes (*Ipomoea batatas*) (Jaetzold et al., 2007).

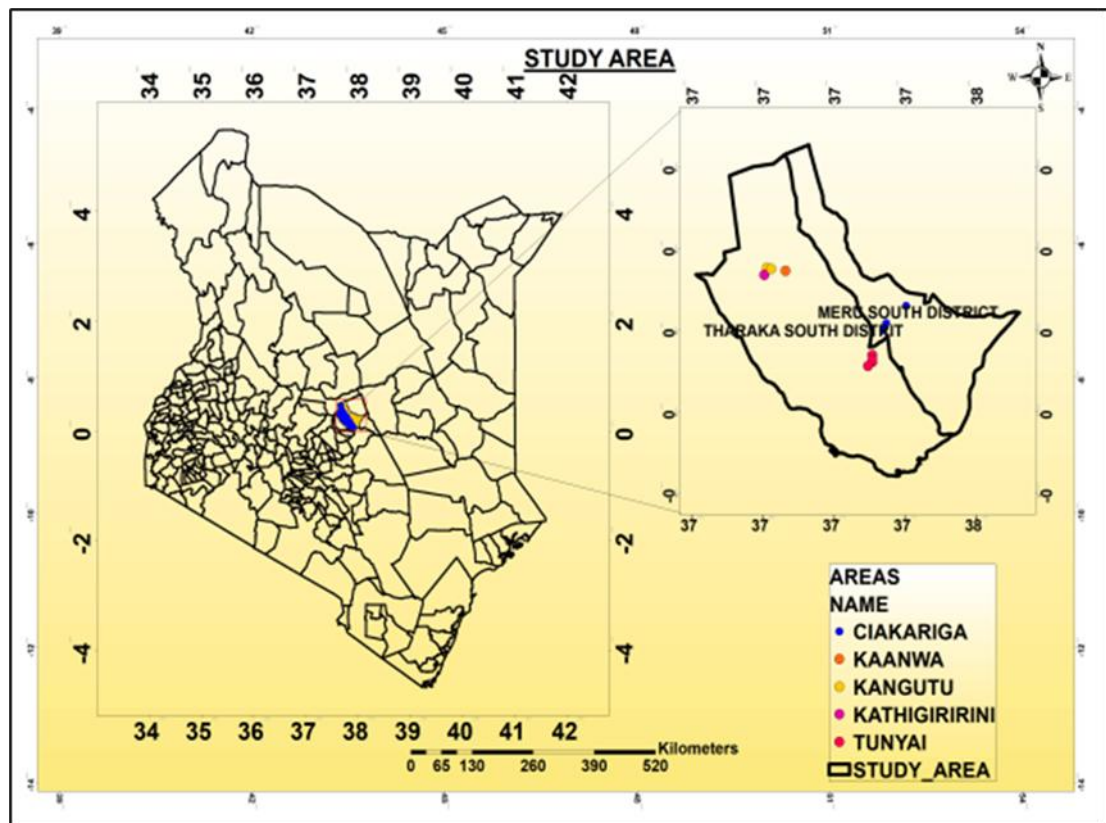


Figure 3.1: Map of the Study area

In addition to climatic and topographic differences of the two study areas, the two sub-counties have varying soil characteristics that influence land use and agricultural productivity (Shisanya et al., 2011; Partey et al., 2014). These baseline properties provided insight into the inherent differences between the two agro-ecological zones and formed the basis for our study. The general soil characteristics of the study sites located in Chuka and Tharaka South Sub-Counties are summarized in Table 3.1.

Table 3.1: General soil properties in the study areas

Soil Property	Unit	Study Area (Sub-County)	
		Chuka	Tharaka South
Agro-ecological zone	-	Upper Midland 1	Lower Midland 5
Soil Type	-	Humic <i>Nitisols</i>	<i>Ferralsols</i>
Texture	-	Clay loam to clay	Sandy clay loam to sandy clay
Bulk Density	g/cm ³	1.1 ± 0.1	1.4 ± 0.1
Soil pH (H ₂ O)	-	5.6 ± 0.2	5.1 ± 0.3
Organic Carbon (OC)	%	2.1 ± 0.4	1.3 ± 0.3
Total Nitrogen (TN)	%	0.18 ± 0.05	0.12 ± 0.03
Available Phosphorus (P)	mg/kg	9.8 ± 2.1	6.4 ± 1.9
Cation Exchange Capacity	cmol(+)/kg	18.5 ± 3.2	9.7 ± 2.5
Exchangeable Calcium (Ca)	cmol(+)/kg	7.4 ± 1.2	3.8 ± 1.0
Exchangeable Magnesium (Mg)	cmol(+)/kg	3.1 ± 0.8	1.4 ± 0.5
Aggregate Stability	% stable agg.	65–75%	40–50%

3.2 Sampling, experimental design, and layout

3.2.1 Selection of farms

A total of 60 farmers' fields were initially sampled, comprising 32 in Chuka and 28 in Tharaka South Sub-Counties, based on their existing agricultural activities. Key factors considered included soil and water management practices, types of fertilization used, crop types cultivated over two years, land preparation techniques, irrigation use, weeding practices, and crop yields during both short and long rain seasons. Sampling this many fields allowed for representing the diversity of agricultural practices in the study area and provided sufficient samples for analyses of Soil Organic Carbon (SOC) levels for all sampled farms as described in section 3.2.2. This preliminary analysis enabled the stratification of sites and the selection of nine experimental fields from each Sub-County. Selection criteria included soil homogeneity, availability and accessibility of the field, and availability of water for simulation. The selected fields were categorized to represent three SOC levels (low, moderate, and adequate) to capture the range of organic carbon variability, based on reported SOC concentrations in similar agro-ecological zones (Vågen et al., 2018), and were subjected to three rainfall intensities (80 mm/hr, 100 mm/hr, and 120 mm/hr) reflecting the regional annual rainfall variation (Smucker, 2008; Partey et al., 2014).

3.2.2 Determination of soil organic carbon levels

Topsoil samples (0–15 cm depth) were collected from the sampled fields using a soil auger and transported to the laboratory for SOC analysis. Organic carbon content was analyzed using the wet oxidation method, following a modified Walkley-Black procedure (Okalebo et al., 2002), as detailed in Appendix 1.

3.2.3 Field experimental design and layout

The experimental layout with a display of the rainfall simulation is shown in plate 3.1. At each of the two study sites, representing the two soil types, parallel rainfall simulation experiments were established using a split-plot laid out in Randomized Complete Block Design (RCBD). The main plots corresponded to SOC levels categorized as low (1.0–1.5%), moderate (1.5–2.5%), and adequate (above 2.5%) (Six et al., 2002; Stewart et al., 2007; Ravikumar & Somashekar, 2013; Abah & Petja, 2015). Sub-plots represented varying rainfall intensities: high (120 mm/hr), moderate (100 mm/hr), and low (80 mm/hr), reflecting the regional annual rainfall variation (Smucker, 2008; Partey et al., 2014). Rainfall simulation was conducted using a land-type sprinkler nozzle rainfall simulator (model 460 788) designed to produce different rainfall intensities. The nozzle was positioned 2 meters above the ground, targeting a 1 m² plot fenced with corrugated iron sheets inserted 10 cm into the ground and extending 15 cm above the surface to prevent overflow. Each plot included a small outlet funnel to collect runoff in sampling jars for volume and sediment yield analysis. To prevent direct rainfall contamination of runoff samples, the sampling jar funnels were covered with polythene sheets.



Plate 3.1: Experimental layout with a display of the rainfall simulation

3.2.4 Calibration of the rainfall simulator

Calibration of the land-type sprinkler nozzle rainfall simulator (model 460 788) was conducted prior to each run to ensure accuracy and consistency of rainfall application. Sub-plots represented three rainfall intensities, high (120 mm/hr), moderate (100 mm/hr), and low (80 mm/hr), reflecting regional annual rainfall variation (Smucker, 2008; Partey et al., 2014). The intensities were verified using a catch-can grid (30 cm spacing, 10 min run) with a tolerance of $\pm 5\%$, while spatial uniformity was evaluated using Christiansen's Coefficient of Uniformity (CU), requiring $CU \geq 0.85$, in line with recommended standards (Iserloh et al., 2016; Meshesha et al., 2016). Drop size distribution was periodically checked using the flour-pellet method, confirming a median drop diameter ($D_{50} \approx 2.2$ mm) and inferred kinetic energy consistent with natural storm conditions for intensities of 80–120 mm/hr (Salles et al., 2016). Runs were conducted at 150 kPa, a pressure within the published range known to approximate the kinetic energy of annual natural rainfall (Beuselinck et al., 2016). Adjustments to nozzle height, overlap, or nozzle type were made after every rainfall event whenever deviations from the study intensities or uniformity were observed.

3.3 Data collection

3.3.1 Determination of surface runoff and sediment loss

In both experiments, rainfall intensities of 80, 100, and 120 mm/hr were applied for 60 minutes, with total simulated rainfall ranging from 1000 to 1500 mm. Runoff began once soil saturation was reached, transitioning from a slow drip to a continuous stream. Runoff and sediment samples were continuously collected in bottles and transported to the University of Embu soil laboratory for analysis. Runoff volumes were measured using a graduated cylinder. Sediments were filtered from runoff water using Whatman filter papers, then oven-dried at 105 °C to constant weight. Sediment mass was measured using an electronic scale accurate to 0.01 g. Total sediment loss per plot was calculated as follows (Okalebo, Gathua, & Woomeer, 2002) in equation 1.

$$\text{Sediment loss (kg/ha)} = \frac{\text{Sediment concentration (g/L)} \times \text{runoff volume (L)}}{\text{plot area (m}^2\text{)} \times 10^{-1}} \text{.Equation 1}$$

3.3.2 Determination of soil bulk density

Undisturbed soil samples were collected per treatment (low, moderate, and adequate SOC levels) and from each soil type using the core sampling method after rainfall simulation (see Appendix 2). Soil bulk density was determined at the University of Embu soil laboratory using the procedure described by Okalebo et al. (2002), calculated in equation 2.

$$\text{Bulk density (g cm}^{-3}\text{)} = \frac{W_2 - W_1}{V} \text{.....Equation 2}$$

Where W2 = Weight of the dried soil;

W1 = Weight of an ovenproof container; and

V = Total soil volume.

3.3.3 Determination of soil hydraulic conductivity

Undisturbed soil samples were collected using core rings after rainfall simulation from different SOC levels and analyzed at the National Agricultural Research Laboratories (NARL) of the Kenya Agricultural and Livestock Research Organization (KALRO) laboratory following the method of Ilek et al. (2014) (Appendix 3), based on Darcy's law for fixed and variable gradient methods. Hydraulic conductivity (K_i) was calculated using the formula in equation 3.

$$K_t = \frac{Q \times L}{A \times T \times \Delta h} \dots\dots\dots \text{Equation 3}$$

Where K_t is the hydraulic conductivity determined as temperature t ($m.h^{-1}$);

Q is the volume of water flowing through the soil sample (m^3);

L is the height of the sample (m);

A is the cross-sectional area of the sample (m^2);

T is the time (h), and

Δh is the difference in levels of the water table (m) in the column and in the outer cylinder of the apparatus.

3.3.4 Determination of soil water retention

Soil water retention capacity was determined at wilting point, field capacity, and saturation point, using the method described by Okalebo et al. (2002) (Appendix 4). Undisturbed soil samples were collected per treatment and soil type after rainfall simulation and analyzed at the National Agricultural Research Laboratories (NARL) of the Kenya Agricultural and Livestock Research Organization (KALRO). Water retention capacity (%) was calculated as indicated in equation 4

$$\text{Water retention capacity (\%)} = \frac{W_2 - W_3}{W_3 - W_1} \times 100 \dots\dots\dots \text{Equation 4}$$

Where: W_1 = weight of container (g),

W_2 = weight of container + wet soil (g); and

W_3 = weight of container + oven dry soil.

3.3.5 Determination of nutrient losses via erosion

Runoff and sediment samples collected continuously from different experimental plots during rainfall simulation were analyzed for nutrient losses. The analysis was conducted at the National Agricultural Research Laboratories (NARL) of the Kenya Agricultural and Livestock Research Organization (KALRO). Runoff volumes were measured using a graduated cylinder. Sediment samples were filtered from runoff water with Whatman filter papers and oven-dried to constant weight, as described in Section 3.3.1. Soil particle size analysis was performed on the eroded sediments and residual soil in the beakers using the hydrometer method (Klute & Dirksen, 1982). Nutrient losses from runoff water were analyzed by transferring measured samples

into digestion flasks. Nitrate (NO₃) content was determined by the Kjeldahl process (Okalebo et al., 2002; Appendix 5). Phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg) concentrations were analyzed from thoroughly mixed and homogenized samples digested with hydrochloric acid (HCl) and nitric acid (HNO₃) using an atomic absorption spectrophotometer (Model SP9, Pye Unicam Ltd., Cambridge, England) as per Okalebo et al. (2002). Phosphorus was further determined by Mehlich 3 extraction following the procedure by Pitman et al. (2005) (Appendix 6). Concentrations of K, Ca, and Mg were measured by flame photometry (Okalebo et al., 2002; Appendix 7). Available sulfate was analyzed using the turbidimetric method (Okalebo et al., 2002; Appendix 8).

Nutrient concentration in runoff (N₁) was calculated according to Fixen et al. (2012) using the formula described by Fixen et al. (2012) as shown in equation 5.

$$N_1 = n_1 \times Rt \dots\dots\dots(\text{Equation 5})$$

Where: N₁ (g) = Total amount of each nutrient lost through runoff;
 Rt (L) = the total amount of runoff measured in every plot; and
 n₁ (g/L) = concentration of each element in the runoff samples

For sediment analysis, oven-dried sediment samples underwent nutrient testing. Total nitrogen content was determined using the Kjeldahl digestion and distillation method (Okalebo et al., 2002; Appendix 9). Phosphorus was measured using the Mehlich 3 extraction procedure described by Pitman et al. (2005) (Appendix 6). Total K, exchangeable Ca, and Mg were measured by flame photometry (Okalebo et al., 2002; Appendix 7), while copper (Cu), iron (Fe), and zinc (Zn) were determined by atomic absorption spectrophotometry (Okalebo et al., 2002; Appendix 10).

The nutrient amount lost via sediment (N₂) was calculated as in equation 6.

$$N_2 = n_2 * S2 \dots\dots\dots(\text{Equation 6})$$

Where: N₂ (g) = the total amount of each nutrient lost in the sediment
 n₂ (g-1) = the concentration of each nutrient in the sediment samples
 S2 (g) = the total amount of soil sediments collected in every plot

To assess the total nutrient loss, nutrient concentrations were computed from the total runoff and sediment samples from each treatment plot using the formula described by Fixen et al. (2012) as shown in equation 7.

$$\text{Total nutrient loss (N)} = N_1 + N_2 \dots\dots\dots(\text{Equation 7})$$

Where: N_1 = Nutrient loss through the runoff,
 N_2 = Nutrient loss through sediment.

3.4 Statistical data analysis

The collected data were subjected to analysis of variance (ANOVA) using XLSTAT version 2023. A mixed-effects ANOVA model was used to test the main effects of SOC levels, rainfall intensities, and their interaction, with details of main effects and interactions presented in the results section. Tukey's Honest Significant Difference (HSD) test was applied to separate means at a 95% confidence level. Pearson correlation analysis was performed to examine relationships between runoff and sediment loss, bulk density, hydraulic conductivity, water retention, and nutrient loss with runoff.

CHAPTER FOUR

RESULTS

4.1 Effects of soil organic carbon and rainfall intensity on soil erosion

4.1.1 Effects of soil organic carbon on runoff and sediment losses

The findings presented in Table 4.1 indicate a statistically significant effect of soil organic carbon (SOC) levels on both surface runoff and sediment loss across *Ferralsols* and *Nitisols*. Surface runoff was significantly ($p < 0.001$) higher in low SOC levels, especially in *Ferralsols* (1703.33 l/m²), compared to *Nitisols* (1103.33 l/m²). As SOC levels increased to moderate, runoff decreased to 1337.78 l/m² in *Ferralsols* and 689.44 l/m² in *Nitisols*. At adequate SOC levels, runoff further declined significantly ($p < 0.005$) to 771.67 l/m² and 720.56 l/m², respectively. The influence of SOC on runoff varied significantly with soil type where in *Ferralsols* low SOC levels led to the highest runoff.

Table 4.1: The Influence of different Soil organic carbon levels on runoff and sediment losses in *Nitisols* and *Ferralsols*.

Parameter	SOC Levels	<i>Ferralsols</i>	<i>Nitisols</i>	SE	p value
Run-off (l/m²)	Low	1703.33 a A	1103.33 a B	46.91	<0.001
	Moderate	1337.78 b A	689.44 b B	26.38	<0.001
	Adequate	771.67 c A	720.56 b B	9.49	0.003
	SE	30.92	20.56		
	p value	<0.001	<0.001		
Parameter	SOC Levels	<i>Ferralsols</i>	<i>Nitisols</i>	SE	p value
Sediment loss (kg/ha)	Low	67.25 a A	57.70 a B	0.83	<0.001
	Moderate	47.62 b A	44.44 b B	0.67	0.008
	Adequate	32.54 c A	27.82 c B	0.94	0.005
	SE	0.95	0.80		
	p value	<0.001	<0.001		

Legend: SOC – Soil Organic Carbon; SE – Standard Error. Different small letters (e.g., a, b, c) within each column indicate significant differences between SOC levels within the same soil type while different capital letters (e.g., A, B) within the same row indicate significant differences between soil types (Ferralsols vs. Nitisols) at the same SOC level ($p < 0.05$).

Sediment loss followed a pattern similar to runoff, with the highest losses recorded at low SOC levels: 67.25 kg/ha in *Ferralsols* and 57.70 kg/ha in *Nitisols*. As SOC increased to moderate, sediment losses declined to 47.62 kg/ha in *Ferralsols* and 44.44 kg/ha in *Nitisols*. The lowest values were observed at adequate SOC 32.54 kg/ha and 27.82 kg/ha, respectively. These reductions were statistically significant (p

<0.001) for *Ferralsols* and *Nitisols*. SOC differed significantly ($p < 0.0001$) by soil type. *Ferralsols* consistently exhibited higher sediment losses across all SOC levels while *Nitisols* demonstrated lower sediment losses at each SOC level, with a notable decline from 57.70 kg/ha to 27.82 kg/ha as SOC increased.

4.1.2 Effects of rainfall intensity on runoff and sediment losses

Rainfall intensity had a statistically significant influence on both surface runoff and sediment loss across the two soil types studied. As shown in Table 4.2, runoff volumes increased with increasing rainfall intensity in both *Ferralsols* and *Nitisols*. At 120 mm/hr, *Ferralsols* recorded the highest runoff (1707.78 l/m²), significantly ($p < 0.001$) higher than in *Nitisols* (1058.89 l/m). Similarly, at 100 mm/hr, runoff was significantly ($p < 0.001$) higher in *Ferralsols* (1351.67 l/m²) than in *Nitisols* (870.00 l/m²). The lowest runoff volumes were observed at 80 mm/hr, with *Ferralsols* recording 753.33 l/m² and *Nitisols* 584.44 l/m².

Table 4.2: Influence of different rainfall intensities on runoff and sediment loss in *Nitisols* and *Ferralsols*

Parameter	Rainfall Intensity	<i>Ferralsols</i>	<i>Nitisols</i>	SE	p value
Run-off (l/m²)	120 mm/hr	1707.78 a A	1058.89 a B	39.71	<0.001
	100 mm/hr	1351.67 b A	870.00 b B	33.43	<0.001
	80 mm/hr	753.33 c A	584.44 c B	11.41	<0.001
	SE	30.92	20.56		
	p value	<0.001	<0.001		
Parameter	Rainfall Intensity	<i>Ferralsols</i>	<i>Nitisols</i>	SE	P Value
Sediment loss (kg/ha)	120 mm/hr	45.14 b A	34.92 c B	0.82	<0.001
	100 mm/hr	47.98 b A	42.21 b B	1.08	0.004
	80 mm/hr	54.29 a A	52.83 a A	1.72	0.178
	SE	0.95	0.80		
	p value	<0.001	<0.001		

Legend: SE – Standard Error. Different small letters (e.g. a, b, c) within each column indicate significant differences between rainfall intensity within the same soil type while different capital letters (e.g., A, B) within the same row indicate significant differences between soil types ($p < 0.05$).

Sediment loss also varied with rainfall intensity and soil type. The highest sediment loss was recorded at 80 mm/hr in both *Ferralsols* (54.29 kg/ha) and *Nitisols* (52.83 kg/ha), although the differences between soil types were not statistically significant ($p > 0.05$). At 100 mm/hr, *Ferralsols* exhibited significantly ($p < 0.001$) greater sediment loss (47.98 kg/ha) which was 13.6% higher than *Nitisols* (42.21 kg/ha). At 120 mm/hr,

sediment loss was again significantly ($p < 0.001$) higher in *Ferralsols* (45.14 kg/ha) which was 29.9% higher compared to *Nitisols* (34.92 kg/ha).

4.1.3 Interactive effects of soil organic carbon and rainfall intensity on runoff and sediment losses

The interactive effects between soil organic carbon (SOC) levels and rainfall intensity significantly ($p < 0.001$) affected both runoff and sediment loss across *Ferralsols* and *Nitisols* (Table 4.3). Generally, runoff decreased with increasing SOC levels, while higher rainfall intensities consistently produced greater runoff, particularly in *Ferralsols*. In plots with low SOC levels, high rainfall intensity (120 mm/hr) produced the highest runoff values, with *Ferralsols* recording 2383.33 l/m² and *Nitisols* 1366.67 l/m². These values were significantly ($p < 0.001$) higher than those observed under low rainfall (80 mm/hr), where runoff dropped to 900.00 l/m² and 810.00 l/m², respectively. As SOC levels increased, runoff significantly ($p < 0.001$) decreased. Under adequate SOC conditions and high rainfall, runoff in *Ferralsols* and *Nitisols* was limited to 950.00 l/m² and 925.00 l/m², respectively. A similar trend was observed in sediment loss. Plots with low SOC under low rainfall intensity recorded the highest sediment losses, with 73.60 kg/ha for *Ferralsols* and 71.19 kg/ha for *Nitisols*. In contrast, under adequate SOC and high rainfall conditions, sediment loss reduced to 29.01 kg/ha and 23.31 kg/ha, respectively.

Table 4.3: Interactive treatment effects (SOC × rainfall intensity) on runoff and sediment loss in *Nitisols* and *Ferralsols*

<i>Treatment (SOC*RI)</i>	Run-off (l/m ²)		Sediment loss (kg/ha)	
	<i>Ferralsols</i>	<i>Nitisols</i>	<i>Ferralsols</i>	<i>Nitisols</i>
Low SOC*Low Rainfall	900.00 ^d	810.00 ^{cd}	73.60 ^a	71.19 ^a
Low SOC*Medium Rainfall	1826.67 ^b	1133.33 ^b	64.87 ^b	55.77 ^b
Low SOC*High Rainfall	2383.33 ^a	1366.67 ^a	63.28 ^b	46.14 ^c
Moderate SOC*Low Rainfall	770.00 ^{de}	473.33 ^e	53.49 ^c	53.92 ^b
Moderate SOC*Medium Rainfall	1453.33 ^c	710.00 ^d	46.24 ^{cd}	44.09 ^c
Moderate SOC*High Rainfall	1790.00 ^b	885.00 ^{cd}	43.15 ^{de}	35.32 ^d
Adequate SOC*Low Rainfall	590.00 ^e	470.00 ^e	35.79 ^{ef}	33.38 ^{de}
Adequate SOC*Medium Rainfall	775.00 ^{de}	766.67 ^{cd}	32.83 ^f	26.79 ^{ef}
Adequate SOC*High Rainfall	950.00 ^d	925.00 ^c	29.01 ^f	23.31 ^f
Standard Error	53.56	35.61	1.64	1.38
p value	<0.001	<0.001	<0.001	<0.001

Legend: SOC – Soil organic carbon; RI – Rainfall Intensities. Means with different small letters within the column are significantly different at p<0.05

4.1.4 Overall influence of soil type, soil organic carbon levels and rainfall intensities on runoff and sediment losses

A three-way analysis of variance (ANOVA) was conducted to assess the effects of soil type (*Ferralsols* and *Nitisols*), soil organic carbon (SOC) levels (Low, Moderate, Adequate), and rainfall intensity (Low: 80 mm/hr, Medium: 100 mm/hr, High: 120 mm/hr) on surface runoff and sediment concentration under simulated rainfall. The ANOVA results (Figure 4.1) reveal highly significant ($p < 0.001$) main effects for all three factors. Soil type significantly influenced runoff volumes with *Ferralsols* generally producing higher runoff than *Nitisols*. SOC levels also had a major effect indicating that lower organic carbon content resulted in greater runoff.

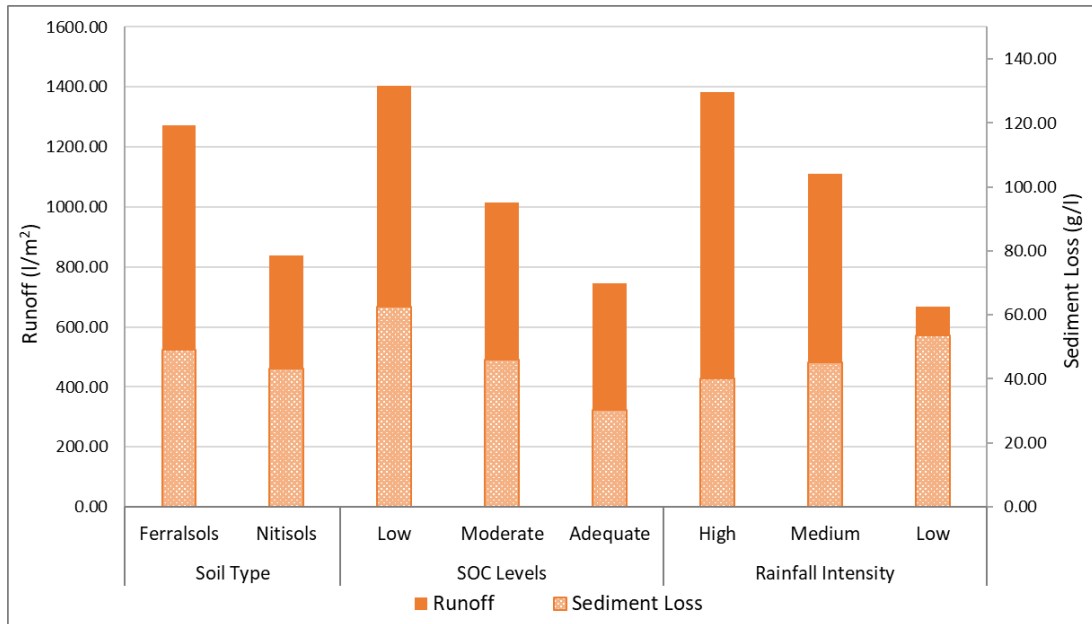


Figure 4.1: Runoff and sediment loss as affected by soil type, soil organic carbon and rainfall intensities in Tharaka-South and Meru-South Sub-Countries. Means with different letters on the bar graph per group are significantly different at $p < 0.05$.

The results of runoff and sediment loss on the two soil types as affected by soil organic carbon and rainfall intensities are displayed in Figure 4.1. The runoff and sediment losses were found to be significantly ($p < 0.001$) influenced by the soil type, soil organic carbon levels and rainfall intensities. On average, Ferralsols recorded the highest runoff of 1270.93 l/m² compared to Nitisols, which recorded a total runoff of 837.78 l/m² (Figure 4.1). Therefore, Ferralsols had a 51.7% higher runoff volume compared to Nitisols.

Regarding soil organic carbon (SOC) levels, low SOC levels recorded the highest runoff of 1403 mm². Moderate SOC levels resulted to a runoff of 1013 mm², while adequate SOC levels showed the lowest runoff, at 746 mm². High rainfall intensity led to the highest runoff of 1383 mm². Medium rainfall intensity resulted in a runoff of 1110 mm², whereas low rainfall intensity showed the lowest runoff, with 668 mm². As a result, a variation of 107% was observed in runoff between high and low rainfall intensities. Similar trends were observed for sediment concentration. All the three main factors had statistically significant ($p < 0.001$) effects. The strongest factor was SOC level reflecting a strong inverse relationship between organic carbon and sediment detachment. Soils with adequate SOC were less erosion-prone, while low

SOC was linked to increased sediment transport. Soil type and rainfall intensity also significantly ($p < 0.001$) affected sediment concentration.

On the other hand, *Ferralsols* recorded the highest sediment loss of 49.14 g/l compared to *Nitisols*, which recorded a sediment loss of 43.32 g/l. *Ferralsols* had a 13.4% higher sediment concentration compared to *Nitisols*. Low SOC levels resulted in the highest sediment loss at 62.47 g/l. Sediment loss at moderate SOC levels was recorded 46.03 g/l, while adequate SOC levels had the lowest sediment loss, with 30.18 g/l. The percentage variation in sediment loss from adequate SOC levels to low SOC levels was approximately 107.1%. The sediment loss under high rainfall intensity was the lowest, at 40.03 g/l. The moderate rainfall intensity resulted in sediment loss of 45.09 g/l, and low rainfall intensity had the highest sediment concentration at 53.56 g/l. Therefore, there is a 33.8% variation in sediment concentration between high and low rainfall intensities. The volume of runoff was found to increase significantly with decreasing rainfall intensities. Notably, the three-way interaction (soil \times SOC \times rainfall) was statistically significant ($p < 0.001$) for runoff, but not for sediment concentration.

4.1.5 Relationship between run-off and sediment loss

Pearson correlation analysis for the relationship between runoff and sediment loss in both soils under different combinations of soil organic carbon levels and rainfall intensities are shown in Table 4.4. Significant ($p < 0.05$) negative correlation was observed between runoff and sediment loss at moderate and low SOC levels in *Ferralsols* under combined rainfall intensities. However, there was significant positive correlations between runoff and sediment loss under all the tested rainfall intensities under combined SOC levels. A similar trend was observed in *Nitisols*, where significant ($p < 0.05$) negative correlation was observed between runoff and sediment loss at all the three SOC levels under combined rainfall intensities. *Nitisols* also showed significant positive correlations between runoff and sediment loss under high and low rainfall intensities under combined SOC levels. Combined analysis showed significant positive correlations between runoff and sediment loss under all the tested rainfall intensities under combined SOC levels but a negative correlation under adequate SOC levels.

Table 4.4: Relationship between runoff and sediment loss in both soil types

Soil Type	SOC Levels	RI Levels	Coefficient	p value
<i>Ferralsols</i>	Adequate	All Combined	-0.567 ^{NS}	0.111
<i>Ferralsols</i>	Moderate	All Combined	-0.968 ^{***}	<0.001
<i>Ferralsols</i>	Low	All Combined	-0.898 ^{***}	<0.001
<i>Ferralsols</i>	All Combined	High (120 mm/hr)	0.943 ^{***}	<0.001
<i>Ferralsols</i>	All Combined	Medium (100 mm/hr)	0.932 ^{***}	<0.001
<i>Ferralsols</i>	All Combined	Low (80 mm/hr)	0.967 ^{**}	<0.001
<i>Ferralsols</i>	All Combined	All Combined	0.418 ^{**}	0.030
<i>Nitisols</i>	Adequate	All Combined	-0.915 ^{***}	0.001
<i>Nitisols</i>	Moderate	All Combined	-0.931 ^{***}	<0.001
<i>Nitisols</i>	Low	All Combined	-0.921 ^{***}	<0.001
<i>Nitisols</i>	All Combined	High (120 mm/hr)	0.789 ^{**}	0.011
<i>Nitisols</i>	All Combined	Medium (100 mm/hr)	0.646 [*]	0.060
<i>Nitisols</i>	All Combined	Low (80 mm/hr)	0.839 ^{**}	0.005
<i>Nitisols</i>	All Combined	All Combined	0.088 ^{NS}	0.661
Both Combined	Adequate	All Combined	-0.590 [*]	0.010
Both Combined	Moderate	All Combined	-0.340 ^{NS}	0.167
Both Combined	Low	All Combined	-0.214 ^{NS}	0.393
Both Combined	All Combined	High (120 mm/hr)	0.891 ^{***}	<0.001
Both Combined	All Combined	Medium (100 mm/hr)	0.774 ^{***}	<0.001
Both Combined	All Combined	Low (80 mm/hr)	0.794 ^{***}	<0.001
Both Combined	All Combined	All Combined	0.346 ^{**}	0.010

Legend: NS – Not significant; *Significant at 10%; **Significant at 5%; ***Significant at 1%

The general effect of soil organic carbon levels and rainfall intensity on runoff volume and sediment concentration on both soils appeared to follow a similar trend (Figure 4.2). The two variables were found to decrease with increase in soil organic carbon but changes in rainfall intensity resulted in a discordant effect on runoff and sedimentation. Apparently, the increase in rainfall intensity appeared to have a strong effect on the runoff volume increasing it beyond the arresting ability of the available soil organic carbon levels. On the contrary, the soil organic carbon levels in both soils appeared to effectively modify the levels of sedimentation to somewhat more stabilized levels regardless of the rainfall intensity (Figure 4.2).

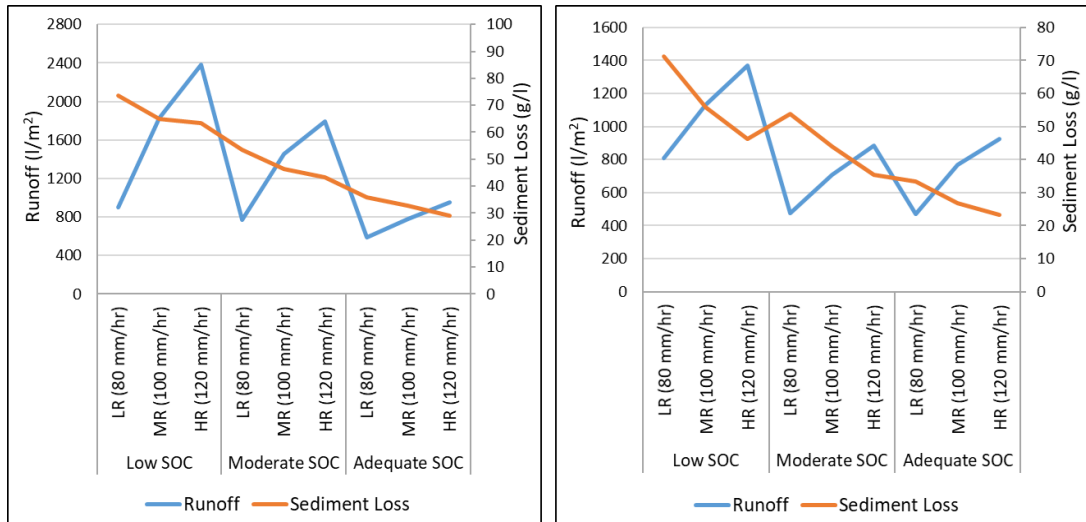


Figure 4.2: Relationship between runoff and sediment loss against varying levels of soil organic carbon and rainfall intensity in *Ferralsols* (right) and *Nitisols* (left). LR: Low Rainfall; MR Medium Rainfall; HR High Rainfall

4.2 Effects of soil organic carbon and rainfall intensity on physical properties

4.2.1 Effects of soil organic carbon and rainfall intensity on bulk density

The results indicate that bulk density was significantly ($p < 0.001$) influenced by SOC levels in both *Ferralsols* and *Nitisols* (Table 4.5). The *Ferralsols* recorded a significantly higher bulk density (1.39 g/cm^3) under low SOC levels than under moderate and adequate SOC levels. On the contrary, the *Nitisols* recorded a significantly lower bulk density (1.05 g/cm^3) under low SOC levels than under moderate and adequate SOC levels (Table 1). However, the rainfall intensity did not show any significant effect on the bulk density of both soils. In addition, there was no significant interaction between the SOC levels and rainfall intensity on both soils indicating that the rainfall intensity did not modify the effect of the SOC levels. A combined analysis further showed that the two soil types varied significantly ($P < 0.0001$) in their bulk densities at low SOC level and high rainfall intensity (120 mm/hr) where *Ferralsols* recorded 32.4% and 21.6% higher bulk density (1.39 and 1.35 g/cm^3) than *Nitisols* (1.05 and 1.11 g/cm^3), respectively (Table 4.5).

Table 4.5: Effect of different organic carbon levels and rainfall intensities on soil bulk density in *Nitisols* and *Ferralsols*

Parameter	Variable	Soil Type		Standard Error	p value
		<i>Ferralsols</i>	<i>Nitisols</i>		
SOC Levels	Low (1.0 – 1.5)	1.39 a A	1.05 b B	0.029	<0.001
	Moderate (1.5 – 2.5)	1.22 b A	1.22 a A	0.037	0.983
	Adequate (>2.5)	1.20 b A	1.15 a A	0.032	0.291
	SE	0.040	0.024		
	p value	0.007	0.001		
Rainfall Intensities	Low (80 mm/hr)	1.22 a A	1.13 a A	0.043	0.172
	Medium (100 mm/hr)	1.24 a A	1.18 a A	0.716	0.170
	High (120 mm/hr)	1.35 a A	1.11 a B	0.024	<0.001
	SE	0.040	0.024		
	p value	0.058	0.175		

Legend: SOC – Soil Organic Carbon; ST – Soil Type; RI – Rainfall Intensity. Different small letters (e.g., a, b, c) within each column indicate significant differences between SOC levels within the same soil type at $p < 0.05$. Different capital letters (e.g., A, B) within the same row indicate significant ($p < 0.05$) differences between soil types (*Ferralsols* vs. *Nitisols*) at the same SOC level.

Table 4.6 presents the combined effects of soil organic carbon (SOC) levels and rainfall intensity (RI) on bulk density for *Ferralsols* and *Nitisols*. The results indicate that the interaction between SOC and rainfall intensity did not significantly ($p > 0.05$) affect bulk density in *Ferralsols* or *Nitisols*

Table 4.6: Interactive effects of different organic carbon levels and rainfall intensities on soil bulk density in *Ferralsols* and *Nitisols*

Treatment (SOC*RI)	Bulk Density (g cm ⁻³)	
	<i>Ferralsols</i>	<i>Nitisols</i>
Low SOC*Low Rainfall Intensity	1.42	1.05
Low SOC*Medium Rainfall Intensity	1.34	1.08
Low SOC*High Rainfall Intensity	1.41	1.03
Moderate SOC*Low Rainfall Intensity	1.19	1.18
Moderate SOC*Medium Rainfall Intensity	1.22	1.32
Moderate SOC*High Rainfall Intensity	1.25	1.16
Adequate SOC*Low Rainfall Intensity	1.04	1.15
Adequate SOC*Medium Rainfall Intensity	1.15	1.14
Adequate SOC*High Rainfall Intensity	1.40	1.15
Standard Error	0.07	0.04
p value	0.108	0.314

The three-way ANOVA on effects of soil type, soil organic carbon (SOC) level, rainfall intensity, and their interactions on soil bulk density (Figure 4.3). The bulk density varied significantly ($p < 0.001$) across the two soils with *Ferralsols* recording

higher bulk density (1.27 g/cm^3) than *Nitisols* (1.14 g/cm^3). However, the effects of SOC levels and rainfall intensity were not significant ($p > 0.05$) on the bulk density.

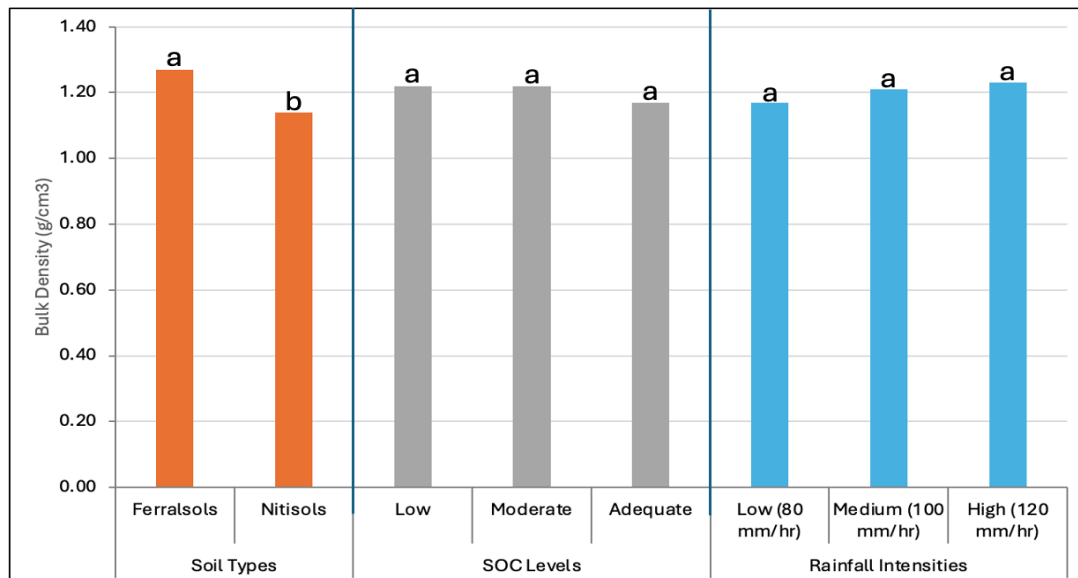


Figure 4.3: Soil bulk density as affected by soil type, soil organic carbon and rainfall intensities. Means with different letters on the bar graph per group are significantly ($p < 0.05$) different.

4.2.2 Effects of soil organic carbon and rainfall intensity on hydraulic conductivity

The data in Table 4.7 illustrate the influence of different SOC levels on the hydraulic conductivity of two soil types: *Ferralsols* and *Nitisols*. The results indicate that soil organic carbon (SOC) levels had a significant ($p < 0.05$) effect on hydraulic conductivity in both *Ferralsols* and *Nitisols*. Rainfall intensity alone had significant ($p > 0.05$) effect on hydraulic conductivity in *Nitisols*. However, under high rainfall intensity (120 mm/hr), *Ferralsols* recorded higher hydraulic conductivity than *Nitisols* though the difference was not significant.

Table 4.7: Influence of different organic carbon levels and rainfall intensities on hydraulic conductivity in *Ferralsols* and *Nitisols*.

Parameter	Variable	Soil Type		Standard Error	P Value
		<i>Ferralsols</i>	<i>Nitisols</i>		
SOC Levels	Low (1.0 – 1.5)	2.86 c A	2.59 b A	0.679	0.790
	Moderate (1.5 – 2.5)	5.71 b A	1.38 b B	0.537	0.000
	Adequate (>2.5)	10.69 a A	10.54 a A	0.662	0.881
	Standard Error	0.694	0.531		
	P Value	<0.001	<0.001		

Parameter	Variable	Soil Type		Standard Error	P Value
		<i>Ferralsols</i>	<i>Nitisols</i>		
Rainfall Intensities	Low (80 mm/hr)	5.62 a A	3.34 c A	0.430	0.172
	Medium (100 mm/hr)	5.73 a A	4.84 bc A	0.716	0.392
	High (120 mm/hr)	7.89 a A	6.35 ab A	0.700	0.144
	Standard Error	0.694	0.531		
	P Value	0.058	0.004		

Legend: SOC – Soil Organic Carbon. Different lowercase letters (e.g., a, b, c) indicate significant differences within the same soil type across treatments (e.g., different SOC levels). Different capital letters (e.g., A, B) within the same row indicate significant differences between soil types (*Ferralsols* vs. *Nitisols*) at the same SOC level ($p < 0.05$).

Table 4.8 presents the interaction effects of soil organic carbon levels and Rainfall Intensity (RI) on hydraulic conductivity (in cm/hr) for *Ferralsols* and *Nitisols*. Results in the table shows that the interaction between SOC levels and rainfall intensity had a significant ($p < 0.05$) effect on hydraulic conductivity in both *Ferralsols* and *Nitisols*. In *Ferralsols*, hydraulic conductivity was highest under adequate SOC combined with high rainfall intensity and differed significantly ($p < 0.001$) from all other treatment combinations. Conductivity values under low and moderate SOC were significantly lower, with means ranging from 1.26 to 8.12 cm/hr. The interaction effect was also significant ($p < 0.001$) in *Nitisols*. The highest hydraulic conductivity was recorded under adequate SOC and high rainfall intensity, which differed significantly from other combinations. Treatments with low and moderate SOC showed lower conductivity, with values ranging from 1.10 to 2.84 cm/hr. Treatments under adequate SOC at low and medium rainfall intensities also recorded higher values than low and moderate SOC.

A three-way ANOVA showed that hydraulic conductivity varied significantly ($p < 0.001$) between the two soils, with *Ferralsols* recording a higher average conductivity (6.42 cm/hr) than *Nitisols* (4.84 cm/hr) (Figure 4.4). Soil organic carbon levels also had a significant ($p < 0.001$) effect, with adequate SOC producing the highest average conductivity (10.62 cm/hr), which was significantly higher than

moderate (3.54 cm/hr) and low (2.73 cm/hr) SOC levels. Rainfall intensity significantly ($p < 0.001$) influenced conductivity, with high intensity (120 mm/hr) producing higher conductivity (7.12 cm/hr) than medium (5.29 cm/hr) and low (4.48 cm/hr) intensities, which did not differ significantly ($p > 0.05$) from each other.

Table 4.8: Interactive effects of different organic carbon levels and rainfall intensities on hydraulic conductivity in Ferralsols and Nitisols

Treatment (SOC*RI)	Hydraulic Conductivity (cm/hr)	
	<i>Ferralsols</i>	<i>Nitisols</i>
Low SOC*Low Rainfall Intensity	1.26 d	2.26 cd
Low SOC*Medium Rainfall Intensity	4.31 bcd	2.84 cd
Low SOC*High Rainfall Intensity	3.00 cd	2.68 cd
Moderate SOC*Low Rainfall Intensity	8.12 bc	1.48 d
Moderate SOC*Medium Rainfall Intensity	3.84 bcd	1.57 d
Moderate SOC*High Rainfall Intensity	5.16 bcd	1.10 d
Adequate SOC*Low Rainfall Intensity	7.48 bc	6.27 bc
Adequate SOC*Medium Rainfall Intensity	9.05 b	10.09 b
Adequate SOC*High Rainfall Intensity	15.53 a	15.27 a
Standard Error	1.20	0.92
p value	0.002	<0.001

Means with different letters within the column are significantly different at $p < 0.05$

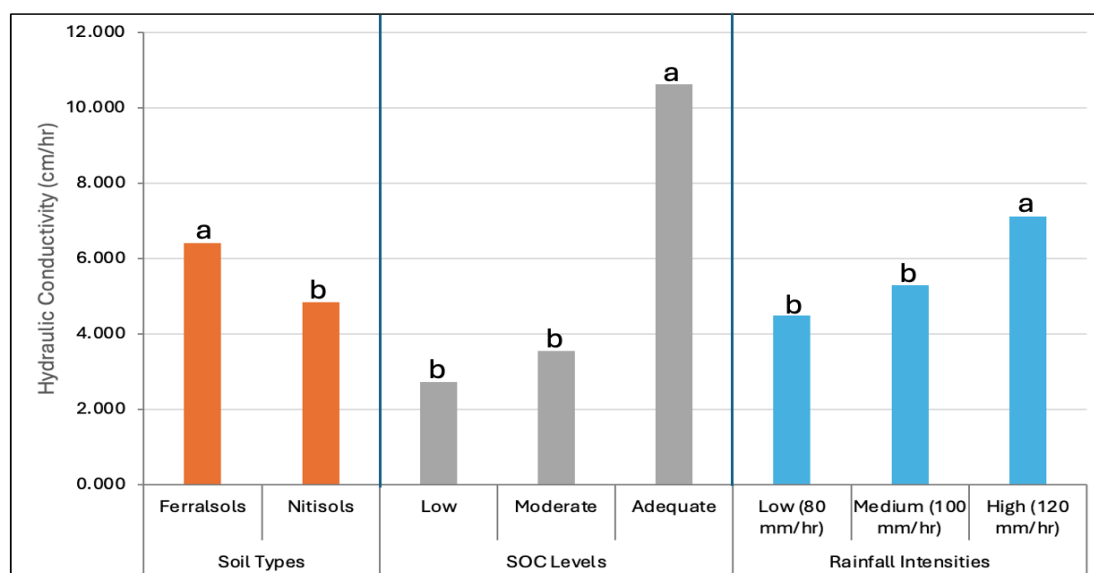


Figure 4.4: Soil hydraulic conductivity as affected by soil type, soil organic carbon and rainfall intensities. Means with different letters on the bars per group are significantly ($p < 0.05$) different

4.2.3 Effects of soil organic carbon and rainfall intensity on water retention

The results of soil water retention at different matric potentials (0 pF to 4.2 pF) are presented in Table 4.9. The SOC levels had a significant ($p < 0.001$) effect on soil water retention in *Ferralsols* at all measured matric potentials. Mean water retention increased significantly from low to adequate SOC levels. In *Nitisols*, SOC levels had no significant ($p > 0.05$) effect on water retention at any matric potential. Table 4.10 presents the influence of different rainfall intensities on soil water retention at varying soil matric potentials. The results show that rainfall intensity had no significant ($p > 0.05$) effect on soil water retention at any matric potential (0 pF to 4.2 pF) in both soil types (*Ferralsols* or *Nitisols*).

Table 4.9: Influence of different organic carbon levels on water retention at six matric potentials in *Ferralsols* and *Nitisols*

Soil Type	SOC Levels	Water retention (%)					
		0pF	2.0Pf	2.3pF	2.5pF	3.7pF	4.2pF
<i>Ferralsols</i>	Low	25.79 ^c	19.82 ^b	17.63 ^b	13.47 ^c	12.28 ^c	10.62 ^b
	Moderate	30.49 ^b	22.51 ^b	18.47 ^b	17.24 ^b	13.53 ^b	11.92 ^a
	Adequate	36.47 ^a	28.13 ^a	23.91 ^a	22.29 ^a	14.99 ^a	12.44 ^a
	SE	1.01	0.99	0.887	1.01	0.27	0.22
	<i>p</i> value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
<i>Nitisols</i>	Low	32.67	31.15	27.89	26.66	18.178	15.30
	Moderate	34.80	30.87	29.12	27.89	17.79	15.13
	Adequate	35.21	28.21	25.64	24.03	17.99	15.12
	SE	1.36	1.46	1.50	1.62	0.59	0.51
	<i>p</i> value	0.300	0.315	0.278	0.257	0.899	0.957

Legend: SOC – Soil Organic Carbon; SE - Standard Error. Means with different letters within the column are significantly different at $p < 0.05$

Table 4.10: Influence of different rainfall intensities on water retention at six matric potentials in *Ferralsols* and *Nitisols*

Soil Type	Rainfall Intensity	Water retention (%)					
		0pF	2.0pF	2.3pF	2.5pF	3.7pF	4.2pF
<i>Ferralsols</i>	80 mm/hr	30.19	23.43	21.17	18.55	13.56	11.72
	100 mm/hr	30.21	24.12	19.73	16.44	13.54	11.72
	120 mm/hr	30.35	22.91	19.12	18.01	13.70	11.54
	SE	1.010	0.991	0.887	1.014	0.274	0.222
	p value	0.316	0.691	0.272	0.335	0.905	0.806
<i>Nitisols</i>	80 mm/hr	37.03	32.42	30.27	29.01	18.15	15.77
	100 mm/hr	34.92	28.77	26.15	24.41	17.69	14.63
	120 mm/hr	35.74	29.02	26.23	25.17	18.12	15.14
	SE	1.36	1.46	1.50	1.62	0.59	0.51
	p value	0.555	0.174	0.116	0.131	0.828	0.306

Legend: RI – Rainfall Intensities; SE - Standard Error.

The combined effect of soil organic carbon and rainfall intensity on soil water retention at six matric potentials (0 pF to 4.2 pF) in *Ferralsols* and *Nitisols* is presented in Table 4.11. Mean water retention values varied across SOC and rainfall combinations in both soils, but the interaction effect was not statistically significant ($p > 0.05$) at any matric potential. Overall, water retention was generally higher in *Nitisols* than in *Ferralsols* under all combinations.

Table 4.11: Interactive effects of different organic carbon levels and rainfall intensities on water retention at six matric potentials in *Ferralsols* and *Nitisols*

Soil Type	SOC*RI Levels	0pF	2.0pF	2.3pF	2.5pF	3.7pF	4.2pF
<i>Ferralsols</i>	Adequate SOC*High RI	39.74	30.88	24.08	22.45	15.00	12.64
	Adequate SOC*Low RI	34.93	27.17	23.86	22.41	15.00	12.16
	Adequate SOC*Medium RI	34.75	26.34	23.79	22.02	14.97	12.53
	Moderate SOC*Low RI	31.46	23.36	20.60	18.55	13.33	12.01
	Moderate SOC*High RI	30.31	21.65	17.94	15.73	13.40	12.15
	Moderate SOC*Medium RI	29.70	22.51	16.87	17.43	13.87	11.59
	Low SOC*Low RI	24.17	19.76	19.05	14.69	12.33	10.98
	Low SOC*Medium RI	26.61	19.87	16.68	14.58	12.27	10.50
	Low SOC*High RI	26.59	19.84	17.17	11.14	12.23	10.35
	Standard error	1.749	1.717	1.536	1.755	0.474	0.385
	p value	0.372	0.474	0.799	0.798	0.963	0.567
<i>Nitisols</i>	Moderate SOC*Low RI	39.13	37.40	36.51	36.06	18.82	16.29
	Low SOC*High RI	38.83	32.14	28.62	28.46	19.53	14.81
	Low SOC*Low RI	37.68	31.16	28.26	26.57	17.80	14.80
	Adequate SOC*Low RI	39.27	28.70	26.03	24.37	17.83	15.62
	Adequate SOC*Medium RI	35.55	28.28	25.79	24.15	18.60	15.15
	Low SOC*Medium RI	36.50	30.14	26.79	24.94	17.20	14.29
	Adequate SOC*High RI	35.81	27.64	25.10	23.56	17.54	14.98
	Moderate SOC*Medium RI	32.69	27.90	25.87	24.14	17.28	14.44
	Moderate SOC*High RI	32.57	27.29	24.98	23.47	17.29	15.24
	Standard error	2.356	2.523	2.590	2.806	1.014	0.876
	P value	0.371	0.211	0.157	0.110	0.371	0.712

Legend: SOC – Soil organic carbon; RI – Rainfall Intensities; 0pF to 4.2pF are water matric potentials.

The combined effect of soil organic carbon and rainfall intensity on soil water retention at six matric potentials (0 pF to 4.2 pF) in *Ferralsols* and *Nitisols* is presented in Table 4.11. Mean water retention values varied across SOC and rainfall combinations in both soils, but the interaction effect was not statistically significant ($p > 0.05$) at any matric potential. Overall, water retention was generally higher in *Nitisols* than in *Ferralsols* under all combinations.

Table 4.12: Soil water retention as affected by soil type, organic carbon and rainfall intensity. main effects and interactions.

Soil Type	0pF	2.0pF	2.3pF	2.5pF	3.7pF	4.2pF
<i>Nitisols</i>	35.89 ^a	30.07 ^a	27.55 ^a	26.19 ^a	17.99 a	15.18 ^a
<i>Ferralsols</i>	30.92 ^b	23.49 ^b	20.01 ^b	17.67 ^b	13.60 b	11.66 ^b
SE	0.664	0.664	0.664	0.664	0.664	0.664
p value	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
SOC Levels	0pF	2.0pF	2.3pF	2.5pF	3.7pF	4.2pF
Adequate	35.84 ^a	28.17	24.78	23.16	16.49 ^a	13.78
Moderate	32.65 ^b	26.69	23.79	22.56	15.66 ^{ab}	13.52
Low	31.73 ^b	25.48	22.76	20.06	15.23 b	12.96
SE	0.814	0.814	0.814	0.814	0.814	0.814
p value	0.003	0.102	0.269	0.080	0.028	0.105
Rainfall Intensities	0pF	2.0pF	2.3pF	2.5pF	3.7pF	4.2pF
80 mm/hr	33.61	27.92	25.72 ^a	23.78	15.85	13.75
100 mm/hr	32.64	25.84	22.63 ^{ab}	21.21	15.70	13.08
120 mm/hr	33.98	26.57	22.98 ^b	20.80	15.83	13.43
SE	0.814	0.814	0.814	0.814	0.814	0.814
p value	0.491	0.236	0.031	0.087	0.934	0.240

Legend: SOC – Soil organic carbon; SE – Standard Error. Means with different letters within the column are significantly different at $p < 0.05$

Table 4.13 shows the Pearson correlation between the bulk density (BD), hydraulic conductivity (HC), and water retention at different matric potentials. In ferralsols, there was no significant correlation between the bulk density and all the except at 2.5pF where a significant negative correlation of -0.437 was recorded. There was also no significant correlation between the bulk density and hydraulic conductivity. On the other hand, the hydraulic conductivity was significantly and positively correlated with all water retention matric potentials. Correlations among the different water retention levels were significant and positive across all levels. For *Nitisols*, the bulk density showed significant negative correlations with water retention 0 pF ($r = -0.501$), 3.7 pF (-0.479) and 4.2 pF ($r = -0.425$). The correlation between the bulk density and hydraulic conductivity was not significant. Similarly, there was no significant correlations between the hydraulic conductivity and all the water retention matric potentials.

A combined analysis of both soils revealed significant negative correlations between the bulk density and all the water retention levels but there was no significant correlation between the bulk density and hydraulic conductivity. There was also no significant correlation between hydraulic conductivity and all the water retention matric potentials except at 0pF where a significant positive correlation of 0.302 was recorded. Correlations between various water retention levels were all significant and positive (Table 4.13).

Table 4.13: Pearson correlations among quantitative variables (bulk density, hydraulic conductivity, and water retention in *Ferralsols* and *Nitisols*)

Soil Type	Variables	BD							
<i>Ferralsols</i>	HC	-0.184	HC						
	0pF	-0.236	0.821	0pF					
	2.0pF	-0.246	0.763	0.943	2.0pF				
	2.3pF	-0.271	0.516	0.645	0.687	2.3pF			
	2.5pF	-0.437	0.586	0.726	0.703	0.771	2.5pF		
	3.7pF	-0.377	0.599	0.721	0.695	0.785	0.833	3.7pF	
	4.2pF	-0.321	0.576	0.580	0.495	0.679	0.717	0.844	
	Soil Type	Variables	BD						
<i>Nitisols</i>	HC	0.019	HC						
	0pF	-0.501	-0.017	0pF					
	2.0pF	-0.288	-0.277	0.858	2.0pF				
	2.3pF	-0.171	-0.257	0.780	0.980	2.3pF			
	2.5pF	-0.147	-0.241	0.734	0.955	0.982	2.5pF		
	3.7pF	-0.479	-0.020	0.526	0.471	0.433	0.462	3.7pF	
	4.2pF	-0.425	-0.080	0.541	0.498	0.456	0.445	0.827	
	Soil Type	Variables	BD						
<i>Both soils</i>	HC	-0.013	HC						
	0pF	-0.459	0.302	0pF					
	2.0pF	-0.444	0.067	0.914	2.0pF				
	2.3pF	-0.430	-0.067	0.763	0.906	2.3pF			
	2.5pF	-0.487	-0.019	0.782	0.899	0.941	2.5pF		
	3.7pF	-0.566	0.001	0.696	0.750	0.785	0.799	3.7pF	
	4.2pF	-0.536	-0.037	0.656	0.713	0.769	0.768	0.947	

Legend: BD – Bulk Density; HC - Hydraulic Conductivity (cm/hr); 0pF to 4.2pF are water matric potentials. Values in bold are different from 0 with a significance level $\alpha = 0.05$.

4.3 Nutrient erosion as influenced by SOC levels and rainfall intensity

4.3.1 Effects of SOC and rainfall intensity on nutrient loss via sediment loss

Table 4.14 summarizes nutrient losses through sediment loss as influenced by soil organic carbon levels in *Ferralsols* and *Nitisols*. In *Ferralsols*, higher SOC levels significantly ($p < 0.001$) increased total nitrogen (TN), potassium (K), phosphorus (P), calcium (Ca), and magnesium (Mg) losses. The TN losses rose from 0.10% at low

SOC to 0.27% at adequate SOC while Ca losses increased sharply from 5.00% (low SOC) to 14.77% (adequate SOC). Copper, iron, zinc, and sodium losses did not differ significantly ($p > 0.05$) across SOC levels in *Ferralsols*. In *Nitisols*, similar trends were observed where higher loss of TN, K, P, Ca, and Mg losses were observed under higher SOC. Iron and zinc losses also varied significantly ($p < 0.01$) with varying SOC levels. The highest Fe losses were obtained under moderate SOC (35.44 mg/l) while the highest Zn losses were witnessed at low SOC (32.23 mg/l). Copper and sodium losses did not show significant ($p > 0.05$) differences. On the other hand, the varying rainfall intensity did not have any significant ($p > 0.05$) influence on the erosion of all the sampled nutrient elements in both soil types.

Table 4.14: Effect of different organic carbon levels on nutrient loss through sediment loss in Ferralsols and Nitisols

Soil Type	SOC Levels	TN (%)	K (%)	P(mg/l)	Ca (%)	Mg (%)	Cu (mg/l)	Fe (mg/l)	Zn (mg/l)	Na (mg/l)
<i>Ferralsols</i>	Low	0.10 b	0.47 b	8.89 b	5.00 b	2.29 b	1.18	15.30	3.81	0.30
	Moderate	0.12 b	0.32 c	14.28 a	4.36 b	4.17 a	2.37	13.69	5.24	0.44
	Adequate	0.27 a	1.09 a	15.83 a	14.77 a	4.02 a	1.16	11.39	6.29	0.39
	SE	0.011	0.37	0.55	0.563	0.231	0.425	1.29	2.556	0.046
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.103	0.130	0.069	0.130
<i>Nitisols</i>	Low	0.15 b	0.74 b	13.11 b	2.22 b	2.52 b	1.41	19.45 b	32.23 a	0.28
	Moderate	0.13 b	0.48 c	8.50 c	1.68 b	3.99 a	2.34	35.44 a	8.91 c	0.19
	Adequate	0.25 a	1.12 a	16.00 a	6.70 a	3.82 a	1.36	16.31 b	26.31 b	0.27
	SE	0.007	0.063	0.662	0.279	0.14	0.514	3.384	1.419	0.046
	p value	<0.001	<0.001	<0.001	<0.001	<0.001	0.341	0.002	<0.001	0.345

SOC – Soil Organic Carbon; TN=Total nitrogen; P =Available phosphorus; K=Exchangeable potassium; Ca= Calcium; Mg=Magnesium; Cu=Copper; Fe= Iron; Zn=Zinc. Means with different letters within the columns are significantly different at $p<0.05$.

Table 4.15: Effect of different rainfall intensities on nutrients loss through sediment loss in Ferralsols and Nitisols

Soil Type	Rainfall Intensity	TN (%)	K (%)	P(mg/l)	Ca (%)	Mg (%)	Cu (mg/l)	Fe (mg/l)	Zn (mg/l)	Na (mg/l)
<i>Ferralsols</i>	Low (80 mm/hr)	0.18	0.70	11.78	3.74	3.41	1.29	20.28	21.44	0.26
	Moderate (100 mm/hr)	0.17	0.87	13.89	3.20	3.60	1.81	25.18	23.57	0.23
	Adequate (120 mm/hr)	0.17	0.77	11.94	3.66	3.32	2.03	25.73	22.45	0.25
	SE	0.011	0.037	0.55	0.563	0.231	0.425	1.29	2.556	0.046
	p value	0.752	0.201	0.518	0.290	0.063	0.806	0.846	0.931	0.759
<i>Nitisols</i>	Low (80 mm/hr)	0.16	0.59	13.39	8.43	3.64	1.35	14.03	4.94	0.38
	Moderate (100 mm/hr)	0.17	0.68	12.00	8.40	3.82	1.65	13.36	5.31	0.35
	Adequate (120 mm/hr)	0.16	0.60	13.11	7.29	3.02	1.72	12.99	5.09	0.39
	SE	0.007	0.063	0.662	0.279	0.14	0.514	3.384	1.419	0.046
	p value	0.267	0.193	0.071	0.358	0.37	0.585	0.472	0.582	0.856

Legend: TN=Total nitrogen; P =Available phosphorus; K=Exchangeable potassium; Ca= Calcium; Mg=Magnesium; Cu=Copper; Fe= Iron; Zn=Zinc.

Table 4.16 presents the interactive effects of soil organic carbon and rainfall intensity on nutrient loss through sediment loss in *Ferralsols* and *Nitisols*. In *Ferralsols*, the SOC and rainfall interactions had a significant ($p < 0.05$) effect on exchangeable potassium and available phosphorus. The adequate SOC levels combined with medium or high rainfall intensity increased losses of these nutrients. However, there were no significant ($p < 0.05$) interactive effects for total nitrogen, calcium, magnesium, copper, iron, zinc, and sodium. In *Nitisols*, a significant ($p < 0.05$) effect was found only for K, with higher SOC levels under medium rainfall intensity significantly influencing higher potassium loss through sediment. All other nutrients were not significantly ($p > 0.05$) affected by the SOC x rainfall interaction.

The combined effects of soil type, SOC levels, and rainfall intensity on sediment nutrient loads are presented in Table 4.17. *Nitisols* recorded significantly ($p < 0.001$) higher exchangeable potassium and iron losses than *Ferralsols*. However, *Ferralsols* had significantly ($p < 0.001$) higher calcium and sodium losses than *Nitisols*. Other nutrients including total nitrogen, phosphorus, magnesium, copper, and zinc showed mixed results, with only zinc also being significantly ($p < 0.001$) higher in *Nitisols*. Soil organic carbon levels also influenced significant ($p < 0.001$) sediment loads for the total nitrogen, potassium, phosphorus, calcium, magnesium, iron and zinc. Adequate SOC consistently resulted in higher nutrient losses for TN, K, P, Ca, and Zn, while moderate SOC showed higher Fe losses. Copper and Sodium losses were not significantly different across SOC levels ($p > 0.05$). On the other hand, the rainfall intensity influenced significant ($p < 0.05$) losses of potassium and magnesium, where higher rainfall tended to increase losses. Losses of TN, P, Ca, Cu, Fe, Zn, and Na were not significantly ($p > 0.05$) affected by rainfall intensity.

Table 4.16: Interactive effects of different organic carbon levels and rainfall intensity on sediment nutrient loads in *Ferralsols* and *Nitisols*

Soil Type	SOC*Rainfall Intensities	Sediment Nutrient Load								
		TN (%)	K (%)	P (mg/l)	Ca (%)	Mg (%)	Cu (mg/l)	Fe (mg/l)	Zn (mg/l)	Na (mg/l)
<i>Ferralsols</i>	Adequate SOC*High RI	0.25	0.99 d	18.00 e	13.20	3.39	1.06	11.97	5.75	0.38
	Adequate SOC*Low RI	0.28	0.96 d	15.00 cd	15.40	4.46	1.27	10.30	6.24	0.45
	Adequate SOC*Medium RI	0.29	1.32 e	14.50 cd	15.70	4.22	1.15	11.90	6.89	0.34
	Moderate SOC*Low RI	0.11	0.37 b	16.50 d	6.10	4.30	2.36	16.47	5.37	0.42
	Moderate SOC*High RI	0.13	0.35 b	13.00 c	4.07	4.09	2.57	11.43	5.40	0.49
	Moderate SOC*Medium RI	0.12	0.25 a	13.33 c	2.90	4.11	2.17	13.17	4.95	0.41
	Low SOC*Low RI	0.10	0.45 c	8.67 ab	3.80	2.16	0.40	15.33	3.21	0.28
	Low SOC*Medium RI	0.11	0.48 c	9.67 b	6.60	3.12	1.61	15.00	4.10	0.30
	Low SOC*High RI	0.10	0.47 c	8.33 a	4.60	1.58	1.53	15.57	4.11	0.32
	SE	0.019	0.064	0.952	0.975	0.400	0.737	2.234	1.213	0.080
	<i>p</i> value	0.636	0.013	0.020	0.063	0.321	0.834	0.623	0.942	0.872
<i>Nitisols</i>	Moderate SOC*Low RI	0.13	0.37 a	8.00	1.33	4.02	0.94	26.93	6.93	0.17
	Low SOC*High RI	0.16	1.00 d	12.67	1.67	2.55	1.28	19.60	31.93	0.13
	Low SOC*Low RI	0.15	0.57 b	13.00	3.40	2.38	1.43	18.80	30.03	0.42
	Adequate SOC*Low RI	0.28	1.16 e	14.33	6.50	3.83	1.48	15.10	27.37	0.19
	Adequate SOC*Medium RI	0.24	1.41 f	19.00	6.30	3.96	1.35	17.50	26.53	0.24
	Low SOC*Medium RI	0.15	0.64 c	13.67	1.60	2.62	1.52	19.90	34.73	0.29
	Adequate SOC*High RI	0.23	0.80 d	14.67	7.30	3.67	1.26	16.33	25.03	0.39
	Moderate SOC*Medium RI	0.13	0.56 b	9.00	1.70	4.23	2.56	38.13	9.43	0.15
	Moderate SOC*High RI	0.12	0.51 b	8.50	2.00	3.75	3.53	41.27	10.38	0.25
	SE	0.012	0.110	1.147	0.483	0.243	0.891	5.862	2.459	0.079
	<i>p</i> value	0.194	0.005	0.349	0.082	0.897	0.529	0.765	0.695	0.070

Legend: SOC – Soil Organic Carbon; RI – Rainfall Intensity; TN=Total nitrogen; P =Available phosphorus; K=Exchangeable potassium; Ca= Calcium; Mg=Magnesium; Cu=Copper; Fe= Iron; Zn=Zinc. Means with different letters within a column are significantly different at $P<0.05$

Table 4.17: Sediment nutrient load as affected by soil type, rainfall intensity and organic carbon levels

Factors	Variables	Sediment nutrients load								
		TN (%)	K (%)	P (mg/l)	Ca (%)	Mg (%)	Cu (mg/l)	Fe (mg/l)	Zn (mg/l)	Na (mg/l)
Soil Type	<i>Ferralsols</i>	0.16	0.63 b	13.00	8.04 a	3.49	1.57	13.46 b	5.11 b	0.38 a
	<i>Nitisols</i>	0.17	0.78 a	12.54	3.53 b	3.44	1.71	23.73 a	22.49 a	0.25 b
	SE	0.005	0.029	0.375	0.255	0.108	0.295	1.445	0.739	0.027
	P Value	0.142	0.001	0.389	<0.001	0.743	0.748	<0.001	<0.001	0.002
SOC Levels	Adequate	0.26 a	1.11 a	15.92 a	10.73 a	3.92 a	1.26	13.85 b	16.30 a	0.33
	Moderate	0.12 b	0.40 c	11.39 b	3.02 b	4.08 a	2.36	24.57 a	7.08 b	0.31
	Low	0.13 b	0.60 b	11.00 b	3.61 b	2.40 b	1.30	17.37 b	18.02 a	0.29
	SE	0.007	0.036	0.459	0.312	0.133	0.362	1.769	0.905	0.033
	P Value	<0.001	<0.001	<0.001	<0.001	<0.001	0.059	0.001	<0.001	0.652
Rainfall Intensity	120 mm/hr	0.16	0.69 b	12.53	5.47	3.17 b	1.87	19.36	13.77	0.33
	100 mm/hr	0.17	0.78 a	13.19	5.80	3.71 a	1.73	19.27	14.44	0.29
	80 mm/hr	0.17	0.65 b	12.58	6.09	3.52 ab	1.31	17.16	13.19	0.32
	SE	0.007	0.036	0.459	0.312	0.133	0.362	1.769	0.905	0.033
	P Value	0.598	0.043	0.529	0.386	0.022	0.532	0.613	0.625	0.685

Legend: TN=Total nitrogen; P =Available phosphorus; K=Exchangeable potassium; Ca= Calcium; Mg=Magnesium; Cu=Copper; Fe= Iron; Zn=Zinc. Means with different letters across the column are significantly different at P<0.05

4.3.2 Effects of SOC levels and rainfall intensity on nutrient loss via runoff

Table 4.18 shows how soil organic carbon levels influenced nutrient loss through runoff in *Ferralsols* and *Nitisols*. In *Ferralsols*, significant effects of SOC levels were observed only in nitrate and calcium losses. The highest nitrate concentration in runoff (1.94 mg N/l) was recorded under moderate SOC compared to adequate (1.30 mg N/l) and low SOC (0.95 mg N/l). For calcium, there were significantly higher losses under adequate SOC (4.44 mg/l) compared to low SOC (3.28 mg/l). Other nutrient elements including potassium, phosphorus, magnesium, and sulphate showed no significant ($p > 0.05$) differences across SOC levels in *Ferralsols*. In *Nitisols*, SOC levels significantly ($p < 0.05$) affected potassium losses with the highest nutrient load being recorded under adequate SOC (1.59 mg/l) compared to low SOC (1.30 mg/l). However, nitrate, phosphorus, magnesium, calcium, and sulphate losses were not significantly different among varying SOC levels.

Table 4.18: Runoff nutrient concentrations as influenced by different organic carbon levels in *Ferralsols* and *Nitisols*

Soil Type	SOC Levels	Runoff Nutrient Load					
		Nitrate (mg/l)	K (mg/l)	P (mg/l)	Mg (mg/l)	Ca (mg/l)	Sulphate (mg/l)
<i>Ferralsols</i>	Low	0.95 ^a	1.20	0.12	2.39	3.28 ^a	2.04
	Moderate	1.94 ^c	1.23	0.14	2.47	3.60 ^{ab}	2.02
	Adequate	1.30 ^b	1.17	0.11	2.53	4.44 ^b	3.19
	SE	0.161	0.049	0.020	0.274	0.272	0.422
	p value	0.002	0.637	0.459	0.933	0.022	0.113
<i>Nitisols</i>	Low	1.03	1.30 ^a	0.10	1.72	3.82	2.16
	Moderate	1.80	1.47 ^{ab}	0.08	2.02	3.47	1.08
	Adequate	1.10	1.59 ^b	0.09	2.28	2.76	1.57
	SE	0.387	0.071	0.013	0.300	0.328	0.385
	p value	0.325	0.034	0.415	0.443	0.094	0.172

Legend: SOC – Soil Organic Carbon; P = Available phosphorus; K = Exchangeable potassium; Ca = Calcium; Mg = Magnesium. Means with different small letters across the column are significantly different at $P < 0.05$

The effect of rainfall intensity on nutrient loss through runoff in *Ferralsols* and *Nitisols* are shown in Table 4.19. In *Ferralsols*, the rainfall intensity did not show any significant ($p > 0.05$) influence on runoff nutrient losses for all the sampled elements. For *Nitisols*, rainfall intensity significantly ($p < 0.05$) influenced nitrate loss, with higher nitrate concentration (2.18 mg N/l) being recorded under the highest rainfall intensity (120 mm/hr) compared to moderate and lower rainfall intensities 0.90 mg N/l

and 0.86 mg N/l, respectively. Potassium, phosphorus, magnesium, calcium, and sulphate showed no significant ($p > 0.05$) variation across rainfall intensities.

Table 4.19: Runoff nutrient loads as influenced by different rainfall intensities in *Ferralsols* and *Nitisols*

Soil Type	Rainfall Intensity	Runoff Nutrient Load					
		Nitrate (mg/l)	K (mg/l)	P (mg/l)	Mg (mg/l)	Ca (mg/l)	Sulphate (mg/l)
<i>Ferralsols</i>	80 mm/hr	1.27	1.19	0.11	2.30	4.13	2.82
	100 mm/hr	1.57	1.22	0.12	2.60	3.64	2.89
	120 mm/hr	1.36	1.19	0.14	2.49	3.54	1.54
	SE	0.161	0.049	0.020	0.274	0.272	0.422
	p value	0.424	0.858	0.476	0.740	0.289	0.067
<i>Nitisols</i>	80 mm/hr	0.86 a	1.44	0.11	2.04	3.11	1.11
	100 mm/hr	0.90 a	1.46	0.09	2.11	3.11	2.16
	120 mm/hr	2.18 b	1.46	0.07	1.87	3.82	1.53
	SE	0.387	0.071	0.013	0.300	0.328	0.385
	p value	0.045	0.992	0.115	0.839	0.238	0.187

Legend: P =Available phosphorus; K=Exchangeable potassium; Ca= Calcium; Mg=Magnesium. Means with different letters within the column are not significantly different at $P < 0.05$

Table 4.20 presents the interactive effects of soil organic carbon and rainfall intensities on runoff nutrient loss in *Ferralsols* and *Nitisols*. For *Ferralsols*, the interaction between SOC levels and rainfall intensity did not significantly ($p > 0.05$) influence nitrate, potassium, phosphorus, magnesium, calcium, or sulphate losses through runoff. In *Nitisols*, the runoff concentration of phosphorus varied across the various interaction of SOC and rainfall intensities. The highest concentration was recorded under low SOC combined with low rainfall intensity (0.18 mg/l) compared to other combinations. However, nitrate, potassium, magnesium, calcium, and sulphate were not significantly ($p > 0.05$) affected by the interaction.

Table 4.20: Interactive effects of soil organic carbon and rainfall intensity on nutrient loss in *Ferralsols* and *Nitisols*

	SOC*Rainfall Intensities	Runoff Nutrient load					
		NO ₃ (mg/l)	K (mg/l)	P (mg/l)	Mg (mg/l)	Ca (mg/l)	SO ₄ (mg/l)
<i>Ferralsols</i>	Adequate SOC*High RI	1.27	1.20	0.13	2.27	3.73	2.20
	Adequate SOC*Low RI	1.23	1.07	0.09	2.73	5.33	3.60
	Adequate SOC*Medium RI	1.40	1.23	0.11	2.60	4.27	3.77
	Moderate SOC*Low RI	1.70	1.30	0.11	2.50	3.33	2.83
	Moderate SOC*High RI	1.97	1.20	0.19	2.13	3.73	0.93
	Moderate SOC*Medium RI	2.17	1.20	0.13	2.77	3.73	2.30
	Low SOC*Low RI	0.87	1.20	0.12	1.67	3.73	2.03
	Low SOC*Medium RI	1.13	1.23	0.12	2.43	2.93	2.60
	Low SOC*High RI	0.85	1.17	0.11	3.07	3.17	1.50
	SE	0.279	0.085	0.035	0.475	0.471	0.731
	p value	0.977	0.558	0.715	0.315	0.303	0.897
<i>Nitisols</i>	Moderate SOC*Low RI	0.40	1.53	0.07 ^a	1.47	2.93	1.50
	Low SOC*High RI	1.47	1.30	0.05 ^b	1.13	4.53	2.73
	Low SOC*Low RI	1.00	1.30	0.18 ^a	2.07	3.73	0.67
	Adequate SOC*Low RI	1.17	1.50	0.09 ^{ab}	2.60	2.67	1.17
	Adequate SOC*Medium RI	0.93	1.57	0.12	2.43	2.40	1.97
	Low SOC*Medium RI	0.63	1.30	0.08	1.97	3.20	3.07
	Adequate SOC*High RI	1.20	1.70	0.07 ^{ab}	1.80	3.20	1.57
	Moderate SOC*Medium RI	1.13	1.50	0.06	1.93	3.73	1.43
	Moderate SOC*High RI	3.87	1.37	0.10	2.67	3.73	0.30
	SE	0.670	0.122	0.022	0.520	0.567	0.666
	p value	0.135	0.667	0.013	0.278	0.734	0.207

Legend: SOC – Soil Organic Carbon; RI – Rainfall Intensities; P =Available phosphorus; K=Exchangeable potassium; Ca= Calcium; Mg=Magnesium

Table 4.21 shows how soil type, combined SOC levels, and rainfall intensities influenced sediment nutrient loads. As compared to *Nitisols*, *Ferralsols* showed significantly ($p < 0.001$) lower concentration of potassium in the runoff but higher ($p < 0.05$) runoff concentrations of potassium, magnesium and sulphate. Nitrate and calcium were not significantly ($p > 0.05$) affected while sulphate was significantly ($p < 0.05$) higher in *Ferralsols*. Based on SOC levels, nitrate loss through runoff was significantly ($p < 0.05$) affected, with moderate SOC showing the highest nitrate concentrations (1.87 mg/l) and low SOC the lowest (0.99 mg/l). Potassium, phosphorus, magnesium, calcium, and sulphate were not significantly ($p > 0.05$) influenced by SOC levels. On the other hand, none of the nutrient elements was significantly ($p > 0.05$) affected by the rainfall intensity.

Table 4.21: Runoff nutrient loads as affected by soil type, combined levels of organic carbon and rainfall intensities

Factors	Variables	Runoff Nutrient load					
		NO ₃ (mg/l)	K (mg/l)	P (mg/l)	Mg (mg/l)	Ca (mg/l)	SO ₄ (mg/l)
Soil type	<i>Ferralsols</i>	1.40	1.20 b	0.12 a	2.46 a	3.77	2.42 a
	<i>Nitisols</i>	1.31	1.45 a	0.09 b	2.01 b	3.35	1.60 b
	SE	0.170	0.035	0.010	0.162	0.175	0.255
	p value	0.720	<0.001	0.025	0.045	0.094	0.030
SOC levels	Adequate	1.20 ab	1.38	0.10	2.41	3.60	2.38
	Moderate	1.87 a	1.35	0.11	2.24	3.53	1.55
	Low	0.99 b	1.25	0.11	2.06	3.55	2.10
	SE	0.209	0.043	0.012	0.198	0.214	0.313
	p value	0.014	0.103	0.837	0.465	0.974	0.178
Rainfall Intensity	120 mm/hr	1.77	1.32	0.11	2.18	3.68	1.54
	100 mm/hr	1.23	1.34	0.10	2.36	3.38	2.52
	80 mm/hr	1.06	1.32	0.11	2.17	3.62	1.97
	SE	0.209	0.043	0.012	0.198	0.214	0.313
	p value	0.057	0.931	0.900	0.759	0.571	0.098

Legend: NO₃ =Nitrate; P =Available phosphorus; K=Exchangeable potassium; Ca= Calcium; Mg=Magnesium; SO₄ = Sulphate. Means with different letters within the column are significantly different at $p<0.05$.

Table 4.22 presents the Pearson correlations between sediment loads of different nutrient elements in *Ferralsols* and *Nitisols*. For *Nitisols*, total nitrogen (TN) showed strong positive correlations with calcium ($r=0.843$), potassium ($r=0.718$), and phosphorus ($r=0.685$). Potassium losses were also positively correlated with those of phosphorus ($r=0.632$) and calcium ($r=0.531$). Iron losses were negatively correlated with those of TN ($r=-0.518$), K (-0.416), P (-0.503), Ca (-0.4370) and Zn (-0.474) but positively correlated to Mg (0.388) and Cu (0.826). There was also significant positive correlation between zinc losses with those of K (0.415) and P (0.617) but zinc was negatively correlated to Mg and Fe. In *Ferralsols*, TN was positively correlated with K, P, Ca, Mg and Zn but negatively correlated to Fe. Calcium was found to be positively correlated to K and P while Magnesium was positively correlated to P and Na. There were also significant positive correlations between Zinc and TN, K, P, Ca and Mg.

Table 4.22: Pearson correlation between sediment nutrient loads

Soil Type	Variables	TN							
<i>Nitisols</i>	K	0.718	K						
	P	0.685	0.632	P					
	Ca	0.843	0.531	0.661	Ca				
	Mg	0.110	0.056	-0.160	0.254	Mg			
	Cu	-0.246	-0.158	-0.223	-0.120	0.312	Cu		
	Fe	-0.518	-0.416	-0.503	-0.437	0.388	0.826	Fe	
	Zn	0.369	0.415	0.617	0.297	-0.544	-0.029	-0.474	Zn
	Na	0.119	-0.103	0.114	0.364	-0.076	-0.097	-0.299	0.206
Soil Type	Variables	TN							
<i>Ferralsols</i>	K	0.926	K						
	P	0.488	0.376	P					
	Ca	0.870	0.892	0.470	Ca				
	Mg	0.463	0.242	0.647	0.328	Mg			
	Cu	-0.178	-0.270	0.079	-0.143	0.288	Cu		
	Fe	-0.419	-0.296	-0.164	-0.338	-0.161	0.134	Fe	
	Zn	0.652	0.507	0.409	0.437	0.676	0.206	-0.138	Zn
	Na	0.203	0.043	0.366	0.004	0.472	0.112	-0.156	0.326
Soil Type	Variables	TN							
Both Soils	K	0.824	K						
	P	0.550	0.479	P					
	Ca	0.700	0.521	0.47	Ca				
	Mg	0.347	0.155	0.31	0.279	Mg			
	Cu	-0.196	-0.193	-0.090	-0.130	0.287	Cu		
	Fe	-0.288	-0.187	-0.359	-0.446	0.137	0.572	Fe	
	Zn	0.262	0.386	0.279	-0.249	-0.157	0.036	0.102	Zn
	Na	0.109	-0.120	0.228	0.301	0.199	-0.032	-0.403	-0.184

Values in bold are different from 0 with a significance level $\alpha=0.05$

There was a significant ($P < 0.05$) positive correlation between the concentration of the macro elements (TN, K, P, Ca, and Mg) in the eroded sediments from *Ferralsols* and *Nitisols* (except for K and Mg which did not show any significant correlation (Table 2). There was also a significant positive correlation between Mg and Cu as well as Cu and Fe. The TN, P and Ca showed a significant negative correlation with Fe while K and P portrayed a significant positive correlation with Zn. The concentration of Na in the eroded sediments was significantly positively correlated with Ca but negatively correlated with Fe.

Table 4.23 presents the Pearson correlation coefficients for runoff nutrient losses. In *Ferralsols*, nitrate showed a moderate positive correlation with phosphorus ($r = 0.549$, significant ($p < 0.05$)). Other correlations, such as nitrate with potassium ($r = -0.122$) and nitrate with magnesium ($r = 0.139$), were weak and not significant ($p > 0.05$). Calcium had a weak negative correlation with magnesium ($r = -0.439$, significant ($p < 0.05$)) but was weakly related to other nutrients without significance ($p > 0.05$). Sulphate generally showed weak, non-significant ($p > 0.05$) relationships with all variables. In *Nitisols*, all correlations were weak and not statistically significant ($p > 0.05$). The highest was between nitrate and calcium ($r = 0.296$), but this did not reach significance ($p > 0.05$). Sulphate showed negative, non-significant correlations with most nutrients. In the combined dataset, nitrate showed a weak but significant positive correlation with phosphorus ($r = 0.244$, significant at $p < 0.05$). Other correlations were weak and non-significant, including nitrate with potassium ($r = -0.109$), magnesium ($r = 0.079$), and calcium ($r = 0.205$) ($p > 0.05$). Calcium's correlation with potassium ($r = -0.276$) and magnesium ($r = -0.248$) remained weak and non-significant ($p > 0.05$). Sulphate displayed no meaningful correlation with other nutrients.

Table 4.23: Pearson correlation between runoff nutrient concentrations

Soil Type	Variables	Nitrate				
<i>Ferralsols</i>	K	-0.122	K			
	P	0.549	-0.088	P		
	Mg	0.139	0.010	-0.113	Mg	
	Ca	-0.011	-0.073	0.037	-0.439	Ca
	Sulphate	0.022	-0.114	-0.156	-0.125	0.279
Soil Type	Variables	Nitrate				
<i>Nitisols</i>	K	-0.101	K			
	P	0.127	-0.095	P		
	Mg	0.048	0.017	-0.007	Mg	
	Ca	0.296	-0.272	0.055	-0.236	Ca
	Sulphate	-0.288	-0.225	-0.411	-0.057	-0.301
Soil Type	Variables	Nitrate				
Both Soils Combined	K	-0.109	K			
	P	0.244	-0.225	P		
	Mg	0.079	-0.139	0.021	Mg	
	Ca	0.205	-0.276	0.102	-0.248	Ca
	Sulphate	-0.154	-0.296	-0.163	-0.003	0.044

Values in bold are different from 0 with a significance level $\alpha=0.05$

CHAPTER FIVE

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

5.1 Discussion

5.1.1 Effect of soil organic carbon levels on soil erosion

The findings show that soil organic carbon (SOC) plays a crucial role in mitigating runoff and sediment loss in *Nitisols* and *Ferralsols* in Tharaka-Nithi County. Soils with adequate SOC recorded significantly lower runoff volumes and sediment concentrations than soils with low or moderate SOC, primarily due to improved aggregate stability and soil structure (Dai et al., 2018). This is consistent with Saha et al. (2010) and Vaezi et al. (2017), who showed that organic matter enhances soil physical attributes and microbial biomass, increasing infiltration and reducing detachment risk. Babur et al. (2021) and Kones et al. (2022) also highlighted SOC's contribution to soil quality and erosion resistance. Similarly, Morgan and Nearing (2011) and Panagos et al. (2022) emphasized that SOC acts as a natural stabilizer, boosting soil resilience to erosive forces through better water infiltration and structural integrity.

The findings also showed that *Ferralsols* were associated with significantly higher runoff than *Nitisols*, which benefit from deeper, more stable blocky structures and greater aggregation due to clay-humus interactions and moderate calcium carbonate content (Kibet et al., 2022). This observation aligns with Sileshi et al. (2020) and Oduor et al. (2023), who noted that *Ferralsols*, despite having a sandy loam to clay texture that can favor infiltration, are prone to surface sealing, compaction, and crusting due to their weak aggregation, low clay activity, and limited calcium carbonate content, particularly when SOC is low. However, when SOC is adequate, both soils showed improved aggregate stability, lower bulk density, and better infiltration (Razzaghi et al., 2023). Additionally, Zhang et al. (2021) and Schütte et al. (2021) highlighted that *Ferralsols*' coarser texture and weaker structural development increase their vulnerability to erosion, emphasizing the critical role of maintaining higher SOC to counter runoff and sediment loss.

Rainfall intensity had a statistically significant effect on runoff and sediment dynamics. As rainfall intensity increased from 80 mm/hr to 120 mm/hr, runoff volumes rose sharply due to infiltration limits being exceeded (Zhao et al., 2019; Wanyonyi et

al., 2022; Ngetich et al., 2008). This trend mirrors results by Biddoccu et al. (2017) who reported that high-intensity storms generate greater kinetic energy, which enhances soil particle detachment and transport. Furthermore, Panagos et al. (2022) indicated that erosive rainfall above 100 mm/hr is particularly damaging in tropical landscapes with low SOC.

Regarding the sediment loss, it was highest at the lowest rainfall intensity (80 mm/hr) rather than the highest, especially in *Nitisols*. This inverse trend may result from soil sealing under high-intensity storms, which increases runoff but reduces detachment (Duan et al., 2017; Zhang et al., 2015). Morgan & Nearing (2011) also noted that raindrop impact at moderate intensities is more efficient at detaching particles before flow concentration occurs. Slope effects can amplify this, with flatter slopes limiting sediment transport capacity and creating a transport-limited erosion regime (Zhang et al., 2015). Duan et al. (2017) also highlighted that low-intensity, prolonged storms enhance subsurface flow, delaying surface erosion.

The effect of rainfall intensity varied by soil type. *Ferralsols* generated more runoff and sediment than *Nitisols* at all intensities, reinforcing the idea that their structural weakness and shallow rooting depth make them more vulnerable to storm events (Schütte et al., 2021). Under storms over 100 mm/hr, *Ferralsols* were particularly vulnerable, losing structure rapidly (Panagos et al., 2022; Nearing et al., 2022). This aligns with Morgan & Nearing (2011) and highlights why *Ferralsols* require more robust SOC management to buffer the impact of tropical storm energy. Interaction effects revealed that low SOC combined with high rainfall intensity resulted in the most severe runoff and sediment losses, particularly in *Ferralsols*. These results echo findings from Panagos et al. (2022) and Biddoccu et al. (2017), who emphasized that SOC could buffer the impact of erosive rainfall by enhancing soil cohesion. González et al. (2019) stressed that *Ferralsols* need sustained organic inputs to offset their weathered mineralogy. Studies by Githongo et al. (2023) confirm that while SOC improves infiltration and aggregate stability, structural measures like terraces and contour bunds (Fenta et al., 2021; Karamage et al., 2019) remain vital, especially where SOC alone cannot overcome inherent soil weaknesses.

5.1.2 Effect of organic carbon and rainfall intensity on soil physical properties

The results clearly demonstrate that soil organic carbon (SOC) levels play a fundamental role in shaping key soil physical properties, notably bulk density (BD), hydraulic conductivity (HC), and soil water retention in both *Ferralsols* and *Nitisols*. Consistent with earlier findings (Rugendo et al., 2023; Gao et al., 2019), higher SOC levels markedly lowered bulk density by improving soil aggregation, enhancing macroporosity, and decreasing compaction risk. This was especially evident in the inherently fragile *Ferralsols*, where SOC enrichment produced the most pronounced improvements due to their weak structural stability and dominance of low-activity clays. This outcome aligns well with the inverse relationship between SOC and BD widely reported for tropical and subtropical soils (Minasny et al., 2022; Bhattacharyya et al., 2023). In contrast, *Nitisols*, characterized by a naturally stable blocky structure and better aggregate stability, sustained lower BD values across all SOC levels, echoing previous findings by Butcher et al. (2020) and Gicheru et al. (2012) that well-structured soils maintain physical integrity even with moderate organic matter.

Rainfall intensity (RI) was also a significant factor influencing BD, especially in *Ferralsols* under extreme rainfall conditions (120 mm/hr). This supports the view that high-intensity rainfall exerts mechanical pressure that disrupts weak soil aggregates, leading to compaction and surface sealing (Zhang et al., 2021). In this study, *Ferralsols* exposed to high rainfall intensity showed a marked increase in BD compared to moderate rainfall treatments, consistent with reports by Nichols et al. (2021) and Mugwe et al. (2009). Similarly, Kinyanjui and Njogu (2022) highlighted that weakly aggregated soils like *Ferralsols* are particularly vulnerable to sealing and pore blockage during heavy storms. In contrast, *Nitisols* maintained relatively stable BD values under varying rainfall intensities, underscoring their inherent resistance to structural collapse under kinetic rainfall energy, a pattern reinforced by Kihara et al. (2022) and Panagea et al. (2021). Although the statistical interaction between SOC and RI on BD was not significant, the clear patterns suggest that for fragile soils like *Ferralsols*, boosting SOC alone is insufficient; complementary soil cover or conservation tillage is vital to prevent compaction under extreme weather (Smith & Jones, 2022; Silva et al., 2021; Kibet et al., 2022).

Hydraulic conductivity (HC) was significantly improved by higher SOC levels across both soil types, but the magnitude and response patterns varied. *Ferralsols* showed a clear, almost linear increase in HC with SOC enrichment, which reflects their greater responsiveness to organic matter due to initially poor structural integrity (Blanco-Canqui & Lal, 2008; Rawls et al., 2003). Enhanced SOC stabilizes aggregates and improves pore continuity, directly facilitating water infiltration while reducing runoff and surface crusting (Sekaran et al., 2021). For *Nitisols*, improvements in HC were more pronounced only when SOC levels crossed a moderate threshold, indicating that their naturally favorable structure provides good baseline infiltration capacity that additional SOC can further boost but only up to a point (Kimetu et al., 2008; Gicheru et al., 2012). This supports observations that mineralogical composition, such as higher clay activity and well-developed blocky structures, condition how much benefit SOC can add to a soil's hydraulic performance (Zizinga et al., 2022; Woldemariam et al., 2024).

Rainfall intensity influenced HC in a complex, soil-specific manner. Initial increases in rainfall generally promoted infiltration by activating macropores and flushing fine particles (Assouline & Narkis, 2021). However, when rainfall intensity was high, *Ferralsols* displayed declining HC due to structural breakdown, surface sealing, and pore clogging, echoing Abid et al. (2023). Meanwhile, *Nitisols* retained stable infiltration under heavy rainfall, highlighting their aggregate durability and resilience (Mutuku et al., 2021; Mugwe et al., 2009). The significant interaction effect between SOC and RI on HC suggests that SOC enrichment can buffer some of the infiltration loss under high rainfall by reinforcing structural stability and maintaining open pore pathways (Bagarello et al., 2022; Bronick & Lal, 2022). Yet the variable response in *Ferralsols* shows that organic inputs alone may not fully safeguard infiltration unless paired with surface covers or reduced tillage (Nguyen et al., 2020).

Soil water retention was also strongly affected by SOC levels across all measured matric suctions, reinforcing the importance of organic matter in improving soil moisture dynamics. *Ferralsols* showed a pronounced increase in mean water content as SOC rose, consistent with previous evidence that SOC boosts porosity, strengthens micropore networks, and stabilizes aggregates (Rawls et al., 2003; Lal, 2020b; Minasny & McBratney, 2018). By comparison, *Nitisols*' inherently stable structure

and high clay content provided superior baseline water-holding capacity, which additional SOC improved only marginally (Mathewos et al., 2024; Bolo et al., 2023). These contrasting responses highlight why site-specific SOC management is critical. *Ferralsols* benefit disproportionately from organic amendments, making SOC build-up a priority for improving drought resilience in these soils, especially in SSA uplands (Watene et al., 2021).

The rainfall intensity did not produce statistically significant effects on soil water retention at any matric suction, echoing findings that internal soil structure and profile depth largely determine water-holding capacity in deeply weathered tropical soils (Ngamwange et al., 2021; Boulange et al., 2019). However, a clear trend showed that *Nitisols* consistently retained more water under all rainfall scenarios, underscoring the stabilizing role of well-developed blocky aggregates and high clay activity (Okello et al., 2021; Ogunwole et al., 2020). The absence of significant RI effects could be due to the limited duration of rainfall simulations, which likely did not allow for enough surface crusting or erosion to significantly alter water retention (Tian et al., 2022). Nonetheless, the pattern that higher SOC buffered moisture retention under high rainfall intensity supports evidence that organic matter fortifies structural resilience against sealing and pore collapse (Obalum et al., 2017; Bolo et al., 2021; Blanco-Canqui & Ruis, 2020).

Correlation analyses provided further insights into the internal relationships among BD, HC, and water retention. The strong negative correlation between BD and water retention at higher matric suctions confirmed that compaction limits porosity and thus storage capacity (Hillel, 2013; Biddoccu et al., 2017). Notably, this relationship was stronger in *Nitisols* than *Ferralsols*, possibly because structurally stable soils may experience sharper declines when structural degradation occurs (Melakeberhan et al., 2021). Meanwhile, the weak or negative correlation between HC and water retention in *Nitisols* indicates that infiltration and moisture storage may operate independently in highly aggregated clay soils, as also noted by Bashagaluke et al. (2018). The strong internal correlation between water retention at adjacent suctions aligns with Leenaars et al. (2020), reflecting the smooth transition of soil moisture states along the retention curve.

The results highlight that raising SOC levels is critical for improving soil physical quality, but that for vulnerable *Ferralsols*, this must be paired with rainfall management strategies like mulching, conservation tillage, or agroforestry to mitigate compaction risks during intense storms (Silva et al., 2021; Naipal et al., 2018). For resilient *Nitisols*, maintaining sufficient SOC safeguards water retention and infiltration, ensuring stable hydrological function under increasingly unpredictable rainfall patterns (Thierfelder et al., 2018; Bayabil et al., 2021; Liu et al., 2023). Overall, the findings stress the need for site-tailored, climate-smart soil management that combines SOC enrichment with conservation practices to secure soil health and water availability in tropical farming landscapes.

5.1.3 Effects of soil organic carbon and rainfall intensity on nutrient loss

The findings of this study demonstrate that soil organic carbon (SOC) levels play a significant role in nutrient losses through sediment in both *Ferralsols* and *Nitisols*. As shown in the data, higher SOC levels significantly increased losses of key macronutrients such as total nitrogen (TN), potassium (K), phosphorus (P), calcium (Ca), and magnesium (Mg). This reflects the dual role of SOC in improving soil aggregate stability and nutrient retention while simultaneously enriching the soil with greater pools of available nutrients that become susceptible to erosion when aggregates detach (Lal, 2003; Six et al., 2002; Karuku et al., 2018). For instance, TN in *Ferralsols* rose from 0.10% at low SOC to 0.27% at adequate SOC, illustrating how more fertile soils can paradoxically contribute greater nutrient losses during erosive events (Shen et al., 2019; Martinez-Mena et al., 2020). A similar trend in *Nitisols*, where TN increased from 0.15% to 0.25%, reinforces this pattern. This relationship echoes findings from other tropical soils, where higher SOC content improves fertility but also raises the pool of mobile nutrients vulnerable to detachment under inadequate ground cover (Wanyama et al., 2024; Singh et al., 2022; Chivenge et al., 2021). Wang et al. (2023) confirmed similar outcomes in temperate soils, where increasing SOC raised sediment-bound nitrogen and phosphorus losses, corroborating the significant increases for TN and P observed in both *Ferralsols* and *Nitisols*.

Because nutrients concentrate in fine, OM-rich fractions, texture and SOC jointly govern sediment-bound nutrient loads: greater SOC increases aggregate stability and reduces total sediment mass, even where concentrations in the smaller exported

fraction rise via selective transport of fines. This mechanism fits texture-mediated OM protection (Plante et al., 2006; Six et al., 2000) and documented microaggregation changes in *Ferralsols* under land use (Balbino et al., 2002), explaining our net decline in N/P/K loads at higher SOC.

Rainfall intensity (80–120 mm/hr) did not significantly affect the loss of most nutrient elements via sediment loss. This aligns with the notion that nutrient detachment in highly weathered tropical soils is governed more by soil properties like mineralogy and SOC interactions than by rainfall alone (Sharpley et al., 2018; Barrow, 2023). However, mobile nutrients such as potassium (K) and magnesium (Mg) showed slightly higher losses under high-intensity rainfall perhaps due to increased mineral mobilization under wet conditions (Sharpley et al., 2018). This supports evidence that sediment nutrient detachment in these highly weathered soils is more strongly governed by mineralogy, SOC interactions, and aggregate stability than by rainfall energy alone (Zhang et al., 2021; Ojo et al., 2022). The strong clay binding and phosphorus fixation capacity of *Ferralsols* and *Nitisols* likely buffered nutrient detachment under varying intensities (Kamau et al., 2021; Bhandari et al., 2023). Notable exceptions were limited to potassium and magnesium, which showed slightly higher losses under high rainfall, likely due to enhanced mineralization and mobilization (Ramos et al., 2018; Moreno-Mateos et al., 2023). Similar effects have been reported under tropical field conditions, where short, intense rainfall promotes soluble nutrient movement (Chen et al., 2020; Yuan et al., 2020).

The interaction between SOC and rainfall intensity produced mixed effects. Although mostly non-significant, some nutrients, such as exchangeable K and available P in *Ferralsols*, showed increased losses when higher SOC levels coincided with medium or high rainfall. This illustrates the dual role of SOC as both a stabilizer and a vector for nutrient mobilization (Lal, 2020a; Zhao et al., 2023). Similar patterns have been reported in Uganda and Nigeria, where high SOC combined with certain rainfall conditions led to more colloidal transport of bound nutrients (Ayele et al., 2021; Adekalu et al., 2023). These findings support Wang et al (2018), who emphasized that erosion-driven nutrient losses depend critically on soil type, rainfall regime, and SOC status.

In runoff, the results of this study also demonstrated that SOC levels significantly affect nutrient losses through runoff, although the pattern varied by nutrient and soil type. For *Ferralsols*, moderate SOC resulted in the highest nitrate runoff, pointing to the complex relationship between SOC, microbial activity, and nitrogen cycling (Tegegne & Haile, 2018). The non-linear trend, where adequate SOC did not always result in the lowest nitrate losses, mirrors findings in temperate regions, where excessive organic matter can increase mineralization but also enhance infiltration, thus moderating runoff (Jones & Chen, 2022). Potassium loss in *Nitisols* increased with SOC levels, showing how K, being weakly adsorbed, can become more mobile when SOC raises cation exchange capacity and organic complexation (Briggs et al., 2020; Mekuria et al., 2024). Such behavior is soil- and climate-specific, as some temperate studies often report reduced K leaching with higher SOC due to different mineralogy and drainage (García-Ruiz et al., 2023).

Rainfall intensity also influenced runoff nutrient losses in nutrient-specific ways. In *Ferralsols*, nitrate, potassium, phosphorus, magnesium, and calcium showed stable concentrations across rainfall intensities, suggesting strong oxide binding and structural buffering (Jones & Wild, 2019). However, nitrate in *Nitisols* increased significantly at the highest rainfall intensity (120 mm/hr), consistent with nitrate's high solubility and tendency to be leached under intense rainfall (Liu et al., 2023; Wang et al., 2022). Phosphorus and potassium concentrations remained stable, underscoring that phosphorus mobility depends more on soil pH and oxide content than rainfall force alone (Kamamia et al., 2022). Stable calcium and sulphate behavior further highlights nutrient-specific hydrological responses in tropical soils (Fatumah et al., 2020).

Correlations among sediment nutrients revealed strong positive links among TN, K, P, and Ca in both soils, indicating that these nutrients often share pathways during detachment and transport (Sharpley et al., 2018; Zhai et al., 2022). Negative associations, like between Fe and TN, may indicate selective binding or competing mineral phases (Barrow, 2023). For runoff, few significant correlations emerged one example being nitrate and phosphorus in *Ferralsols*, suggesting shared dissolved pathways in surface flow (Elbasiouny et al., 2022). The absence of stronger correlations for other runoff nutrients suggests that rainfall–soil interactions, infiltration, and micro-topography govern runoff nutrient separation more than

nutrient-nutrient interactions (Butcher et al., 2020; Giacometti et al., 2020). These patterns confirm that soil type, SOC, and rainfall intensity mainly influence runoff nutrient losses in tropical agroecosystems through independent mechanisms rather than strong interactive effects (Nyamadzawo et al., 2022; Odour et al., 2023; Grabowski et al., 2024). This highlights the need for integrated nutrient management that strengthens SOC while controlling runoff and erosion through complementary measures such as cover cropping, buffer strips, conservation tillage, terracing, and contour farming (Kisaka et al., 2016; Obiero et al., 2021).

5.2 Conclusion

The study confirms that adequate soil organic carbon (SOC) is essential for reducing surface runoff, sediment loss, and nutrient depletion in both *Nitisols* and *Ferralsols* by improving soil structure, infiltration, and key physical properties like bulk density and hydraulic conductivity. While adequate SOC levels generally enhance resilience to varying rainfall intensities, especially in *Nitisols*, *Ferralsols* remain more erosion-prone under heavy rains, highlighting the need for tailored SOC and water management strategies. The interaction between SOC and rainfall intensity also affects nutrient retention for elements like nitrogen, phosphorus, potassium, and calcium, underlining the importance of integrated, soil-type-specific management to sustain soil function and climate resilience in vulnerable ecosystems. Managing soils to achieve adequate SOC is essential for sustaining soil function, minimizing erosion, and enhancing climate resilience, and therefore, strategies that can improve SOC should be promoted and tailored to each soil type.

5.3 Recommendations

Based on the results the following are the recommendations:

1. Farmers should adopt practices that maintain or increase SOC above 2.5% (adequate level), particularly in *Ferralsol* regions, to reduce runoff, erosion, and boost long-term soil resilience. Policymakers should facilitate these efforts by developing incentives, extension services, and programs promoting soil and water conservation, including contour farming, mulching, and agroforestry, particularly in areas with high rainfall intensity.
2. For *Ferralsols* and *Nitisols*, strategies like compost use, crop residues, and reduced tillage should be prioritized to raise SOC levels. Higher SOC improves soil

structure, porosity, water infiltration, and moisture retention, key traits for helping soils resist droughts and floods, especially in SOC-sensitive *Ferralsols*.

3. To curb nutrient loss in *Nitisols* and *Ferralsols*, land practices should boost SOC while accounting for rainfall intensity. Higher SOC reduces the export of key nutrients (N, P, K, Ca, micronutrients), particularly under moderate rainfall. Combining organic matter inputs with adaptive water management enhances soil fertility and erosion control, ensuring sustainable productivity in fragile soils under changing climate conditions.
4. Tailor land management to soil texture differences between *Ferralsols* and *Nitisols*. *Ferralsols* need frequent organic inputs and mulching due to low nutrient retention, while *Nitisols* benefit from reduced compaction and occasional deep tillage. These targeted practices enhance SOC strategies and improve nutrient and water efficiency.
5. Implement localized training to educate farmers on SOC-building, erosion control, and water conservation. Use farmer field schools, demos, and digital tools to increase adoption. This is vital in *Ferralsol* and *Nitisol* regions where technical support is often lacking.

5.4 Areas of further research

- Long-term field monitoring of SOC and nutrient dynamics under natural rainfall. Conduct extended field studies to monitor the effects of varying SOC levels on nutrient losses and soil erosion under natural rainfall regimes. This will help validate laboratory or simulated rainfall findings and capture seasonal and inter-annual variability in nutrient dynamics, providing more robust, real-world data for sustainable land management strategies.
- Socio-economic assessment of SOC management practices for smallholder farmers. Investigate the socio-economic feasibility, adoption barriers, and benefits of SOC-enhancing practices among smallholder farmers in *Ferralsol* and *Nitisol* regions. This research should include cost-benefit analyses and explore how improved SOC management influences farmer livelihoods, food security, and resilience to climate variability.
- Assessment of microbial and biological soil properties in relation to SOC Levels and Erosion Resilience. Future research should explore how varying SOC levels influence soil microbial communities and biological activity, and

how these biological factors contribute to soil structure stability and erosion resilience in *Ferralsols* and *Nitisols*. Understanding the biological mechanisms behind SOC's protective effects can inform more holistic soil conservation practices.

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LIST OF APPENDICES

Appendix 1: Protocol for determination of organic carbon

The organic carbon was determined using the oxidation procedure as follows:

1. Sample preparation:
 - a) Collect representative soil samples and air-dry them.
 - b) Remove any visible debris or coarse particles from the soil samples.
 - c) Weigh a suitable amount of the air-dry soil sample (Wt.) using a balance and record the weight.
2. Blank preparation:
 - a) Prepare a blank solution by adding a known volume (V_Blank) of ferrous ammonium sulfate solution to a titration flask or container.
 - b) The volume of the blank solution should be sufficient for titration and should not contain any soil sample.
3. Sample titration:
 - a) Take another titration flask or container and add the soil sample to it.
 - b) Add a known volume (V Sample) of ferrous ammonium sulfate solution to the titration flask containing the soil sample.
 - c) Swirl or mix the contents thoroughly to ensure proper mixing.
4. Titration process:
 - a) Start the titration by slowly adding the blank solution to the blank flask while continuously swirling or mixing the contents.
 - b) Observe the endpoint of the titration, which is typically indicated by a color change or appearance of a specific indicator.
 - c) Record the volume (V Blank) of the blank solution required to reach the endpoint.
 - d) Repeat the same titration process for the soil sample using the sample titration flask and record the volume (V_Sample) of the ferrous ammonium sulfate solution required to reach the endpoint.

Organic carbon was then quantified using the following formula:

$$\text{Organic carbon \%} = \frac{V_{\text{Blank}} - V_{\text{Sample}} \times M \times 3 \times 10^{-3} \times 100}{Wt}$$

Where: Blank=Volume (ml) of ferrous ammonium sulphate solution required to titrate the blank, VSample=Volume (ml) of ferrous ammonium sulphate solution required to titrate the sample, Wt. =Weight (g) of air-dry soil, 3×10^{-3} = Equivalent weight of carbon, 100=percentage, M=Molarity of ferrous ammonium sulphate solution (approximately 0.5M i.e. 10/Vblank)

Appendix 2: Protocol for determination of Bulk density

1. Soil samples were collected using core sampling method and trimmed to remove any excess material, ensuring that the samples have a uniform shape and size.
2. An ovenproof container was selected and its weight, W1, was measured before placing any soil.
3. A cylindrical metal ring of known volume and diameter was used as a sampling tool.
4. The metal ring was carefully inserted into the soil at the desired depth, ensuring a snug fit.
5. The excess soil around the ring was carefully removed to obtain a clean and level soil surface.
6. The metal ring with the soil sample was carefully extracted from the ground, ensuring minimal disturbance.
7. The soil sample, still inside the metal ring, was transferred into the ovenproof container.
8. The combined weight of the dried soil and the container, W2, was measured.
9. The weight of the container, W1, was subtracted from the combined weight (W2) to obtain the weight of the dried soil.
10. The volume of the metal ring, V, was measured or calculated based on its known dimensions.

Bulk density was computed as follows;

$$\text{Bulk density } (g \text{ cm}^{-3}) = \frac{W2 \text{ g} - W1 \text{ g}}{V \text{ cm}^3}$$

Where W2 = Weight of the dried soil, W1 = Weight of an ovenproof container, and V = Total soil volume.

Appendix 3: Protocol for determination of Hydraulic conductivity

1. Soil samples were collected using core sampling method and trimmed to remove any excess material, ensuring that the samples have a uniform shape and size.
2. Saturation of Soil Samples:
 - a) A constant-head permeameter or a variable-head permeameter apparatus was set up.
 - b) The trimmed soil samples were weighed to determine their initial mass (M_0). The soil samples were placed in the permeameter apparatus and saturated with water by slowly applying water from the bottom.
 - c) Saturation of the samples continued until no air bubbles were observed, and the water level remained constant at the top of the sample.
 - d) The saturated soil samples were weighed to determine their saturated mass (M_{sat}).
3. Permeability Test:
 - a) A constant-head or falling-head permeability test apparatus was set up
 - b) The saturated soil samples were placed in the permeability test apparatus.
 - c) The flow of water through the soil sample was started and allowed to stabilize.
 - d) The flow rate of water passing through the sample over a specific time period was measured.
 - e) The difference in hydraulic head across the sample during the test was measured.
 - f) The permeability test was repeated for multiple hydraulic gradients or head differences.
 - g) All the necessary data for each test were recorded.
4. Data Analysis:
 - a) The average flow rate (Q) was calculated for each hydraulic gradient or head difference tested.
 - b) The effective cross-sectional area (A) of the soil sample was determined.

Hydraulic conductivity was then determined using the formula provided below;

$$K_t = \frac{Q \cdot L}{A \cdot T \cdot \Delta h}$$

Where K_t = hydraulic conductivity determined as temperature t ($m.h^{-1}$), Q is the volume of water flowing through the soil sample (m^3), L is the height of the sample (m), A is the cross-sectional area of the sample (m^2), T is the time (h), and Δh is the difference in levels of the water table in the column and in the outer cylinder of the apparatus (m).

Appendix 4: Protocol for determination of Water retention

1. Samples were collected for analysis of soil water retention capacity.
2. Rubber sample rings or metal rings with cheese cloth were used.
3. The rings were fastened to one end with a rubber band around a pre-soaked - 15 bar ceramic plate.
4. The rings were filled with soil in triplicate, and the plate was placed in a large tray.
5. Tap water was added slowly, filling the sample rings halfway.
6. The samples were soaked overnight.
7. The outflow tube on the ceramic plate was sealed with a clamp.
8. Excess fluid was drained out of the tray using a syringe/siphon.
9. The plate with samples was placed in a pressure chamber.
10. Two outflow tubes of the ceramic plate were fitted inside and outside the chamber.
11. The free end of the tube was placed in a beaker of water.
12. The outflow tube was unclamped to allow water to flow freely from the ceramic plate to the beaker outside the chamber.
13. A damp cloth was placed over the samples in the chamber to maintain high humidity.
14. The samples were allowed to equilibrate for 2 to 4 days.
15. Air pressure was applied slowly to the chamber until 15 bar was reached.
16. The samples were then allowed to equilibrate further.
17. Pressure was released slowly, and the samples were removed from the chamber.

Water retention was then determined using the formula provided below;

$$\text{Water retention capacity (\%)} = \frac{W_2 - W_3}{W_3 - W_1} \times 100$$

Where, W1 = weight of container (g), W2 = weight of container + wet soil (g) and W3 = weight of container + oven dry soil.

Appendix 5: Protocol for determination of Nitrate (NO₃)

The procedure for determining nitrate (NO₃) content using the Kjeldahl process, as described by Okalebo et al. (2002), involved the following steps:

1. Sample preparation:
 - a) Soil samples were collected and prepared for analysis.
 - b) The collected soil samples were air-dried and sieved to remove any coarse particles or debris.
 - c) A subsample of the sieved soil was weighed into a digestion vessel.
 - d) The digestion vessel was labeled accordingly.
2. Digestion procedure:
 - a) A suitable digestion method was chosen based on the nature of the samples and the target analyte (nitrate).
 - b) The Kjeldahl digestion method, which involves the conversion of nitrate to ammonium ions through a series of chemical reactions, was employed.
 - c) The digestion vessel containing the soil sample was treated with a reducing agent, a mixture of sodium sulfite and sodium hydroxide.
 - d) Sulfuric acid was added to the digestion vessel to initiate the digestion process and provide the necessary acidic conditions.
 - e) The digestion vessel was heated using a digestion unit until complete digestion of the organic matter and conversion of nitrate to ammonium ions occurred.
 - f) After digestion, the digested solution was allowed to cool, and distilled water was added to dilute the digestate.
 - g) The diluted digestate was transferred to a clean container for further analysis.
3. Nitrate determination:
 - a) The nitrate content in the diluted digestate was determined using a suitable method, such as colorimetry or spectrophotometry.
 - b) A nitrate-reactive agent, typically a diazotizing reagent or an organic dye, was added to the diluted digestate.
 - c) The resulting color intensity or absorbance was measured at a specific wavelength using a spectrophotometer.
 - d) The absorbance readings were compared to a calibration curve generated from standard solutions of known nitrate concentrations.
 - e) The nitrate concentration in the diluted digestate was calculated based on the calibration curve.

The concentration of (NO₃) was quantified as follows:

$$\text{NO}_3 \quad (\mu\text{g kg}^{-1}) = \frac{(a-b) \times V \times \text{MCF} \times 1000}{w}$$

where a = concentration of NO₃ + -N in the solution, b = concentration of NO₃ + -N the blank, v = volume of the extract; w = weight of the fresh soil; MCF = moisture correction factor.

Appendix 6: Protocol for Total Phosphorous content

The procedure for phosphorus determination was done using the Mehlich 3 extracts method, as described by Pittman et al. (2005). It involved the following steps:

1. Soil samples were collected and prepared for analysis.
2. The collected soil samples were air-dried and then sieved to remove any large particles or debris.
3. A subsample of the sieved soil was weighed into a digestion vessel.
4. A mixture of Mehlich 3 extractant solution, consisting of hydrochloric acid (HCl), ammonium fluoride (NH₄F), nitric acid (HNO₃), and EDTA, was added to the digestion vessel containing the soil sample.
5. The digestion vessel was covered and left to sit for a specific period, allowing the extraction of phosphorus from the soil into the solution.
6. After the extraction time, the digestion vessel was agitated or shaken to ensure thorough mixing of the soil and extractant solution.
7. The extract was then filtered to separate the soil particles from the solution using filter paper or a filtration system.
8. The filtered extract was collected in a clean container, and any residue or particles were discarded.
9. The collected extract was analyzed for phosphorus content using a suitable method, such as calorimetry or spectrophotometry.
10. The phosphorus concentration in the extract was determined by comparing the absorbance or color intensity of the sample against a set of standard solutions with known phosphorus concentrations.
11. The results were recorded and reported as the concentration of phosphorus in the soil sample.

The total phosphorous (P) was enumerated using the following formula:

$$P (mg\ kg^{-3}) = \frac{a \times v}{W}$$

Where a = the concentration of P in the sample; v = volume of the extracting solution; w = weight of the soil sample.

Appendix 7: Protocol for determination of Potassium, Sodium, Calcium and Magnesium

The procedure for determining available potassium, sodium, calcium, and magnesium using the flame photometer method developed by Okalebo et al. (2002), involved the following steps:

1. Soil samples were collected and prepared for analysis.
2. The collected soil samples were air-dried and sieved to remove any coarse particles or debris.
3. A subsample of the sieved soil was weighed into a digestion vessel.
4. A known volume of ammonium acetate solution was added to the digestion vessel containing the soil sample.
5. The digestion vessel was covered and shaken vigorously to ensure proper extraction of the exchangeable cations (potassium, sodium, calcium, and magnesium) from the soil.
6. After shaking, the contents of the digestion vessel were allowed to settle for a specific period to allow the soil particles to settle down.
7. The supernatant solution was decanted or filtered to separate it from the soil particles.
8. The filtered extract was collected in a clean container and labeled accordingly.
9. The extract was then transferred into flame photometer sample cups or cuvettes.
10. The flame photometer instrument was calibrated using standard solutions of known concentrations for each of the cations (potassium, sodium, calcium, and magnesium).
11. The flame photometer was set to the appropriate wavelength for each specific cation.
12. The sample cups or cuvettes containing the extract were placed in the flame photometer, and the instrument was operated according to the manufacturer's instructions.
13. The flame photometer measured the intensity of the emission from each cation, and the readings were recorded.
14. The concentration of each cation in the soil extract was determined by comparing the readings obtained from the soil extract to the calibration curve generated from the standard solutions.
15. The results were recorded and reported as the available potassium, sodium, calcium, and magnesium concentrations in the soil sample.

The concentration of K, Na, Ca and Mg was quantified as follows:

$$\text{K, Na, Ca and Mg (mg kg}^{-3}\text{)} = \frac{(a - b) \times V \times f \times 1000}{1000 \times W}$$

Where a = the concentration of K, Ca and Mg in the sample; b = the concentration K in the blank; v = volume of the extracting solution; f = dilution factor; w = weight of the soil sample.

Appendix 8: Protocol for determination of Sulphate

The procedure for determining sulphate using the turbid metric method developed by Okalebo et al. (2002) involved the following steps:

1. Soil samples were collected and prepared for analysis.
2. The collected soil samples were air-dried and sieved to remove any large particles or debris.
3. A subsample of the sieved soil was weighed into a digestion vessel.
4. Distilled water was added to the digestion vessel containing the soil sample, creating a soil-to-water ratio suitable for sulfate extraction.
5. The digestion vessel was covered and shaken vigorously to ensure proper extraction of sulfate from the soil.
6. After shaking, the contents of the digestion vessel were allowed to settle for a specific period to allow the soil particles to settle down.
7. The supernatant solution was decanted or filtered to separate it from the soil particles.
8. The filtered extract was collected in a clean container and labeled accordingly.
9. A turbidimetric reagent, typically barium chloride or barium sulfate solution, was prepared.
10. A measured volume of the filtered soil extract was transferred into a cuvette or test tube.
11. A known volume of the turbidimetric reagent was added to the cuvette or test tube containing the soil extract.
12. The cuvette or test tube was mixed thoroughly to ensure proper reaction between the sulfate ions and the turbidimetric reagent.
13. The turbidity of the resulting solution was measured using a turbidimeter or a spectrophotometer set at a specific wavelength.
14. The turbidity reading obtained from the soil extract was compared to a calibration curve generated using standard solutions of known sulfate concentrations.
15. The sulfate concentration in the soil extract was determined based on the calibration curve.
16. The results were recorded and reported as the sulfate concentration in the soil sample.

Sulphur in the samples was then computed in S (mg kg⁻¹) using the formula;

$$\text{Sulphur (mg kg}^{-1}\text{)} = \frac{(a-b) \times v \times f}{w}$$

Where a = concentration of S in the solution; b = concentration of S in the mean values of the blanks; v = final volume of the sample digest; w = weight of the sample taken; f = dilution factor

Appendix 9: Protocol for Total Nitrogen content

The procedure for analyzing total nitrogen was done using the Kjeldahl method and distillation procedure that involved the following steps:

1. Samples were collected and prepared for analysis.
2. The collected samples were weighed and transferred into digestion flasks.
3. A mixture of concentrated sulfuric acid and catalysts, such as potassium sulfate or copper sulfate, was added to the digestion flasks.
4. The digestion flasks were heated using a Kjeldahl digestion unit until complete digestion of the organic matter occurred.
5. After digestion, the flasks were allowed to cool, and distilled water was added to the flasks to dilute the digestate.
6. A mixture of sodium hydroxide and sodium thiosulfate was added to the diluted digestate to raise the pH and neutralize the excess acid.
7. The distillation apparatus, including a condenser, receiver, and collecting flask, was set up.
8. The diluted digestate was then distilled using steam distillation.
9. The distillate, which contained the ammonia released from the sample, was collected in the receiver flask.
10. The collected distillate was titrated with standardized hydrochloric acid solution using an indicator, such as phenolphthalein or methyl orange.
11. The endpoint of the titration, indicated by a color change in the indicator, was recorded.
12. The volume of the hydrochloric acid used in the titration was noted.
13. The amount of nitrogen present in the sample was calculated using the volume of hydrochloric acid used, the molarity of the acid, and the stoichiometry of the reaction.
14. The calculated nitrogen content was reported as a percentage or concentration in the original sample.

The total nitrogen (N) was then calculated using the following formula:

$$\% \text{ N} = \frac{(V-B) \times N \times R \times 14.01 \times 100}{Wt_2 \times 1000}$$

Where: V=Volume of 0.01 N H₂SO₄ titrated for the sample (mL), B=Digested blank titration volume (ml), N=Normality of H₂SO₄ solution, 14.01=Atomic weight of N, R=Ratio between total volume of the digest and the digest volume used for distillation, Wt1=Weight of EDTA (g), Wt2=Weight of air-dry soil (g), 186.1=Equivalent weight of the EDTA

Appendix 10: Protocol for determination of Copper, Iron and Zinc

Determination of copper (Cu), iron (Fe), and zinc (Zn) was done using atomic absorption, as described by Okalebo et al. (2002), and involved the following steps:

1. Sample preparation:
 - a) Soil samples were collected and prepared for analysis.
 - b) The collected soil samples were air-dried and sieved to remove any coarse particles or debris.
 - c) A subsample of the sieved soil was weighed into a digestion vessel.
 - d) The digestion vessel was labelled accordingly.
2. Digestion procedure:
 - a) A suitable digestion method was chosen based on the nature of the samples and the elements being analyzed.
 - b) Commonly used digestion methods include wet digestion using acids (such as aqua regia or concentrated HCl and HNO₃) or dry ashing techniques.
 - c) The digestion procedure was carried out where digestion vessels were heated to appropriate conditions to ensure complete decomposition of the organic matter and solubilization of the target elements.
 - d) After digestion, the samples were allowed to cool, and the digested solutions were transferred to clean containers.
3. Atomic absorption measurement:
 - a) The atomic absorption spectrometer was set up and calibrated according to the manufacturer's instructions and instrument specifications.
 - b) Standard solutions of known concentrations for each element (Cu, Fe, and Zn) were prepared.
 - c) Calibration curves were generated by measuring the absorbance of the standard solutions at specific wavelengths.
 - d) The digested soil samples were aspirated into the flame of the atomic absorption spectrometer, and the absorbance of each element was measured.
 - e) The instrument settings (such as lamp current, slit width, and flame conditions) were adjusted as necessary to optimize the measurements.
 - f) The absorbance readings obtained from the samples were compared to the calibration curves to determine the concentrations of Cu, Fe, and Zn in the soil samples.
4. The concentration of each element in the soil samples was calculated based on the absorbance readings and the calibration curves. b. Blank analyses and replicates, were performed to ensure the accuracy and precision of the measurements. The concentration of Cu, Fe and Zn was quantified as follows:

$$\text{Cu, Fe, and Zn (mg kg}^{-3}\text{)} = \frac{(a - b) \times V \times f \times 1000}{1000 \times W}$$

Where a = the concentration of Cu, Fe and Zn in the sample; b = the concentration K in the blank; v = volume of the extracting solution; f = dilution factor; w = weight of the soil sample.